Recommendations for Determining Regional Instream Flow Criteria for Priority Tributaries to the Sacramento-San Joaquin Delta

A report to the California State Water Resources Control Board

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Forward by the Delta Science Program

Working with a broad range of agencies and stakeholders, the Delta Science Program developed the Delta Science Plan in 2013. The Delta Science Plan is intended to strengthen, organize, and communicate science to provide relevant, credible, and legitimate decision-support for policy and management actions. One of its objectives is to enable and promote science synthesis. One of the primary tools for providing this synthesis is the organization and facilitation of independent panels charged with integrating information from multiple sources on a particular scientific question in order to gain new insights and to effectively communicate this new information. This report is the result of one such effort conducted in response to a request to the Delta Science Program from the State Water Resources Control Board (Board).

Board staff conveyed this request to the Delta Science Program in the form of a cover letter and report that outlined example flow criteria methods, approaches to consider, and the Board's requirements and constraints. Working with Board staff, the Delta Science Program determined the appropriate synthesis mechanism and, under the direction of the Lead Scientist, selected the panelists. Funding for this synthesis effort was provided by the Board. As with all of the independent review, synthesis, and advice documents prepared for the Delta Science Program, the content, substance, and recommendations in this report are those of the panel, not the Delta Science Program or Delta Stewardship Council.

Additional information about this synthesis project can be found on the Delta Science Program's web site: http://deltacouncil.ca.gov/science-event/10114.

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1. Request to Committee

Through a request to the Delta Science Program, we have been asked to provide written recommendations for the California State Water Resources Control Board (SWRCB) for identifying methods to determine instream flow criteria that are 1) scientifically defensible, 2) cost-effective, 3) applicable at the watershed scale, and 4) capable of implementation in a timely manner. The main focus for these methods will be the tributaries to the Sacramento-San Joaquin Delta (Bay-Delta). Two potential regional methods (a regionalized version of the Instream Flow Incremental Methodology (IFIM) for Pennsylvania and Maryland and the Ecological Limits of Hydrologic Alteration (ELOHA) methodology) were described in a July 2013 document prepared by the SWRCB for consideration as appropriate methodologies for application in California by the review committee.

1.1 Specific Requests from the SWRCB Regarding Review of Flow Criteria Methods

- Identification of methodology that is scientifically defensible, cost-effective, representative at the watershed scale, and timely relative to implementation.
- Input on how recommended methodology or methodologies can be augmented or refined in the future.
- How to develop flow criteria that apply to the majority of the watershed within a tributary that addresses multiple species, different life stages, and different fluvial processes.

1.2 Guidance for Phase 4 of the Bay-Delta Water Quality Control Plan

Phase 4 of the Bay-Delta Water Quality Control Plan calls for the development and implementation of policies for water quality control that include the development of flow criteria and flow objectives for priority tributaries of the Bay-Delta (with a focus on the Sacramento River watershed). The SWRCB has asked for guidance from the committee on how best to 1) develop flow criteria and 2) develop flow objectives and implementation plans.

The members of the review committee have considerable experience in developing flow criteria and implementing these flow criteria in Florida, Texas, and California. The committee has used three appendices to share some of our experience for determining both local and regional flow criteria in California, Florida, and Texas. The committee sees summarizing key lessons learned elsewhere and referencing the more detailed appendices as a useful way to provide specific guidance to the SWRCB. The committee also has looked at the two regional methods described by SWRCB staff and provided some thoughts on the strengths and weaknesses of these approaches and presented what we see as key steps in successfully developing flow criteria that can be implemented and evaluated for effectiveness.

We have structured the report into four sections. The first section summarizes our charge and the tasks we have been requested to provide. The second section reviews the two regional proposed methodologies that were summarized by staff from the SWRCB. The third section provides recommendations on a hybrid approach to setting flow criteria that draws from the two regional methods that were discussed and incorporates the committee's consensus view on the required steps for developing flow criteria for priority tributaries to the Sacramento-San Joaquin Delta. These steps reflect decades of experience in setting scientifically defensible flow criteria in Florida, Texas, and California. The fourth section provides some conclusions that we hope are helpful for the SWRCB.

2. Review of Proposed Methodologies

The committee appreciates the highlighting of strengths and weaknesses for the two potential regional methods that were made by SWRCB staff in their July 2013 document titled "Potential Methods to Develop Flow Criteria for Priority Tributaries to the Sacramento-San Joaquin Delta." The general thoughts of the committee concerning the strengths, weaknesses, and uncertainties of the two methods (regional IFIM and ELOHA) are bulleted below.

2.1 Inputs on the IFIM Regional Habitat Based Method

Some strengths of the regionalized IFIM method

- The IFIM method can incorporate site specific information using one or many tools (e.g. Physical Habitat Simulation (PHABSIM), Riverine Habitat Simulation (RHABSIM), Critical Riffle Assessment (CRA), Wetted Perimeter Method (WPM), Hydrologic Engineering Center – River Analysis System (HEC-RAS), Sedimentation and River Hydraulics – Two Dimensional (SRH-2D) Model, and FLO-2D); most of these methods focus on characterizing instream habitat as a function of discharge.
- The IFIM framework allows for multiple tools and user inputs to be utilized in determining flow criteria.

Some weaknesses of the regionalized IFIM method

- The method cannot be applied for systems where there are no data (relies on known conditions); however, this constraint seems unlikely for hydrologic data but more likely for ecologic data for most sites to be assessed in California. The regionalized Pennsylvania and Maryland Method (PMM) requires that site specific assessments are somehow extrapolated to areas with no data or limited data, yet how to carry out this extrapolation is not clear from the materials we reviewed.
- The regional IFIM method typically relies on potentially subjective classification of like stream segments using some type of geomorphic characterization.

- The PMM focuses on species-specific habitat relationships, omitting other important factors such as temperature constraints on fish and invertebrate populations and the role of food webs in producing adequate food resources for higher trophic levels.
- Ecological processes such as primary production, community respiration, decomposition, and nutrient cycling are not addressed.

Some uncertainties of the PMM approach to IFIM

- Relies on static habitat conditions by establishing a reference baseline that may change (e.g. due to climate warming, land use change, floodplain vegetation dynamics, channel avulsion, etc.).
- Invasive species impacts and pressures are not easily addressed within the framework of the regional IFIM.

2.2 Inputs on the ELOHA Method

Some strengths of the ELOHA method

- It is possible to apply this method even if no site specific data exist, although the method does require that data are available from a similar type of stream or river.
- Statistical methods can incorporate variability/range of conditions and degree of hydrologic alterations.
- Natural flow regimes and processes are used as the hydrologic foundation and in developing ecological-flow relationships; the natural flow regime is the baseline against which change is measured.
- The method is watershed-wide in scale and multiple species are incorporated into the assessment.
- Adaptive management is incorporated as a key aspect of the ELOHA methodology.

Some weaknesses of the ELOHA method

- May be harder to incorporate site specific information using existing tools/data (PHABSIM, RHABSIM, CRA, WPM, HEC-RAS, SRH-2D, FLO-2D, etc.); the method prefers establishing ecological relationships rather that habitat based relationships.
- Relies on a potentially subjective classification scheme for like streams (like the regionalized IFIM approach).
- Relies on historic conditions for alteration calculations that may not apply under climate change (warming and/or precipitation changes) or extensive land use alteration (also true for the regionalized IFIM).
- Requires relations between ecology and hydrologic alteration that are sometimes difficult to define and support (e.g. Arthington et al. 2012).

Some uncertainties of the ELOHA method

- Regional conditions may change with climate warming and/or precipitation changes - non-stationarity may create new normal condition; statistical relationships will change as climate changes.
- A degree of alteration approach is more appropriate for larger rivers with high land use impacts than smaller rivers/creeks with water quality issues, passage issues, or a few key alterations (e.g. bypass reaches).
- Incorporation of temperature requirements is vague – is this done via ecological-flow relationships?

- There is less of a track record on which to pass judgment on the efficacy of the ELOHA method – Is the ELOHA method politically defensible?

2.3 Comments on the Two Approaches

We have conceptualized the Regional IFIM Habitat Based Method (PMM) as consisting of these four fundamental steps: Step 1– group streams according to specified characteristics; Step 2– identify important biological resources and fluvial processes through an IFIM framework; Step 3– perform site-specific, habitat-based studies on a few representative stream segments; Step 4– apply results of studies to entire suite of stream segments. The ELOHA method consists of these five steps: Step 1– build a hydrologic foundation (analysis of hydrology with flow component separation); Step 2– classify (group) rivers according to flow regime and/or geomorphology; Step 3– analyze recent flow alterations relative to historic records; Step 4– define flow alteration–ecological response relationships (a "key element" of ELOHA); Step 5– using results from Step 4, derive recommended flow regimes based on an "informed social process." To suggest or infer that the PMM and ELOHA are fundamentally different frameworks creates in our view a false dichotomy. There are some distinctions that can be made between the two frameworks, but these may be moot in the context that the SRWCB proposes to use them. In short, both approaches are fairly similar in their data needs and analyses.

For example, Step 1 of the PMM and Step 2 of ELOHA are analogous as outlined above. If one is going to extrapolate using site-specific information to areas (stream segments) without site-specific information, it is logical to assume that these extrapolations are most applicable to streams of similar hydrology and/or geomorphology type. To quote Poff et al. (2010), "For each river type there is a range of natural hydrologic variation that regulates characteristic ecological processes and habitat characteristics . . ., and that represent the baseline or reference condition against which ecological responses to alteration are measured across multiple river segments falling along a gradient of hydrologic alteration." While ELOHA clearly states that the natural flow regime is the baseline, it is also implicit in the PMM since in a regionalized approach you must begin with the assumption that habitat availability is similar in similar stream types. This type of analysis can only be done if it is assumed that sites begin with the same baseline flow condition. The IFIM framework is fundamentally a bottom-up approach (adds various flows to a static minimum as needed) versus ELOHA, which is more of a top-down approach (starts with the full natural flow regime and removes flow until there are major ecological consequences). *Both approaches have merit, and we suggest drawing from both in the Phase 4 efforts by staff from the SWRCB.*

The committee also wants to emphasize that there are some added considerations that should be given some attention when developing regional flow criteria for priority tributaries of the Sacramento-San Joaquin Delta.

1. The regionalization methodology should take into account hydro-climate drivers like the El Niño Southern Oscillation (ENSO) phenomenon and the Pacific Decadal Oscillation (PDO) that change runoff characteristics on both an annual and decadal time step. There is a strong latitudinal gradient from north to south on the impacts of these climate drivers on precipitation and hydrology that deserve consideration when setting flow criteria (see, for example, Benson et al. 2003, Gutzler et al. 2002, Schonher and Nicholson 1989).
2. There is a need to consider temperature regime, sediment transport and lateral connectivity in whatever methodology is adopted. How best to incorporate these considerations into the ELOHA framework remain to be determined. Reliance on flow alteration statistics alone may or may not address these issues.

3. Techniques such as PHABSIM have been successfully applied in hundreds if not thousands of instances and produce quantifiable results that are readily amendable to incremental analysis. The major criticism of PHABSIM is that reductions or increases in habitat (weighted usable area in the case of PHABSIM) do not necessarily equate to changes in fish abundance or biomass. Some effort to link habitat with flow is warranted in the development of these flow criteria.

In summary, the committee sees the best way forward to be the adoption of an approach that draws from the strengths of both the IFIM and ELOHA methodologies acknowledging the climatology, hydrology, and geomorphology of California.

3. Recommendations

The committee recommends a hybrid approach that includes elements of the IFIM and ELOHA methodologies plus successful components from both setting and implementing flow criteria in other locations (e.g. Florida and Texas). Because the regionalized IFIM (PMM) and ELOHA methods have numerous elements or steps in common, the two approaches are not mutually exclusive. A hybrid of both approaches therefore seems most appropriate – start with the ELOHA method and use site-specific information where additional data are available. Existing site-specific data may also be useful for developing more general discharge-ecology relationships (e.g. California examples in Appendix 1). Further insight can be gained by looking to the extensive experience in Florida and Texas where methodologies have been developed with recommendations that have been thoroughly reviewed and challenged, and the subsequent flow criteria have been successfully implemented (Appendices 2 and 3). We therefore envision and discuss below a seven step process that incorporates or merges concepts in both methods considered by the SWRCB, and methods applied in other regions of the US.

Although some may view the ELOHA approach as new, it does build on a considerable amount of work that was done previously, borrowing from approaches and concepts that evolved over time, including those in the IFIM. Perhaps what is most unique about the ELOHA process is the idea that sufficient data gathered on a given type of system can be extrapolated to other similar systems where ecologically based flow criteria is needed. This is a particularly attractive idea because, as Poff et al. (2010) explain, flow regimes are being anthropogenically impacted at a rate faster than ecological flow criteria can be developed using site-specific approaches. While a more regional approach is desired either due to time or resource constraints, it should be acknowledged that a site-specific approach would be more scientifically defensible simply because uncertainties associated with extrapolation would be avoided.

Unlike ELOHA, IFIM (as originally developed) was a site-specific approach, but was adapted in the PMM application so that it could be regionally applied. Extrapolation of site-specific results was accomplished using the same logic as used in ELOHA, that is, sampled streams within a class are expected to have comparable [ecologic] versus discharge relationships (Denslinger et al. 1998).

As described by Poff et al. (2010), regional flow standards are achieved by:

- Building a “hydrologic foundation” of baseline and current hydrographs for stream segments throughout the region
- Classifying stream segments into a few distinctive flow regime types that are anticipated to have different ecological characteristics
- Determining the deviation of current flows from baseline flows
- Developing flow alteration-ecological response relationships for each stream type

It is interesting to note that some of the more critical aspects of the ELOHA framework (i.e., society and policy challenges associated with adopting environmental flow standards) admittedly receive “only cursory treatment" in ELOHA's seminal paper (Poff et al. 2010). Successful implementation of flow standards commonly rests more heavily on these societal challenges than any challenges that are of a more scientific nature.

3.1 Recommended Methodology–A Seven Step Approach

The committee discussed the common steps that have been instrumental in preparing flow criteria for streams and rivers from our collective experiences in three different parts of the United States over the past two decades. More detailed discussion with examples of applications utilizing these steps can be found in the appendices. We see seven steps as critical in determining instream flow criteria that are 1) scientifically defensible, 2) cost-effective, 3) applicable at the watershed scale, and 4) capable of implementation in a timely manner. The steps are:

Step 1) Stream segment classification

While there are a number of classification systems that might be used, the logic behind selection of a given classification system is that the ecology of a stream segment is a direct function of its hydrology. "The flow regime is a primary determinant of the structure and function of aquatic and riparian ecosystems for streams and river" (Poff et al. 2010). Although the PMM was directed specifically at two species of trout, the authors of that report (Denslinger et al. 1998) realized that,"[t]o develop a regional procedure for assessing impacts of withdrawals on any stream in a region, the streams need to be classified according to important characteristics related to fishery habitat. . . . The purpose of the stream classification system was to identify classes of streams that have similar key physical features. Key physical features are those that have a direct influence on physical variables (e.g. depth and velocity) and stream attributes (substrate and cover) used to quantify fish habitat." In short, regionalization of an approach (the ability to extrapolate site-specific ecologic relationships to water bodies without site-specific information) is accomplished under the assumption that similar hydrology (and geology) results in similar ecology. Both the PMM and ELOHA methods require some form of stream segment classification in order to extrapolate regionally.

In California, two stream classification methods are more commonly used than others. The Montgomery and Buffington (1997) stream classification is well-suited to the montane river regions in the state and is generally favored in academic research studies as it is process-based. The methodology directly relates to the physical processes and characteristics that drive channel form, such as slope, discharge (transport capacity) and sediment supply. So stream alterations that affect these processes (ex: a dam changing flows or blocking sediment) may affect the stream reach-type and subsequently the macrohabitats within the reach. Each reach-type is distinct enough that different sets of habitats typically occur with each reach type. Yet, the reach-type categories are broad enough that most practitioners will categorize stream reaches similarly. The Rosgen (1994) stream classification method is a form-based categorization that is generally favored in consulting studies, such as those completed in FERC relicensing projects. Two levels of classification can be applied; the first is very broad resulting in only a few types in California, while the second is much more detailed requiring some level of training and understanding of the 54 finer-scale categories. Whether or not the form-based categories readily relate to channel processes and potential future changes in channel form is much debated in the literature (e.g. Simon et al. 2007, Roper et al. 2008).

For the purposes of classifying streams in order to apply regional flow criteria, specific characteristics such as watershed size, hydrologic regime, dominant geomorphology and faunal assemblages should be considered. A process-based classification scheme such as Montgomery and Buffington (1997) could be useful in categorizing the geomorphic aspects of various river systems and could be easily set within a geographic classification scheme that recognizes primary climatic drivers and coupled with key ecological data such as the presence of desired native species assemblages.

Step 2) Hydrologic analysis that includes separation of the hydrology into key flow regime components (blocking) and an analysis of historical changes

The examples provided for California, Texas, and Florida acknowledge that "multiple flow regimes are needed to maintain biotic and abiotic resources within a river system" (Hill et al. 1991). For example, the Southwest Florida Water Management District (SWFWMD) developed an approach that divided the fairly predictable annual flow regime for most streams in southwest Florida into component parts ("blocks") based on an understanding of regional hydrology, and then tailored monitoring (acquisition of site-specific data) so as to protect various ecological components in each of these blocks (see Florida example in Appendix 2). Although a site-specific approach is used by the SWFWMD in developing environmental flow criteria, it is similar to ELOHA in that it is designed to protect a range of flows to address the needs of multiple resources (e.g., fish passage, species specific instream habitats, inundation of woody habitats, and the river-floodplain connection). A major distinction between the PMM method as described by Denslinger et al. (1998) and the ELOHA method is that the later addresses, at least in theory, the complete natural flow regime while the PMM was directed solely at trout habitat. There is no reason, however, why the PMM could not have been tailored to other resources of concern other than trout; this would essentially make the PMM and ELOHA equivalent in most respects.

We advocate the development of flow criteria based on more than the consideration of species specific habitats (such as is done in PHABSIM) so that the full range of flows is considered in some manner. As explained in the ELOHA approach (see Poff et al. 2010, Figure 3 and related text), the shape of the natural hydrograph will to a large extent determine what metrics (i.e., ecology-flow relationships) should be explored. For example, the successful recruitment of native riparian trees for a snowmelt-dominated river often depends on seed release being coincident with timing of flows of sufficient magnitude to raft seeds onto suitable riverbank habitat (e.g., cottonwood in western North America). Similarly, Yarnell et al. (2010) developed a conceptual model of the spring snowmelt recession with specific California examples demonstrating that "changes in the shape of the spring snowmelt recession hydrograph can have both direct and indirect effects on aquatic and riparian species." For example, shifts in the timing of the start of the recession coupled with higher rates of change can directly affect cottonwood recruitment or foothill yellow-legged frog egg survival, whereas decreases in flow magnitude could adversely affect the availability of suitable habitat for both species. Consideration of trout habitat or populations, for example, would not necessarily ensure protection of other species or processes. For this reason, we suggest that multiple metrics should be considered as discussed further in Step 3 below.

Step 3) Site-specific field work that addresses key information gaps

Because a regionalized approach involves sampling presumably fewer sites so that inferences can be made regarding a population of sites, it offers a savings of effort and resources over more traditional site-specific case-by-case studies. However, it should not be assumed that one can simply take whatever site specific information exists in whatever format, run it through a statistical blender, and hope to end up with something that is not so homogenized that it is useful. A thorough analysis of what data exists and what information gaps remain is needed to ensure that any additional data collection ultimately results in better understanding of the relationships between ecological aspects and the hydrologic regime.

The SWRCB recognizes that there are not available resources and time to conduct the needed site-specific studies without a regional approach. However, as demonstrated in the PMM document, considerable site-specific information was needed to apply their regional approach to a rather restricted set of streams. These constraints would also be true for ELOHA; some site specific data must be acquired, and the amount and extent is determined by the resources to be protected (i.e., ecological indicators to be used in developing flow alteration-ecological response relationships). In order to maximize limited resources, field efforts should be targeted toward representative species assemblages and processes considered most important in the overall context of the region. Existing studies may provide data for certain aspects, such as instream habitat requirements of notable fish species, but additional data collection on ecological process (e.g. floodplain connectivity, benthic productivity or native assemblages) will likely be needed.

Under an "economy of scale" approach, co-locating new ecological study sites with existing sites from IFIM studies could further maximize resources and allow for more thorough analysis of habitat-flow-ecology relationships. For example, field crews at SWFWMD made multiple measurements at co-located sites. Wetted perimeter and fish passage depth measurements were made at riffle sites concurrent with elevation measurements needed for PHABSIM. The survey data were then not only used in PHABSIM, but in subsequent HEC-RAS modeling used to assess fish passage, over-bank flows, and inundation of woody habitats. While this required greater effort at a particular field site, overall costs were optimized to the extent possible.

As reported by the SWRCB in their methodology assessment, "there are many site-specific IFIM studies being conducted in Bay-Delta tributary watersheds by various groups." However, the majority of these studies focus on the instream habitat needs of specific fish species, rather than broader ecological relationships. Poff et al. (2010) specifically acknowledge that "applications of habitat-based methods like the wetted perimeter approach (PHABSIM or MesoHABSIM) could provide habitat information used in the ELOHA framework." However, it is likely that some additional data will need to be collected on not only multiple aspects of the flow regime, but multiple species and assemblages as well.

Denslinger et al. (1998) explicitly state that the main purpose of their PMM studies was to develop instream flow protection standards to protect trout populations from the effect of withdrawals. While they also acknowledged that there were other priority issues that should be addressed, they restricted the application of their approach to only a sub-set of stream segments and a sub-set of possible flow regimes (i.e., the regime that would protect trout habitat as assessed by PHABSIM using locally derived habitat suitability curves (HSC)).

The committee does not generally endorse a method that targets only a few particular species as was done in the PMM. Such an approach would not address the full range of flows necessary to maintain multiple ecological processes inherent in the natural flow regime (Poff et al. 1997). In our view, an approach that does not address the entire flow regime should only be applied if the stream or river system is considered altered beyond repair, and the objective becomes maintenance or recovery of certain target species or processes.

Step 4) Extrapolation of findings/understanding of processes and relationships from one site to other sites.

This is the essence of making a regional assessment of setting flow criteria work effectively. The PMM was relatively successful in developing a regional approach primarily because they used: 1) a quantifiable metric for extrapolation (fish habitat), 2) a classification system that involved consideration of hydrology and geomorphology, and 3) a considerable amount of site-specific information. The major short-coming of the approach, however, was that it did not address the complete flow regime or the hydrogeomorphic processes that sustain ecological functions. In contrast, the ELOHA approach "was explicitly designed to address the issues that have prevented other methods from being applied widely" (Richter et al. 2011), and specifically focuses on flow-ecology relationships. In their application of the ELOHA method, Arthington et al. (2012) found that hydrologic metrics alone explained relatively little variation in assemblage structure for riparian and aquatic vegetation and fish. Without consideration of the geomorphic setting and processes inherent to river systems, an understanding of the flow effects on ecology is limited. We suggest that the key to extrapolation across the region is to focus on key hydrologic components that drive geomorphic and ecologic processes in river systems. Specific to California's hydroclimatic conditions, these include (at a minimum) peak and overbank flood flows that scour and move sediment, spring recession flows that provide key ecological cues for native species, summer baseflows that sustain aquatic habitat through the dry season, and first flush event after the extended dry season that mobilizes nutrients and turbidity.

Each of the primary flow components can be quantified in a manner that allows for extrapolation across systems. For example, Oregon (due to passage of House Bill 3369 in 2009) developed a white paper (Norris 2010) outlining how they might address channel maintenance and ecological low flows in a regional manner. A major part of their process involved the application of the "Oregon Method" (very similar to PHABSIM) used to assess the amount of fish habitat for spawning, migration, and rearing available under different flow rates. Norris (2010) also referenced work completed in Oregon to address channel/habitat maintenance flows with specific guidance provided by Robison (2007). This guidance is similar to that developed by the California SWRCB for northern California coastal streams (i.e., North Coast Instream Flow Policy, SWRCB 2013), which focused on providing 2-year exceedance flows. Similar calculations of flood exceedance could be used to address larger peak flow events such as the 5 or 10-year flood that inundate floodplains and reset ecological processes. However, the Oregon methodology did not consider "biological triggering flows" that stimulate and facilitate important life stage behavior such as migration or spawning for target species. Although some criticized the use of the word "triggering" (see peer review comments in Norris 2010), the white paper clearly established the need to protect "the range of flows that create or maintain key ecosystem functions and habitat features" with the explicit recognition that "[a]n adequately protected ecological flow regime includes baseflows as well as a variety of elevated flows that provide habitat maintenance and other ecosystem functions." Consistent with the idea of "biological triggering flows", several examples of flow "cues" are provided in the California examples in Appendix 1. Spring recession flows can be quantified in a manner that allows for extrapolation by focusing on ramping rates (Yarnell et al. 2013), while floodplain inundation can be quantified by assessing flood recurrence intervals in relation to channel geomorphology. We suggest that these ecologically important flows could be addressed in a regional approach by focusing on quantifiable metrics related to river processes rather than specific flow magnitudes or values that may not translate across systems.

Finally, the committee suggests that extrapolating processes rather than specific numbers (target flows, inundation depths, peak magnitude flows, etc.) is more likely to be successful when generalizing flow/ecology relationships at regional scales. For example, ensuring that a peak magnitude flow that causes scour on the floodplain happens every 5-10 years, rather than flows of some specific value occurring every five years, extrapolates the process rather than specific flows. Similarly, spring recessions declining at a rate of less than 10% per day on ensures a suitable duration of slow decline regardless of the starting magnitude of flow or the size of the stream. . Setting flow criteria that extrapolate key processes are preferred over exporting specific values from one ecosystem to another.

Step 5) Production of an environmental flow regime that meets the needs of multiple ecosystem components (e.g. species) and processes (e.g. sediment dynamics that influence geomorphology, habitat connectivity, and production dynamics).

The formation of a regional flow regime is where the ELOHA method differs conceptually from the PMM method. While the PMM methodology as applied in Pennsylvania and Maryland could have incorporated analyses to address multiple ecosystem components, the method explicitly limited its scope to evaluating habitat for two species of trout. Conceptually, however, the IFIM approach could be expanded to address multiple ecosystem components, including species other than fish and key ecosystem processes such as primary and secondary production, nutrient cycling, and decomposition. The resources of primary concern and their responses to altered flow regimes within a reach or catchment should be targeted for assessment.

Steps 1-4 produce the information base upon which to propose recommended environmental flow regimes that best meet the needs of critical species and crucial physical, chemical, and hydrological processes. Breaking the annual hydrograph into distinct blocks with different flow characteristics allows the life history of species of concern to be better addressed throughout the annual hydrograph. Defined attributes of the blocks that influence key physical and chemical processes of the stream or river ecosystem also can be evaluated. The recommended flow regime goes beyond just the magnitude of flow to consideration of the timing of different flows, the frequency of flow types, the duration of characteristic flows, and the rate of change for both increasing and decreasing flows. Effective and scientifically informed completion of the first four steps lays the foundation for producing flow criteria throughout the annual hydrograph that are protective of floodplain species and key stream and river processes.

Step 6) Interaction between scientists and stakeholders so there is buy-in for actions and outcomes proposed for adoption.

Ideally, stakeholder involvement is ongoing from the earliest stages of selecting the appropriate stream classification system, to selection of resources of concern for which to develop data for regionalization, and finally when making judgments regarding acceptable risks and trade-offs. However, it is essential that all stakeholders are involved in the final discussion and selection of an environmental flow regime so that there is support and consensus regarding subsequent management and monitoring. For example, in the FERC relicensing process, all stakeholders have the opportunity to participate in and contribute to the process of determining managed flow regimes below dams. While some resource agencies (e.g. US Forest Service or US Fish and Wildlife) may wield greater influence as they are signatories on the license, all parties including public participants may provide input to the negotiated outcomes. In some cases, this has led to non-traditional agreements that include allocations of water for recreational uses alongside ecological and hydropower needs (e.g. see Appendix 1C). Following the issuance of the license, many hydropower projects in California have furthered stakeholder involvement by creating a formal group (termed Ecological Resources Committee, Natural Resource Group, etc.) that continues to evaluate the impacts and effects of newly instituted flow regimes (e.g. see Appendix 1C). Not only do these groups create a formal process for adaptive management, but they provide a means for continuing dialogue and involvement of all stakeholders. The SWRCB has considerable experience engaging scientists and stakeholders in decision-making efforts. The committee too has had much experience working with stakeholders and scientists, and we simply wish to reiterate the high degree of importance that this step has in successfully developing and implementing flow criteria (e.g. Pahl-Wostl et al. 2013).

Step 7) An adaptive management protocol with robust implementation measurements to support the decision-making process for evaluating implemented flow criteria.

Much has been written about adaptive management. The use of adaptive management is now required by the Delta Reform Act of 2009 in California, and the Delta Plan of 2013 presents an appendix to the plan (appendix C - http://deltacouncil.ca.gov/sites/default/files/documents/files/AppC_Adaptive%20Management_2013.pdf) that lays out protocols for carrying out effective adaptive management. Adaptive management is defined by California law as "a framework and flexible decision making process for ongoing knowledge acquisition, monitoring, and evaluation leading to continuous improvements in management planning and implementation of a project to achieve specified objectives." Adaptive management provides flexibility and feedback to the management of natural resources in the face of considerable uncertainty. The Delta Reform Act also calls for "a science-based, transparent, and formal adaptive management strategy for ongoing ecosystem restoration and water management decisions." The Delta Plan puts forth a three-phase ("Plan", "Do", and "Evaluate and Respond") and nine-step adaptive management approach. Intended outcomes of this approach include broader and more consistent use of adaptive management, the application and development of best scientific information, and an increased likelihood of success for water and environmental decision-making under conditions of uncertainty. Because this adaptive management protocol has been developed by the Delta Science Program and approved by the Delta Stewardship Council, the committee recommends the use of this protocol by the SWRCB as they set flow criteria for priority tributaries to the Sacrament-San Joaquin Delta.

4. Conclusions

The SWRCB requested written recommendations that identify a method or methods to determine in-stream flow criteria that are scientifically defensible, cost-effective, applicable at the catchment scale, and can be implemented in a timely manner. This effort is in support of Phase 4 of the SWRCB's process for updating and developing flow objectives for priority tributaries of the California Delta as recommended in the final Delta Plan that was adopted by the Delta Stewardship Council on May 16, 2013. Objectives of Phase 4 include development of non-binding flow criteria, development of flow objectives and implementation plans, and the development of policies that incorporate flow objectives, methods for adaptive management, and implementation plans. Two regional flow criteria methods were researched and presented for review by SWRCB staff. These methods are a regionalized IFIM used in Pennsylvania and Maryland and the more recently developed ELOHA method currently being tested and applied at various locations worldwide. The committee has reviewed these two methods and made recommendations for setting flow criteria based on extensive experience in developing and implementing flow criteria in Florida, Texas, and California.

The committee does not advocate an either/or decision between the IFIM and ELOHA methods. Both methods have strengths and weaknesses, and all methods have known uncertainties. Instead, we advocate a hybrid approach with flexibility to utilize the best scientific information for various river segments and catchments being assessed. We do advocate that specific steps be employed as flow criteria are developed for the priority tributaries to the Sacramento-San Joaquin Delta. The first three necessary steps include 1) stream and river classification based on geomorphic, hydrologic, geographic, and/or faunal characteristics, 2) hydrologic analyses that separate the hydrograph into flow regimes (blocks) and examine historical changes, and 3) assessment of whether any site-specific field work is required in the catchment or river reach to address specific information gaps. Four additional steps are delineated as follows 4) extrapolation of understanding of flow-ecology relationships from other sites to the study catchment or segment, 5) production of an environmental flow regime that meets the needs of species and ecosystem processes in the system, 6) assuring clear and transparent dialogue and interaction between scientists and stakeholders, and 7) designing an effective adaptive management protocol with robust implementation measurements to support the decision-making process. There are examples where these seven steps have been successfully applied, and the appendices to this report provide personal experiences from the committee in setting and implementing flow criteria in Florida, Texas, and California. We hope this information will be useful in determining flow criteria for priority tributaries of the Sacramento-San Joaquin Delta that are scientifically defensible, cost-effective, applicable at the catchment scale, and can be implemented in a timely manner.

5. References

Arthington, A.H., S.J. Mackay, C.S. James, R.J. Rolls, D. Sternberg, A. Barnes, and S.J. Capon. 2012. Ecological limits of hydrologic alteration: a test of the ELOHA framework in south-east Queensland. Waterlines Report Series No 75, 176 pp. http://nwc.gov.au/__data/assets/pdf_file/0015/21723/Waterlines-75-Ecological-limits-of-hydrologic-alteration.pdf

Benson, L., B. Linsley, J. Smoot, S. Mensing, S. Lund, S. Stine, and A. Sarna-Wojcicki. 2003. Influence of the Pacific Decadal Oscillation on the climate of the Sierra Nevada, California and Nevada. Quaternary Research 59: 1451-1459.

Denslinger, T.L., W.A. Gast, J.J Hauenstein, D.W. Heicher, J. Henriksen, D.R. Jackson, G.J. Lazorchick, J.E. McSparran, T.W. Stoe, and L. Young. 1998. Instream flow studies: Pennsylvania and Maryland. Susquehanna River Basin Commission, Harrisburg, Pennsylvania. 308 pp.

Gutzler, D.S., D.M. Kann, and C. Thornbrugh. 2002. Modulation of ENSO-based long-lead outlooks of Southwestern U.S. winter precipitation by the Pacific Decadal Oscillation. Weather and Forecasting 17: 1163-1172.

Hill, M.T., W.S. Platts, and R.L. Beschta. 1991. Ecological and geological concepts for instream and out-of-channel flow requirements. Rivers 2(3): 198-210.

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109: 596-611.

Norris, B.F. (editor). 2010. White Paper: Peak and Ecological Flow; a Scientific Framework for Implementing Oregon HB 3360. Peak and Ecological Flow Technical Advisory Committee. Oregon Water Resources Department. 91 pp. www.**oregon**.gov/owrd/docs/EFTAG_Final.pdf

Pahl-Wostl, C., A. Arthington, J. Bogardi, S.E. Bunn, H. Hoff, L. Lebel, E. Nikitina, M. Palmer, L.N. Poff, K. Richards, M. Schlüter, R. Schulze, A. St-Hilaire, R. Tharme, K. Tockner, and D. Tsegai. 2013. Environmental flows and water governance: managing sustainable water use. Current Opinion in Environmental Sustainability 5: 1-11.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47: 769–784.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M. Freeman, J. Henriksen, R.B. Jacobson, J. Kennen, D.M. Merritt, J. O'Keeffe, J.D. Olden, K. Rogers, R.E. Tharme and A. Warner. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology 55: 147-170.

Richter, B.D., M.M. Davis, C. Apse and C. Konrad. 2011. A presumptive standard for environmental flow protection. River Research and Applications. (wileyonlinelibrary.com) DOI: 10.1002/rra.1511.

Robison, E. 2007. Calculating Channel maintenance/elevated Instream Flows when evaluating Water Right Applications for out of stream and storage water rights. Water Quantity and Quality Section. Oregon Department of Fish and Wildlife. Salem, Oregon. 36 pp. http://www.dfw.state.or.us/fish/water/docs/ODFW_Guidance_on_Allocating_Peak_Flows.pdf

Roper, B.B., J.M. Buffington, E. Archer, C. Moyer, and M. Ward. 2008. The role of observer variation in determining Rosgen stream types in northeastern Oregon mountain streams. Journal of the American Water Resources Association 44(2): 417–427.

Rosgen, D.L. 1994. A classification of natural rivers. Catena 22: 169-199.

Schonher, T., and S.E. Nicholson. 1989. The relationship between California rainfall and ENSO events. Journal of Climate 2: 1258-1269.

Simon, A., M. Doyle, M. Kondolf, F.D. Shields Jr., B. Rhoads, and M. McPhillips. 2007. Critical Evaluation of How the Rosgen Classification and Associated "Natural Channel Design" Methods Fail to Integrate and Quantify Fluvial Processes and Channel Response. Journal of the American Water Resources Association 43(5):1117–1131.

SWRCB. 2013. October 4, 2013 Draft. Policy for maintaining instream flows in Northern California Coastal Streams. State Water Resources Control Board. California Environmental Protection Agency. 34 pp. + appendices.

Yarnell, S.M, R.A. Peek, D.E. Rheinheimer, A.J. Lind, and J.H. Viers. 2013. Management of the Spring Snowmelt Recession: An Integrated Analysis of Empirical, Hydrodynamic, and Hydropower Modeling Applications. Final Report. California Energy Commission. Publication number: CEC-500-2013-TBD.

Yarnell, S.M., J.H. Viers and J.F. Mount. 2010. Ecology and management of the spring snowmelt recession. BioScience 60: 114–127.

Appendix 1: Setting Flow Requirements - Examples from California

A. Restoration of the Spring Snowmelt Recession

As flow management in regulated rivers moves towards a more comprehensive perspective that places increasing value on environmental flows and maintenance of biodiversity alongside municipal uses such as water supply and hydropower, questions arise as to how best achieve a balance between a more natural flow regime and necessary alterations in flow for water storage or delivery. A return to a full natural flow regime is not possible in most regulated systems, but restoration of certain key aspects of the natural flow regime that provides critical ecological benefits is not only possible but necessary if native species are to persist.

In the Mediterranean climate of California—characterized by dry, hot summers and wet, cool winters—winter floods provide an extreme contrast to summer drought. Native aquatic species necessarily have evolved adaptations to survive these harsh extremes, with many relying on the singular annual event of the spring snowmelt recession as a predictable reprieve. With gradually declining flows and a low frequency of pulses, the spring recession provides a stable transition from high abiotic pressures (e.g., scour, turbidity) during winter high flows to high biotic pressures (e.g., competition, predation) during late-summer and fall low flows (Yarnell et al. 2010). During the spring recession, predictable flow conditions coincide with high resource availability, resulting in high reproductive success, growth rates, and survivorship for species adapted to this seasonal flow regime. In regulated river systems where the spring snowmelt recession is often captured behind dams or diverted for hydropower, restoration of a more natural spring flow regime can provide distinct ecological benefits, such as breeding and migration cues, increased habitat availability, and greater hydraulic habitat diversity.

One example of a species that is directly affected by changes to the spring snowmelt recession is the foothill yellow-legged frog (*Rana boylii*), a river-breeding amphibian native to mid-elevation streams in California and southern Oregon that is designated a California Species of Special Concern due to declining populations. Individuals breed annually in early spring following the start of the spring snowmelt recession, timing their reproduction so as to minimize the risk of egg scour caused by unpredictable late-spring storms, and to maximize growth during summer low flows. Frogs lay egg masses on open, newly scoured cobble bars, where the eggs must remain submerged for up to two weeks until tadpoles hatch. After hatching, tadpoles graze in shallow, warm, near-shore environments throughout the summer until metamorphosis occurs in fall. Although they are well adapted to the natural seasonal cycle of flow in Mediterranean climates, egg masses are still vulnerable to scour from late-season storms and to desiccation from rapid decreases in spring flow, whereas tadpoles are susceptible to scour from rapid changes in flow during the summer (Kupferberg et al. 2009; Yarnell et al. 2012). As a result, frogs are extremely vulnerable to altered flow regimes and have been extirpated from most highly regulated river systems (Lind, 2005).

In some regulated rivers where winter flows are diverted or captured behind reservoirs and baseflows dominate the remainder of the year, small frog populations have persisted downstream of dams despite alterations to the hydrograph. In dry years when flows remain close to baseflow year-round, frog populations can successfully reproduce. However, in wet years when high flows spill over dams, spring flow conditions can be unpredictable and devastating. Rapid changes in flow not only alter instream habitat conditions but can miscue or eliminate the environmental flow cues utilized by frogs to initiate breeding. If flows are stable and temperatures warm in early spring, frogs may initiate breeding, only to have egg masses scoured by a subsequent late-spring spill flow over a dam. If egg masses are laid during high spill flows, the abrupt curtailment of flow when spill ceases can result in drastic sudden decreases in flow depth downstream and desiccation of eggs and tadpoles. Due to the longevity of the frogs, small populations can persist in these moderately regulated systems *if* the occurrence of unpredictable spring spill flows is infrequent or rare. However, conservation of robust frog populations requires a spring flow regime that appropriately mimics the natural ecological cues to which this species has evolved.

Prescribing a spring flow regime that gradually ramps down from a spring spill event or that mimics the timing and rate of change of a natural spring snowmelt recession will reduce the potential for frog egg or tadpole mortality while also providing high habitat availability for multiple native species. Recent research has shown that due to the prevailing hydroclimatic conditions across California and the moderately uniform nature of the Sierra Nevada mountain range, the spring snowmelt recession is consistent across the range with regard to its shape, or the rate of change with which flows decrease (Epke, 2011). Regardless of elevation, latitude or watershed size, spring snowmelt flows in each of the major Sierra rivers typically decrease at a rate of 5-8% per day until summer baseflow levels are attained. This consistency not only highlights the flow predictability to which species have evolved, but provides a quantifiable method for how to prescribe spring flows in regulated systems. Spill flows over dams can be stepped down at a rate of 5-8% per day over the course of several weeks until baseflows are achieved, creating naturally decreasing flow conditions that provide the ecological cues to which native species are adapted (Yarnell et al. 2013).

While there is a marginal cost to continuing to release water from a reservoir after naturally high flows have begun to decrease (Rheinheimer et al. 2012), the ecological benefit of restoring key ecological cues needed by native species to successfully reproduce is substantial. This approach has been implemented recently in two large hydroelectric projects in the northern Sierra Nevada. In the Middle Fork Project (FERC #2079) in the American river watershed, a spring ecological flow pulse was added to the flow prescription in above normal and wet years (PCWA, 2012).The pulse was designed to mimic a spring snowmelt pulse occurring in early May with a descending limb that decreased at a rate of 14% per day and lasted a minimum of 15 days. In wet years when spill occurs over the dam, spill flows will be stepped down to baseflow at a similar rate and duration in order to limit potential desiccation of frog egg masses downstream. Similarly, in the large complex Yuba-Bear/Drum-Spaulding hydroelectric projects (FERC #2266, 2310) in the upper Yuba River watershed, stakeholders negotiated specific spill cessation flows that are to occur below each large dam in the system (NID 2012, PG&E 2012). The spill cessation flow schedule mimics natural spring recession flows by ramping down high flows at a rate of 8.5% per day over three weeks until baseflow is reached. While these types of flow measures do not fully restore the natural spring recession in every year, they do limit the impacts of altered spring flows and provide the necessary ecological cues for successful reproduction of native species in wetter years.

Another example of the ecological importance of mimicking natural spring flow conditions in a managed river system can be found in the lower Cosumnes River floodplain. As the last large unregulated watershed in the Sierra Nevada, the Cosumnes River provides an opportunity to observe natural ecological riverine processes in the managed landscape of the central valley. Although a natural flow regime remains, small diversions occur throughout the Cosumnes basin and the river is highly channelized due to agricultural use in the historic floodplain. Located at the base of the Sierra foothills on the valley floor, the Cosumnes River Preserve has several restored floodplains that provide vegetated floodplain habitat for native spring spawning splittail and juvenile chinook salmon rearing during spring high flows. Research within and adjacent to the preserve helps to provide information on ecological processes in the contrasting environments of river reaches with and without accessible floodplains.

Research on floodplain dynamics in the preserve shows the ecological importance of not only sustained floodplain inundation but gradually receding spring flows as migratory cues for native fish (Ahearn et al. 2006, Grosholz and Gallo 2006, Jeffres et al. 2008). Typically in spring, the Cosumnes floodplain is inundated with high winter flows from January to April depending on the water year type, and flows recede from the floodplain in May and June as the snowmelt recession occurs. The inundated floodplain is a key aspect of the river ecosystem as it provides space for foodweb dynamics to occur. As flows increase across the floodplain, soil becomes wetted creating a bloom of phytoplankton, which subsequently creates a bloom in zooplankton as they fed on the phytoplankton. Juvenile salmonids rearing in the floodplain then feed on the zooplankton growing rapidly until spring flows begin to recede. Simultaneously, splittail utilize the inundated floodplain habitat for breeding, with larval fish emerging within several weeks. Using the spring recession as a key ecological cue, juvenile splittail and juvenile salmon then follow the receding flows back to the main channel, where salmon outmigrate to the ocean and splittail migrate to the delta. These ecological processes and cues are dependent upon sustained floodplain inundation of a minimum of three weeks and recession flows that decrease at rates gradual enough to cue the migratory response. Restoration of not only floodplain habitat but these key flood processes, particularly the timing, duration and pattern of spring floods and recession, is essential to successful persistence of native aquatic species in California's rivers.

References

Ahearn, D. S., J. H. Viers, J. F. Mount, and R. A. Dahlgren. 2006. Priming the productivity pump: flood pulse driven trends in suspended algal biomass distribution across a restored floodplain. Freshwater Biology 51:1417-1433.

Epke, G.A. 2011. Spring snowmelt recession in rivers of the western Sierra Nevada mountains. Master's Thesis. Hydrologic Sciences. University of California, Davis.

Grosholz. E. and E. Gallo. 2006. The influence of flood cycle and fish predation on invertebrate production on a restored California floodplain. Hydrobiologia 568(1):91-109.

Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environmental Biology of Fishes 83:449-458

Kupferberg S.J., A.J. Lind, S.M. Yarnell, and J.F. Mount. 2009. Pulsed Flow Effects on the Foothill Yellow-legged Frog (*Rana boylii*): Integration of Empirical, Experimental and Hydrodynamic Modeling Approaches. California Energy Commission, PIER. Report no. CEC 500-2009-002.

Lind, A.J. 2005. Reintroduction of a declining amphibian: determining an ecologically feasible approach for the foothill yellow-legged frog (*Rana boylii*) through analysis of decline factors, genetic structure, and habitat associations. Ph.D. Dissertation, University of California, Davis. (March) 169 pp.

Nevada Irrigation District (NID). 2012. Revised FS Preliminary Conditions and Recommendations Provided Under 18 CFR § 4.34 (b) (1) In Connection with the Application for Relicensing for the Yuba-Bear Hydroelectric Project (FERC No. 2266). August 2012.

Pacific Gas & Electric (PG&E). 2012. Revised FS Preliminary Conditions and Recommendations Provided Under 18 CFR § 4.34 (b) (1) In Connection with the Application for Relicensing for the Drum-Spaulding Hydroelectric Project (FERC No. 2310). August 2012.

Placer County Water Agency (PCWA). 2012. Forest Service Final Conditions and Recommendations Provided Under 18 CFR § 4.34 (b) (1) In Connection with the Application for Relicensing for the Middle American River Project (FERC No. 2079). November 2012.

Rheinheimer, D.E., S.M. Yarnell, and J.H. Viers. 2012. Hydropower costs of environmental flows and climate warming in California's upper Yuba River watershed. River Research and Applications: DOI: 10.1002/rra.2612.

Yarnell, S.M., J.H. Viers and J.F. Mount. 2010. Ecology and management of the spring snowmelt recession. BioScience 60: 114–127.

Yarnell, S.M., A.J. Lind and J.F. Mount. 2012. Dynamic flow modelling of riverine amphibian habitat with application to regulated flow management. River Research and Applications 28: 177–191.

Yarnell, S.M, R.A. Peek, D.E. Rheinheimer, A.J. Lind, and J.H. Viers. 2013. Management of the Spring Snowmelt Recession: An Integrated Analysis of Empirical, Hydrodynamic, and Hydropower Modeling Applications. Final Report. California Energy Commission. Publication number: CEC-500-2013-TBD.

B. Restoration of a Natural Flow Regime on Putah Creek

Summarized from Kiernan et al. (2012):

Putah Creek, located on the western side of California's central valley in the lower Sacramento River basin, is regulated by releases from Monticello Dam in the upper watershed and the Putah Creek Diversion Dam 13 km downstream that supplies water for Solano County. Minimum instream flows below the diversion dam were insufficient to maintain perennial stream flow to the creek's confluence with the Yolo bypass, and after a series of dry years in the 1980s, large sections of the creek went dry resulting in a substantial fish kill in the lower watershed. Following litigation, the court ordered an increase in minimum instream flows and negotiation of flows that would benefit native fish. Following a series of wet years that created flows similar to the historical natural flow regime and a small resurgence in native species (Marchetti and Moyle 2001), a negotiated settlement (the Putah Creek Accord) was reached in 2000 that used the natural flow regime concept (Poff et al. 1997) to prescribe specific flow requirements for Putah Creek.

The Putah Creek Accord included three specific operational requirements that benefited fish and other aquatic organisms (Moyle et al. 1998). 1) Spring spawning and summer rearing flows for native fish. Following a short high-flow pulse in the spring between mid-February and March to cue native spawning, flows were to remain elevated for one month above summer baseflows to support increased habitat for spawning. Summer baseflows were then to be sufficient to maintain flowing water throughout the creek from the diversion dam to the confluence with the Yolo bypass, providing cold water rearing habitat for native fish species. 2) Supplemental pulse flows to attract and support anadromous fish. Beginning in November, minimum stream flows must be sufficient to maintain stream habitat and include a five-day pulse flow in November or December to attract and enable adult chinook salmon to migrate up Putah Creek from the Yolo Bypass. 3) Drought Flows. Even in drought years when reservoir levels are low, minimum flows must be sufficient to ensure permanent stream flow from the diversion dam to the Interstate 80 crossing. These three flow requirements collectively created an annual flow regime that mimicked the primary components of a natural flow regime by providing increased flows in late fall as would naturally occur at the start of the wet season, increased flows in spring as would occur during the spring runoff period, and maintenance of flow through the low flow season to ensure perenniality of the stream.

Monitoring of the fish populations in Putah Creek for nine years following the implementation of the Putah Creek Accord flow regime showed a steady and dramatic increase in native fish populations such that they regained dominance throughout the majority of Putah Creek below the diversion dam within four years (Kiernan et al 2012). Additionally, non-native fish species were displaced to the downstream-most reaches of the creek due to the restoration of appropriately timed high-discharge events. The restoration of native fishes was achieved by manipulating stream flows at biologically important times of the year, specifically increasing flows substantially in spring and moderately in summer and decreasing flows in winter. As a result, the new flow regime required only a small increase (21%) in the total volume of water delivered downstream (i.e., water that was not diverted for other uses) during most water years.

References

Kiernan J.D., P.B. Moyle and P.K. Crain. 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. Ecological Applications, 22(5): 1472–1482.

Marchetti, M. P., and P. B. Moyle. 2001. Effects of flow regime on fish assemblages in a regulated California stream. Ecological Applications 11:530–539.

Moyle, P. B., M. P. Marchetti, J. Baldridge, and T. L. Taylor. 1998. Fish health and diversity: justifying flows for a California stream. Fisheries 23:6–15.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47:769–784.

C. Adaptive Management and Reconciliation on the North Fork Feather River

In one of the largest watersheds in the Sierra Nevada, the North Fork Feather River (NF Feather) drains the northern end of the mountain range from near Lassen Peak into the central valley. With a large runoff volume (mean annual flow of 3000 cfs) and an elevational drop of 35 feet per mile, the watershed was developed for hydropower beginning in the early 20th century. Known as the “stairway of power”, a drop of water landing near the crest of the Sierra in the watershed can pass through up to 8 powerhouses on its journey to the valley floor. With a total generation capacity of 756 MW, the dams and powerhouses in the watershed have a significant economic value. As such, the watershed was operated to maximize hydropower with predominately flat minimum instream flows year-round in each of the river reaches.

At the end of the 20th century however, perspectives began to shift as many of the dams in the watershed came up for relicensing through the FERC process (http://www.ferc.gov/industries/hydropower/gen-info/licensing.asp). The relicensing process is a collaborative endeavor among various stakeholders—utilities, state and federal resource agencies, tribes, irrigators, conservationists and recreationists—that provides an opportunity to re-operate dams with consideration for multiple interests, such as environmental needs, water quality, water supply, and recreation in addition to hydropower generation. Stakeholders typically spend 3 years designing, implementing and reviewing study results on the impacts of a dam and its operations on downstream resources. They then negotiate an instream flow schedule that accounts for the multiple interests, and submit the final negotiated conditions to FERC for approval.

In the case of the NF Feather, the first dams to be relicensed were the Rock Creek and Cresta dams and powerhouses. Encompassing 16 miles of river in the middle of the stairway, the Rock Creek-Cresta project (FERC #1962) diverts water from each reservoir through tunnels that bypass the river to the corresponding powerhouse downstream, generating a combined total of 185 MW of power (http://www.hydroreform.org/projects/rock-creek-cresta-p-1962). This section of river is also valued among recreationalists for its whitewater boating and fishing opportunities. As such, there was considerable disagreement about the operation of the project under a new license, and in 1998, the utility (Pacific Gas & Electric, PG&E) convened settlement negotiations with various stakeholders. The

Rock Creek-Cresta Relicensing Collaborative, which included stakeholders from various state and federal resource agencies, PG&E, local interests, whitewater enthusiasts (American Whitewater, AW) and fisherman (California Sportfishing Protection Alliance, CSPA), successfully reached agreement in 2000, leading to a new license in 2001.The new license established specific minimum flow ranges based on season and water year type, and new summer recreational flows, a key victory for AW. The license also provided funding for studies of the impacts of the new flow regime on downstream aquatic biota, as well as the formation of an Ecological Resources Committee (ERC) comprised of interested stakeholders who would evaluate the study results and suggest alterations to the flow regime if needed.

Studies to determine appropriate levels for recreational releases and potential ensuing impacts on aquatic biota began following the agreement in 2000.Of particular concern to resource agencies was the presence of a population of Foothill Yellow-legged Frogs (FYLF) that resided in the Cresta reach. FYLF are a river-obligate species that rely on specific habitat and flow conditions during their spring breeding and summer rearing seasons (Lind 2005, Yarnell et al. 2012). The impact of changing the spring and summer flow regimes on the populations was unknown, so studies were designed to compare conditions in the Cresta reach with the adjacent regulated reach just downstream of the Poe dam, where a large stable FYLF population occurred.

As per the agreement, recreational flow pulses occurring over one weekend per month began in the summer of 2002 in the Cresta reach. Scientists tracked the FYLF populations over the next three years in both the Cresta and Poe reaches and by 2005 began to see a marked decline in the Cresta FYLF population. In 2006, the ERC and US Forest Service exercised its right to suspend all recreational releases for one year as they reviewed study data and waited to see if the population might rebound. While no single study completed during the first several years of recreational releases could prove that the summer recreational pulse flows were causing the Cresta population decline, data from the multiple studies along with new academic research initiated in 2005 by UC Davis combined to create a weight of evidence that strongly suggested that altered summer flow regimes were prohibiting successful FYLF reproduction (Kupferberg et al. 2009). As a result, in 2007, the ERC created a three-year recreational flow plan for the upstream Rock Creek reach that did not contain FYLF, but again cancelled summer flow pulses on the Cresta reach.

In 2008, the ERC faced a difficult and unprecedented decision about how to deal with the negotiated recreational flows that had been provided in the new license for the Cresta reach. While whitewater enthusiasts did not want to harm sensitive species like the FYLF, they did want to boat the river and were not easily going to give up their hard-won allocation of water. Yet, fishing enthusiasts and resource agency personnel wanted to see a more natural flow regime that would benefit the native aquatic ecology. After much discussion, stakeholders in the ERC landed on a compromise that would ultimately have far-reaching effects. AW would take their allocation of water and 'stack' it in the spring time when flows would naturally be higher, leaving the later summer months at constant low flows, similar to the natural flow regime. Boaters would lose their monthly flow releases during the warm late summer months, but would gain month-long releases throughout May, June and July in wetter years. Flows would then gradually step-down to summer baseflows so that FYLF egg masses and tadpoles would not be stranded by a sudden decrease in water level. The more natural flow regime also met the interests of many fishermen who sought better instream habitat conditions for not only fish, but for the benthic community on which fish rely.

The new flow schedule was implemented by PG&E in the Cresta reach in 2009. As of 2013, the FYLF population in the Cresta remains critically low and may not recover from the previous impacts. However, support for this new approach in designing more natural flow regimes during the critical springtime has been widespread. AW alongside resource agency personnel continues to advocate for restoring spring flows in regulated rivers by allocating water for higher flows in spring that meets ecological and geomorphic needs as well as provides recreational boating opportunities. As a result, new spring flow regimes have been negotiated in the Pit, McCloud, Middle Fork American and Upper Yuba rivers that better mimic a natural flow regime.

References

Kupferberg S.J., A.J. Lind, S.M. Yarnell, and J.F. Mount. 2009. Pulsed Flow Effects on the Foothill Yellow-legged Frog (*Rana boylii*): Integration of Empirical, Experimental and Hydrodynamic Modeling Approaches. California Energy Commission, PIER. Report no. CEC 500-2009-002.

Lind, A.J. 2005. Reintroduction of a declining amphibian: determining an ecologically feasible approach for the foothill yellow-legged frog (*Rana boylii*) through analysis of decline factors, genetic structure, and habitat associations. Ph.D. Dissertation, University of California, Davis. (March) 169 pp.

Yarnell, S.M., A.J. Lind and J.F. Mount. 2012. Dynamic flow modelling of riverine amphibian habitat with application to regulated flow management. River Research and Applications 28: 177–191.

Appendix 2: Setting Flow Criteria - The Southwest Florida Water Management District Experience

The environmental flows methodology developed by the Southwest Florida Water Management District (SWFWMD), one of five water management districts in the state of Florida, is described in some detail in the Instream Flow Council's (IFC) book, *Integrated Approaches to River Resource Stewardship* (Locke et al. 2008). While the approaches taken in the eight case studies summarized by the IFC vary, "they share common elements: good science, knowledgeable and committed participants, good cooperation and interaction, adequate funding, and a supportive legal environment" (Locke et al. 2008). The Florida Water Resources Act (FWRA) of 1972 required the development of Minimum Flows and Levels on water bodies throughout the state to protect them from "significant harm" due to water withdrawals. The FWRA not only established the legal framework for establishing minimum flows and levels, but because the water management districts have taxing authority within their jurisdictions, provided the means for funding the necessary studies to develop environmental flows and the fiscal resources to implement recovery strategies when needed.

A prerequisite of any environmental flow study should be a basic understanding of the hydrology of the area. Although the methodology has evolved somewhat over time, due to a commitment to peer review for each proposed environmental flow, the SWFWMD approach is built around the natural flow paradigm. Due to an earlier peer review recommendation (Gore et al. 2002) and guided by the realization that "multiple flow regimes are needed to maintain biotic and abiotic resources within a river ecosystem" (Hill et al. 1991), the SWFWMD developed an approach that divided the fairly predictable annual flow regime into component parts ("blocks") based on an understanding of regional hydrology. The SWFWMD evaluated stream hydrographs throughout the state and the southeastern United States (Kelly 2004, Kelly and Gore 2007) to better understand regional differences in hydrology and the impact that climatic changes potentially played in the shape of the annual hydrograph and differences in multidecadal flows. The SWFWMD discerned two distinct flow patterns in most streams and rivers across Florida. One was characteristic of rivers in the more northern part of the state (e.g., Ochlockonee River), and one was characteristic of the rivers in the southern part of the state (e.g., Peace River; including all rivers in the SWFWMD). There was a band of sites across the state that exhibited a mix of the two patterns (e.g., St. Marys River). One other dominate hydrographic type was discerned for rivers dominated by spring flow from the Floridan aquifer; these sites exhibit a rather constant flow regardless of season.

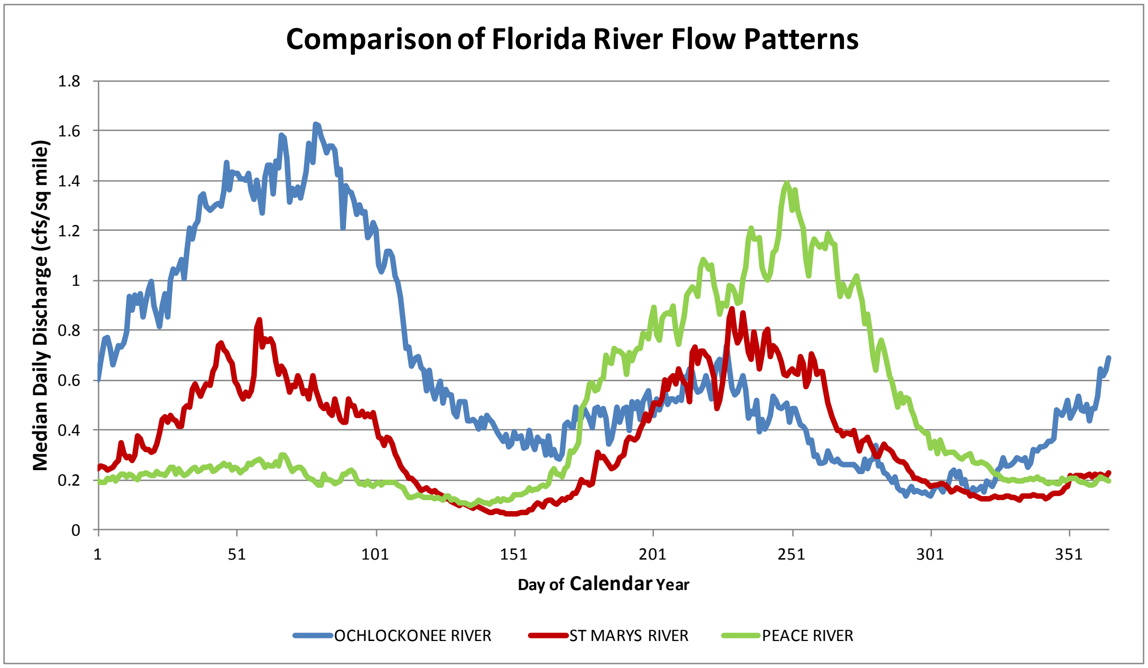

Figure 1. Comparison of three river flow patterns characteristic of most streams and rivers in Florida.

During the evaluation of flow patterns, it also became apparent that there were multidecadal differences in the natural flow regime that should be taken into account when evaluating baseline conditions and establishing flow standards. For example, there had been considerable flow declines in the Peace River over time; however, the primary cause of these declines (whether climatic or withdrawal related) had been the subject of some debate. Building on work done by Enfield et al. (2001), it was postulated that changes in north Atlantic Ocean sea surface temperature had a significant impact on rainfall patterns over much of Florida (particularly peninsular Florida) because multidecadal shifts in sea surface temperature affect the number of tropical storms and hurricanes that could potentially add additional rainfall to the typical wet season rainfall pattern over this part of Florida. Differences of only a few inches in total annual rainfall can lead to substantial percent changes in mean annual runoff over decadal periods even in the absence of withdrawal impacts, and these need to be accounted for. This was handled by using two unimpaired flow records representing multidecadal periods of high and low rainfall on which to base potential (allowable) flow reductions due to withdrawals. Because a percent of flow approach was used in determining allowable reductions, the multidecadal baseline flow period that provided the more restricted percent flow recommendation was the one used to develop the final flow recommendations. It was reasoned that the lesser of the two potential recommendations would be protective of flows regardless of the multidecadal period encountered.

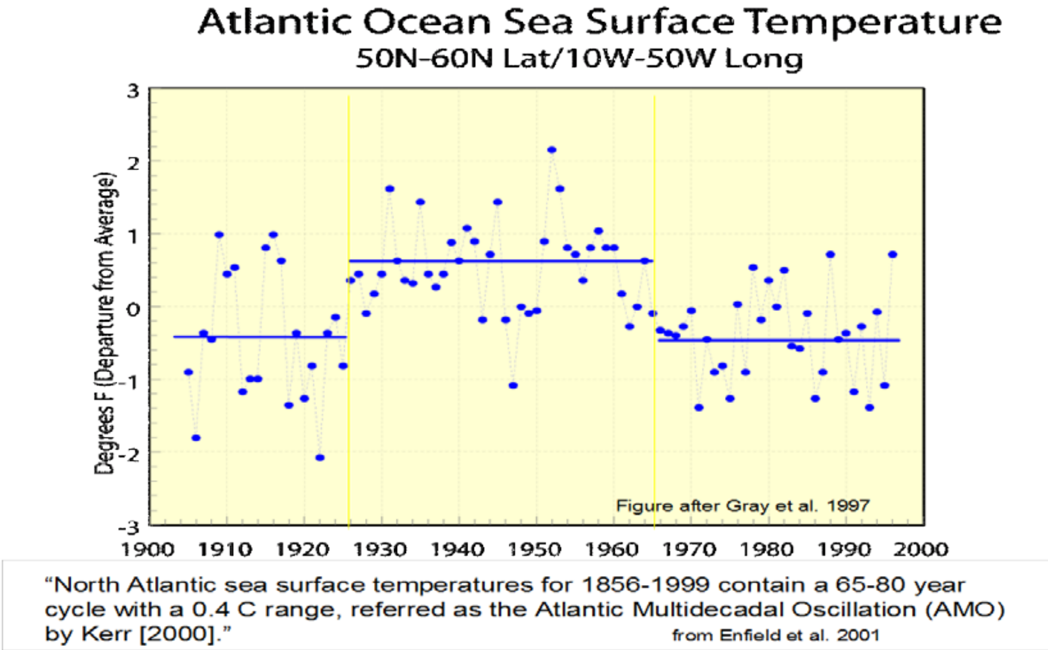

Figure 2. Multidecadal variation in Atlantic Ocean sea surface temperature.

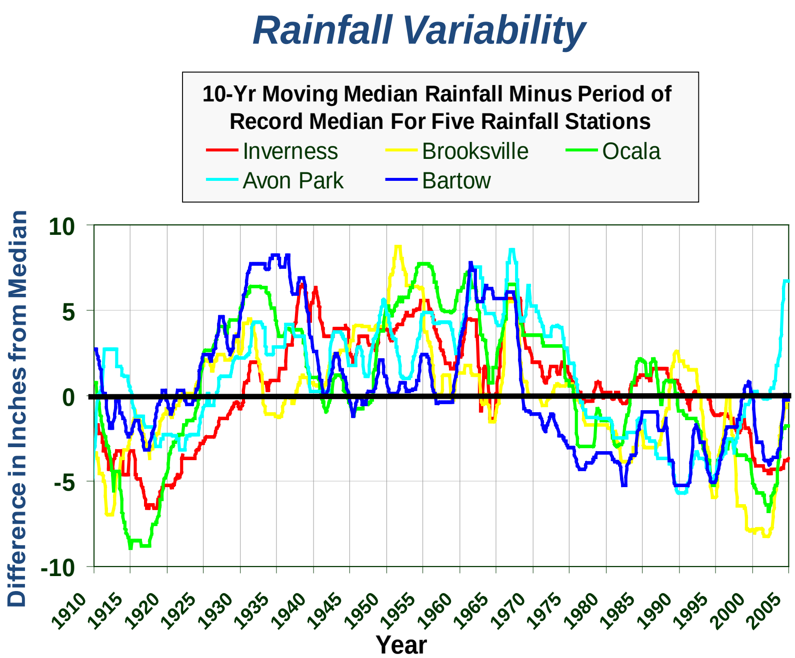

Figure 3. Comparison of multidecadal variation in rainfall in southwest Florida as measured at five long-term rainfall sites.

As a result of the hydrographic analysis, the SWFWMD divided the annual hydrograph into three component parts: a low flow block, a high flow block, and an intermediate flow block. Hill et al. (1991) in discussing the need for multiple flow regimes and in keeping with the natural flow paradigm recommended that consideration should be given to maintaining:

1) Flood flows that determine the boundaries of and shape floodplain and valley features;
2) Overbank flows that maintain riparian habitats,
3) In-channel flows that keep immediate streambanks and channels functioning; and
4) In-stream flows that meet critical fish requirements.

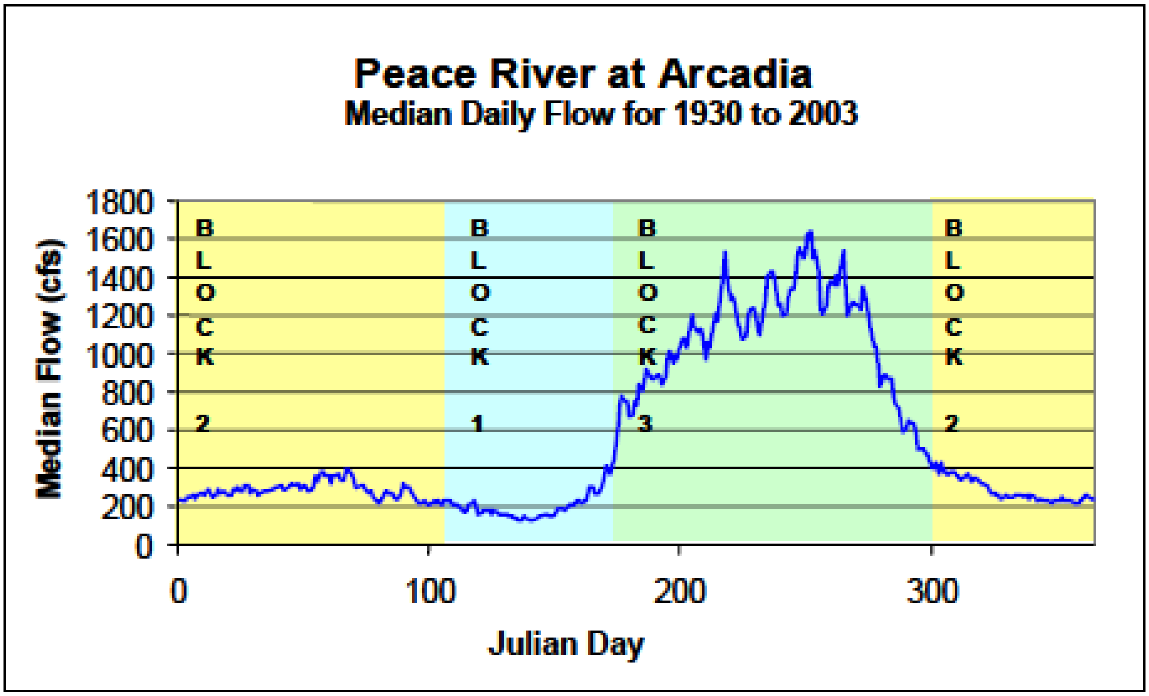

Figure 4. Median daily flow at Peace River at Arcadia, FL. with hydrograph separated into high, median and low flow blocks.

Based on these recommendations, it was conceptualized that ecological flows methodologies must include more than a consideration of immediate fish needs or the absolute minimum required to sustain a particular species or populations of animals. Ecological flows should take into consideration "how streamflows affect channels, transport sediments, and influence vegetation" (Hill et al. 1991), and "that the full range of natural intra-and inter-annual variation of hydrologic regimes is necessary to [fully] sustain the native biodiversity" (Richter et al. 1996). Successful completion of the life-cycle of many aquatic species is dependent upon a range of flows, and alterations to the flow regime may negatively impact these organisms as a result of changes in physical, chemical and biological factors associated with particular flow conditions. South African researchers, as cited by Postel and Richter (2003), listed eight general principles for managing river flows:

- "A modified flow regime should mimic the natural one, so that the natural timing of different kinds of flows is preserved.
- A river's natural perenniality or nonperenniality should be retained.
- Most water should be harvested from a river during wet months; little should be taken during the dry months.
- The seasonal pattern of higher baseflows in wet season should be retained.
- Floods should be present during the natural wet season.
- The duration of floods could be shortened, but within limits.
- It is better to retain certain floods at full magnitude and to eliminate others entirely than to preserve all or most floods at diminished levels.
- The first flood (or one of the first) of the wet season should be fully retained."

Using the natural flow paradigm and the guiding principles listed above, the SWFWMD realized that a suite of tools should be used to protect the natural flow regime based on seasonal flow needs. It is important to realize that the suite of tools selected by the SWFWMD was a subset of the many instream flow methods available for use. The particular tools chosen by the SWFWMD were based on perceived resources of concern and the availability of data or the ability to collect needed data within a reasonable timeframe. In a larger sense, the SWFWMD was employing a framework that could be adapted for use elsewhere with the actual methods used within the framework based on upon identified ecological resources to be protected and available fiscal resources.

Since the water management districts in Florida have permitting authority with respect to water withdrawals and are to protect from "significant harm", the SWFWMD realized that the natural flow regime could best be protected by issuing permits on a percent-of-flow approach (Flannery et al. 2002, Postel and Richter 2003). Essentially, the SWFWMD began with the unaltered flow regime (i.e., unaffected by withdrawals), and using various modeling techniques and tools, removed flows in a sort of "top down approach" until important resources were deemed to be "significantly harmed".

Similar to the "bypass flows" proposed in the Pennsylvania-Maryland Method (PMM) and given the goal of maintaining perenniality of a stream based on its natural flow regime, both wetted perimeter and fish passage flows are routinely evaluated by the SWFWMD with a Hydrologic Engineering Centers River Analysis System (HEC-RAS) model "to develop a low flow threshold which identifies flows that are to be protected in their entirety (i.e., flows that are not available for consumptive use)" (Kelly et al. 2005). The low flow threshold is established at the higher of these two standards. The low flow threshold when applicable (i.e., on perennial streams based on an examination of unimpaired flows) is applied in all flow blocks.

In order to determine the percent of flow that may potentially be used for consumptive uses during flow block 1 (seasonally low flows) and flow block 2 (median and generally within bank flows), inundation of within channel habitats is assessed. Within channel habitats include woody and vegetative habitats. Wood habitats included snag (dead) and exposed tree roots (e.g., cypress trees are a common feature of many Florida streams and their exposed roots provide habitat for many species). The median elevation of these various habitats was determined at various transects (river reaches), their inundation frequencies assessed based on unimpaired flows using a HEC-RAS model to establish the relationship between flows and elevation at any particular stream location. Significant harm (discussed below) was determined by removing a percent of unimpaired flows (within flow blocks) until the significant harm threshold (percent reduction in number of days that a give flow was exceeded) was crossed. In addition to assessing instream habitat inundation of vegetation, Physical Habitat Simulation (PHABSIM) modeling was also used in flow blocks 1 and 2 to assess gain or loss of fish and macroinvertebrate habitat under decreasing flows due to modeled water withdrawals.

A criticism of PHABSIM has been that it picks "winner and losers" by selecting one or a couple of species to the potential detriment of others. The SWFWMD avoided this criticism by selecting multiple species, fish guilds and macroinvertebrate diversity for evaluation. The criterion used for determining a flow recommendation using PHABSIM was no more than a certain (in the case of SWFWMD, a 15% reduction) percent change in habitat for any species or guild for any life stage. In other words, only a certain percent deviation from the natural flow regime was allowed; thus no species was given preference over any other species (i.e., this value judgment was avoided).

Although PHABSIM could be applied under the highest flow conditions in theory, habitat metrics are usually assessed within banks using PHABSIM. For this reason, a different criterion was applied to block 3 flows at the time of year when flows based on the natural hydrograph are likely to inundate habitats at higher elevations (e.g., exposed tree roots, floodplain wetlands, etc.). For this reason, the criterion used was the number of days that a certain flow was exceeded during the high flow season. These flows were equated to given elevations that lead to connection with the floodplain. Using modeling (e.g., HEC-RAS), the number of days that the stream reached a given elevation under the unimpaired flow regime was determined, and using modeling, a percent of flows was removed until the number of days of inundation/connection with a desired habitat was reduced by a given percentage.

Using the approach described above, the SWFWMD evaluated stream hydrology to ascertain the "natural flow regime". Using a combination of methods, they developed a flow prescription of seasonally allowable (acceptable) flow reductions as determined by the resource(s) to be protected. Using this approach, they were able to provide a flow recommendation that would preserve the seasonal look of the natural flow regime, although in a somewhat dampened condition.

The MFL statute in Florida provides that in cases where flows are altered to such an extent that they do not meet or would fall below proposed environmental flows, a recovery plan is required. For example, prior to significant lowering of the Floridan aquifer due to regionally dispersed groundwater withdrawals, the Upper Peace River was a perennially flowing stream. However, due to lowering of the Floridan aquifer and loss of artisan baseflow, flow in the upper river frequently became intermittent. Proposed environmental flows required low flow thresholds based on fish passage and wetted perimeter inflection points for three USGS gages in the upper watershed. It was deemed infeasible to raise the Floridan aquifer groundwater level by cutting back sufficiently on permitted withdrawals because of economic concerns. As a result, the SWFWMD adopted a recovery strategy (at a cost of approximately 100 million dollars) centered around creating additional storage in an upstream lake by raising the control structure and storing excess flows during the rainy season to be released when flows at USGS gages would fall below the low flow threshold. The proposed environmental flows were not adopted until a recovery plan was developed; this allowed for considerable public input and review so that costs and benefits were thoroughly vetted prior to adoption of both the proposed environmental flows and attendant recovery strategy. Both were adopted by the Governing Board of the SWFWMD, and the recovery strategy is now being implemented.

References

Enfield, D., A. Mestas-Nunez, and P. Trimble. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. Geophysical Research Letters 28(10): 2077-2080.

Flannery, M.S., E.B. Peebles, and R.T. Montgomery. 2002. A percent-of-flow approach for managing reductions of freshwater inflows from unimpounded rivers to southwest Florida estuaries. Estuaries 25(68): 1318-1332.

Gore, J., C. Dahm, and C. Klimas. 2002. A review of "Upper Peace River: An Analysis of Minimum Flows and Levels". Prepared for the Southwest Florida Water Management District. Brooksville, FL. 31 pp.http://www.swfwmd.state.fl.us/projects/mfl/reports/peace_river_review.pdf

Hill, M.T., W.S. Platts, and R.L. Beschta. 1991. Ecological and geological concepts for instream and out-of-channel flows requirements. Rivers 2(3): 198-210.

Kelly, M.H. 2004.Florida river flow patterns and the Atlantic multidecadal oscillation. Ecologic Evaluation Section. Southwest Florida Water Management District. Brooksville, FL. 80 pp. + appendices. http://www.swfwmd.state.fl.us/documents/reports/riverflow_patterns.pdf

Kelly, M.H., A.B. Munson, J. Morales and D. Leeper. 2005. Proposed Minimum Flows and Levels for the Middle Segment of the Peace River. Ecologic Evaluation Section. Southwest Florida Water Management District. Brooksville, FL. 177 pp.

Kelly, M.H. and J.A. Gore. 2007. Florida river flow patterns and the Atlantic Multidecadal Oscillation. River Research and Applications 24:598-616.

Locke, A., C. Stalnaker, S. Zellmer, K. Williams, H. Beecher, T. Richards, C. Robertson, A. Wald, A. Paul and T. Annear. 2008. Integrated Approaches to River Resource Management: Case Studies, Science Law, People, and Policy. Instream Flow Council, Cheyenne, WY.430 pp.

Postel, S. and B. Richter. 2003. Rivers for Life: Managing Water for People and Nature. Island Press. Washington, D.C., 253 pp.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10(4):1163-1174.

Note: all reports dealing with establishment of Minimum Flows and Levels (i.e., Environmental Flows) at the Southwest Florida Water Management District can be found at:
http://www.swfwmd.state.fl.us/projects/mfl/mfl_reports.php

Appendix 3: Texas Senate Bill 3: A Rapid, Science-Based Approach for Estimating Environmental Flow Requirements

In 2001 the Texas legislature passed Senate Bill 2 (SB2) to create the Texas Instream Flow Program (TIFP), which charged three state natural resource agencies to collaborate on field studies to determine flow conditions to support "a sound ecological environment" within the state's rivers and streams. Given limited human and financial resources, priority studies initiated on a handful of river and stream segments. Senate Bill 3 (SB3), passed in 2007, established an aggressive schedule for determining environmental flow standards adequate to support a sound ecological environment in all of the state's river basins and bay systems. SB3 set out a new regulatory approach to protect environmental flows through the use of environmental flow standards developed through a local stakeholder process culminating in Texas Commission on Environmental Quality (TCEQ) rulemaking. SB3 directed the use of an environmental flow regime in developing flow standards and defined an environmental flow regime as a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats.

The SB3 schedule did not allow for the development of multi-year site-specific instream flow studies such as those undertaken by the TIFP. Instead, SB3 requires that environmental flow standards be predicated upon the best science and data currently available. Adaptive management will be used to refine the flow standards. Aided by new findings from the TIFP, flow standards are to be reviewed not less than every 10 years. In order to effectively use the results from the TIFP studies through an adaptive management process, the initial SB3 flow standards should be consistent with the environmental flow regime framework applied in the TIFP studies. The immediate task for developing the flow standards required under SB3 is to identify, within a short time frame and without the benefit of completed TIFP studies, science-based methods for determining an environmental flow regime at a particular stream location. SB3 created a state Science Advisory Committee (SAC) that assisted science teams and stakeholder groups of the various basin/bay regions with technical and strategic guidance. Among the series of SAC guidance documents, the following aspects would be particularly relevant for the SWRCB to consider.

Hydrological Analysis

The magnitude of streamflow and its variation play determine the characteristics of any riverine ecosystem. Where data are insufficient to establish relationships between streamflow and biological response, the historical streamflow data themselves can provide a meaningful basis for establishing, as a first approximation, environmental flow recommendations that are considered to be protective of current conditions. These initial recommendations must be subjected to refinement and adjustment based on available biological data and other information to better reflect actual ecosystem needs.

To aid the scientists, stakeholders, regulators, and policymakers involved in SB3, a tool called the Hydrology-based Environmental Flow Regime (HEFR) was developed by the state's natural resource agency (Texas Parks and Wildlife Department) with input from other agencies and organizations. HEFR is a relatively flexible, statistical approach for developing a flow regime matrix that is consistent with the TIFP in the sense that it identifies multiple flow regime components of various levels across different months, seasons, or years. HEFR was used by all seven of the SB3 basin and bay science teams as they developed environmental flow regime recommendations.

HEFR produces summary statistics of flow regime components. Generally, either the Environmental Flow Components (EFC) method or the Modified Base Flow Index with Threshold (MBFIT) method (both implemented in a Microsoft Excel™ spreadsheet) is used to parse a hydrologic record into separate flow regime components. Excel is then used to efficiently develop summary statistics of these flow regime components.

In the context of SB3, the HEFR methodology has several advantages, including: (1) it is computationally efficient, allowing for repeated tests and exploratory analyses, (2) there is significant flexibility in setting parameters to parse the hydrograph as well as summary statistics of the flow regime components, (3) the results have the same format as expected results from the TIFP studies, and (4) it provides an initial set of recommendations that reflect key aspects of the natural flow regime, including multiple flow components and hydrologic conditions.

Sediment Dynamics Analysis

The erosion, transport, and deposition of sediment are as important to the complexity and structural diversity of rivers, riparian zones, deltas, and estuaries as the conveyance of water itself. The balance between the force of water and the resistance of sediment creates the many fluvial patterns that provide habitats and conditions to which aquatic and riparian species are adapted. If only flows are considered, without the associated sediment dynamics, then the resulting assessment of the state's rivers and bays would be incomplete, reducing the likelihood of successful conservation or rehabilitation.

As an alternative to determining a sediment-transport regime to maintain biodiversity and productivity of fluvial ecosystems, methodological approaches were explored to facilitate quantification of sediment loads for observed flows or environmental flow prescriptions. These methods use historical data, including sediment-load measurements or river channel dimensions, thereby providing a context for contemporary conditions. Evaluation of sediment loads eventually needs to be related to habitat structure, function, and change, which requires interdisciplinary research among specialists in biology, geomorphology, and hydrology.

Nutrient and Water Quality Analysis

Changes in a flow regime can be expected to produce changes in water quality conditions. The challenge is to ensure that the recommended flow regime protects water quality, particularly during low, or subsistence, flow conditions, and also considers water quality needs during higher flow conditions. Water quality criteria developed by the state address the acceptable levels of suspended solids, nutrients, toxics, indicator bacteria, dissolved oxygen, pH, and other parameters. Under some circumstances all of these might play a role in the determination of an environmental flow regime.

Ecological Analysis

The time limitation and inability to conduct site-specific field studies during the SB3 process meant that evaluation of biological factors in the development of instream flow recommendations had to be efficient and relatively generalized. As more site-specific and detailed results emerge from the TIFP and other studies, the instream flow regime recommendations and standards can be refined as appropriate through the adaptive management process. Below is an outline of essential steps for ecological analysis (sometimes referred to as "biological overlays") in developing environmental flow recommendations under SB3.

1. Establish clear, operational objectives for support of “a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies”. This step should involve input not only from scientists, but also from regional stakeholders with guidance from the SAC and state agency personnel involved with the TIFP. Operational objectives are: (1) maintain native biodiversity to the extent that is reasonable under recent conditions of climate, major infrastructure developments, and biological invasions; (2) maintain environmental quality and ecosystem productivity in support of this biodiversity and the recreational, commercial, and aesthetic uses of the renewable natural resources that it provides; and (3) maintain both short-term and long-term dynamics of habitats that support native biodiversity.
2. Compile and evaluate readily available biological information, especially for important species within the basin of interest. Early in this process, key indicator species must be identified, and these species are a primary focus of the biological overlay. Care must be taken to identify a suitable set of indicator species that, when their ecological requirements are met, will provide broad protection for most of the biological components of the ecosystem. When reviewing and summarizing studies and findings for the basin, certain kinds of biological and other ecological information desired for the analysis may be sparse or completely lacking. In such instances, options include use of biological data from adjacent river systems, inferences based on life history information compiled from the literature, and reliance on general habitat suitability criteria developed for species from multiple regions.
3. Obtain and evaluate landscape and biological data. The geographic distribution of identified river types should be estimated. Existing maps, such as NHD maps, can be used as base maps since much useful non-biological data are available, such as location of perennial streams, riparian and floodplain areas that flood under overbanking flows, and locations of contiguous habitat areas such as marshes, oxbows, and abandoned channel lagoons. Data are then assembled on base maps at appropriate scales of resolution. Such data may include species distribution throughout the basin or portions thereof, the geographic range of state and federally listed threatened or endangered fish species and species of concern, location of any critical habitat or sensitive areas.
4. Biological information is used to inform the parameterization of HEFR (or other hydrologic methods), and the underlying decision points needed to produce a flow regime matrix. Some decisions should occur prior to generation of the flow regime matrix (pre-processing). These include the period of record for the analysis, the number of instream flow components and choice of hydrographic separation method. Once pre-processing decisions are made, decision points for modification of default parameters for both the hydrographic separation method and the HEFR analysis can be accomplished with available biological data in order to generate a flow regime matrix.
5. Evaluate and refine the initial flow matrix. The initial flow regime matrix produced by HEFR analysis should be evaluated to ensure that the components of the biological system, their water quality requirements, and geomorphic processes that create and maintain their habitats are maintained. This final step is perhaps the most critical one in the environmental flow evaluation process. Based on the quantification of flow parameters, development of causal connections and geospatial information, information may be available that specifically links biological information to aspects of the flow regime. Even if specific biological information is not available to inform all decision points in the hydrographic separation, any available information should be used. For generation of the flow regime matrix, both specific biological information and more general biological information, particularly with respect to seasonality,

should be considered to modify the HEFR default parameters that generated the initial flow regime matrix.

Relationships between water quality parameters and flow need to be quantified and evaluated and adjusted to ensure water quality parameters (e.g. DO and temperature) are maintained in a suitable range to ensure aquatic life persists/endures. Available water quality models need to be evaluated/updated for examining DO and temperature, especially under conditions of low flow. Flows need to be sufficient to support key habitats and habitat needs for focal species, populations, or guilds of representative lotic organisms.

Base flows provide suitable and diverse habitat conditions and support the survival, growth, and reproduction of aquatic organisms. Information on indicator or key species can be used to validate and refine base flow estimates. Specifically, quantified biotic response-flow relationships discovered in literature reviews can be used directly by comparing HEFR-derived estimates with specific flow requirements. A variety of tools can be used to evaluate suitable habitat. Incremental methods that relate habitat quality, quantity, and diversity to streamflow may be available for some rivers. Where cross-sections and rating curves are available, hydraulic rating methods can be used to relate habitat-flow relationships. Qualitative life history information and conceptual models of indicator species' life cycles also can be used.

High flow pulses have important roles in maintaining water quality, physical processes, aquatic habitat connectivity, and a variety of roles in the ecology of aquatic and riparian species. Because they usually represent the greatest volume of water passing downstream on an annual basis, high flow pulses also tend to be the flow components targeted for storage and diversion for human uses. Pulse characteristics (such as the magnitude, timing, duration, and frequency) should be evaluated and refined relative to life history information for focal species. Approaches to address lateral connectivity to oxbows or other riparian habitats include review of species life history information, targeted sampling, and hydraulic modeling to identify flow levels needed to provide lateral and longitudinal connections.

Finally, the SAC proposed multi-disciplinary integration workshops to overlay information from various disciplines, allowing for adjustments and refinements in a systematic manner that would reduce the potential for conflict between the needs of different ecosystem components and points of view associated with different disciplines. Under SB3, each basin science team had one year to produce a recommendation report that details the information reviewed, data acquired, analyses performed, key assumptions, specific environmental flow regime recommendations for strategically selected gage locations from through the basin, and recommendations for implementation of the flow regime protections and studies to address gaps in knowledge and data. These science-team reports provided the basis for discussions and analyses by the basin stakeholder committees, SAC, public, and TCEQ. Following a period of public comment on draft environmental flow standards, the TCEQ sets standards that will be used to guide the permitting process for future water rights in the basin. These standards can be revised based on new information during periodic reviews that must be conducted at least every 10 years.

References

NRC (National Research Council). 2005. *The Science of Instream Flows: A Review of the Texas Instream Flow Program*. National Academy Press, Washington, D.C., 149 pp.

SAC (Science Advisory Committee to the Texas Environmental Flows Advisory Committee). 2009/1.Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology. Report # SAC-2009-01-Rev1. Austin, TX.

SAC (Science Advisory Committee to the Texas Environmental Flows Advisory Committee). 2009/2.*Geographic Scope of Instream Flow Recommendations*. Report # SAC-2009-02. Austin, TX.

SAC (Science Advisory Committee to the Texas Environmental Flows Advisory Committee). 2009/3.*Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries Within the Context of the Senate Bill 3 Environmental Flows Process*. Report # SAC-2009-03. Austin, TX.

SAC (Science Advisory Committee to the Texas Environmental Flows Advisory Committee). 2009/4.*Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process*. Report # Report # SAC-2009-04. Austin, TX.

SAC (Science Advisory Committee to the Texas Environmental Flows Advisory Committee). 2009/5.*Essential Steps for Biological Overlays in Developing Senate Bill 3 Instream Flow Recommendations*. Report # SAC-2009-05. Austin, TX.

SAC (Science Advisory Committee to the Texas Environmental Flows Advisory Committee). 2009/6.*Nutrient and Water Quality Overlay for Hydrology-based Instream Flow Recommendations*. Report # SAC-2009-06. Austin, TX.

TIFP (Texas Instream Flow Program). 2008. *Texas Instream Flow Studies: Technical Overview*. Prepared by Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board. TWDB Report No. 369, Austin, TX, 137 pp.

Website for Texas Senate Bill 3 Environmental Flows Programs –

http://www.tceq.state.tx.us/permitting/water_supply/water_rights/eflows/