APPLICATIONS OF THE ECOLOGICAL LIMITS OF HYDROLOGIC ALTERATION (ELOHA) IN THE UNITED STATES

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Abstract

The Ecological Limits of Hydrologic Alteration (ELOHA) is a new framework for broadly assessing environmental flow needs when time or resource constraints preclude in-depth studies for all rivers in a region. The main steps of ELOHA are to: (1) build a hydrologic foundation, (2) characterize river types according to their flow regimes and geomorphic features, (3) compute present-day degrees of flow alteration, (4) define flow alteration-ecological response relationships, and (5) use flow alteration – ecological response relationships to manage environmental flows through an informed social process. Several projects within the United States are currently applying elements of ELOHA to accelerate the integration of environmental flows into regional water resource planning and management. By outlining some of these applications, this paper illustrates the use and flexibility of ELOHA. In Pennsylvania, daily streamflow data from 136 relatively unimpaired gauge sites were used to categorize streams throughout the 117,348-km^2 state into 5 types, based on 71 hydrologic statistics. A pilot study of the 71,250-km^2 Susquehanna basin in Pennsylvania identified linear relationships between aquatic invertebrate metrics and proportion of water withdrawn from 298 sites. In Tennessee, scientists identified functional relationships between insectivorous fish metrics and three hydrologic metrics -- constancy, frequency of moderate flooding, and streamflow recession rate -- based on data from 39 streamflow sites in the 106,200-km^2 Tennessee River valley. In Michigan, scientists and stakeholders developed an online computer program, which allows prospective water users to determine whether their proposed ground-water or surface-water withdrawals would adversely impact river resources, defined as a percent of fish guild reduction. The tool links ground-water, surface-water, and fish-community models for 11,000 stream segments classified into 11 stream types in the 253,793-km^2 state. In Arizona, researchers conceptualized flow alteration – ecological response relationships for the 8,000-km^2 Verde River basin in a collaborative expert process. The relationships are helping water managers interpret separate ground-water modeling results in terms of the ecological impacts of proposed ground-water pumping scenarios. In Colorado, an expert team developed preliminary flow-ecology relationships for high-gradient, subalpine streams in the 770-km^2 Fraser River basin, which supplies water to the City of Denver, to guide decisions regarding the timing of diversions from different locations. In Washington, researchers have completed a Bayesian classification of flow regime types, for which flow-ecology relationships are being established as a basis for setting environmental flow targets for rivers throughout the 176,477-km^2 state.

1. INTRODUCTION

Decades of site-specific environmental flow assessments throughout the world have significantly advanced understanding of how streamflow processes affect the structure and function of riverine ecosystems. Application of literally hundreds of methods in a broad range of settings has fueled the imperative that ecological condition be considered explicitly in the determination and implementation of environmental flows (Dyson et al. 2003; National Science and Technology Council 2004; Global Water System Project 2005; Brisbane Declaration 2007; Comprehensive Assessment of Water Management in Agriculture 2007). However, methods that do so, such as DRIFT (Downstream Response to Imposed Flow Transformation), BBM (Building Block Method), and a number of other "holistic" approaches, are often time-consuming and expensive to carry out. The pace and intensity of flow alteration in the world's rivers are widely believed to exceed the ability of scientists to conduct holistic assessments on a river-by-river basis (Tharme 2003; Acreman and Dunbar 2004; Annear et al. 2004; Arthington et al. 2006).

To address these concerns, international scientists from ten organizations developed a new methodological framework for assessing environmental flow needs for many streams and rivers simultaneously. Referred to as the *Ecological Limits of Hydrologic Alteration* (ELOHA), this framework is designed to meet the twin challenges of directly addressing ecological condition and greatly accelerating environmental flow assessment and implementation. ELOHA systematically synthesizes the knowledge and experience gained from individual river studies to support and guide the development of environmental flow standards at the *regional* scale. This framework particularly responds to the needs of regional and national water managers to define environmental flow standards for many rivers simultaneously -- including those for which little hydrologic or ecological information presently exists -- to effectively integrate human and ecosystem water needs in a timely and comprehensive manner (Arthington et al. 2006; Poff et al. in press; Tharme and Kendy this volume).

Several entities within the United States are currently applying elements of ELOHA, contributing to the growing international experience with this new framework. The intent of this paper is to foster communication about the work in progress with others who are facing similar challenges, as well as with those interested in learning more about ELOHA. These and other case studies (Anon 2008; Arthington this volume; www.conserveonline.org/workspaces/ELOHA) have advanced our understanding of the limits and capabilities of this new and evolving regional approach to environmental flow management.

2. CASE STUDIES

ELOHA is carried out in a stepwise fashion with feedback loops and iterations (See Tharme and Kendy this volume, Fig. 2). The main steps are to: (1) build a hydrologic foundation, (2) characterize river types according to their flow regimes and geomorphic features, (3) compute present-day degrees of flow alteration, (4) define flow alteration-ecological response relationships, and (5) use flow alteration – ecological response relationships to manage environmental flows through an informed social process (Poff et al. in press; Tharme and Kendy this volume). This paper is organized accordingly, presenting case studies as they apply to each step of the framework.

Building a Hydrologic Foundation

The hydrologic foundation is a geographically-indexed database of daily streamflow hydrographs representing both baseline (pre-development) and current conditions for every control point in the region over a common period of about twenty years. The difference between baseline and current conditions is calculated and compared to ecological condition. However, rarely are ecological data collected in concert with flow data. Therefore, hydrologic modeling is used to extend periods of record for measured streamflow gauges and to synthesize hydrographs for control points that lack measured data. The hydrologic foundation is also the quantitative basis for delineating river types. Finally, after environmental flows are determined, the hydrologic foundation serves as a decision support system for integrating them into regional water planning and management.

Building a hydrologic foundation for ELOHA can be expensive and time-consuming, so ideally the hydrologic foundation can be built from existing water management models. In the United States only a few such models are in use. The Texas Water Availability Model (http://www.tceq.state.tx.us/permitting/water_supply/water_rights/wam.html#model) is a water balance model that simulates river and reservoir management and water allocation (Wurbs 2005). It is currently being converted from a monthly to a daily time step, which will enable environmental flow management. Colorado's Stream Simulation Model (StateMod, http://cdss.state.co.us/DNN/Products/SurfaceWaterModel/tabid/69/Default.aspx) is a monthly and daily water allocation and accounting model capable of making comparative analyses of various historic and future water management policies. CALSIM (http://modeling.water.ca.gov/hydro/model/index.html) is a water resources simulation model used by the California Bay-Delta Program for river basin planning. The Sacramento River Ecological Flows Tool (SacEFT) improves decision making by linking CALSIM to environmental flow scenario testing (www.delta.dfg.ca.gov/erp/sacriverecoflows.asp).

Several states use rainfall-runoff (watershed) models such as PRMS, SWAT, HSPF, OASIS, and TOPMODEL in their water quality programs. Water managers in Virginia and Pennsylvania are exploring ways to adapt these existing models to build hydrologic foundations for their states (Apse et al 2008).

Characterizing River Types

ELOHA extends the use of limited ecological data by assuming that ecosystems with similar streamflow attributes and geomorphic characteristics respond similarly to flow alteration. Several statistical approaches have been used to group rivers or river segments into hydrologically unique river types.

The Pennsylvania Instream Flow Advisory Committee recently completed a one-year assessment of the data, tools, models, and resources available to apply ELOHA in the 117,348-km^2 State of Pennsylvania. To define river types, first, 205 hydrologic metrics were derived from mean daily discharge data for 136 relatively unimpaired stream gauges. Next, a principal components analysis (PCA) eliminated redundancy, thereby reducing the number of metrics from 205 to 151. Three different clustering procedures were then tested for their ability to group Pennsylvania's streams according to flow regime and to identify the ecologically relevant flow metrics that best characterize them. Ultimately, five river types were defined based on a subset of 11 metrics that describe streamflow magnitude, variability of high flows, and flood frequency (Apse et al. 2008). This approach was similarly used to define river types in New Jersey, Missouri, and Massachusetts (Kennen et al. 2007; Cade 2008).

In Washington State, researchers have completed a statewide hydrologic classification based on 99 metrics describing ecologically relevant characteristics of the natural flow regime (J.D. Olden *unpublished data*). Metrics were calculated from continuous time series (>15 years of record) of mean daily discharge data for 52 stream gauges, and classification was undertaken using a fuzzy partitional method - Bayesian mixture modeling. This analysis has identified distinctive flow regime types that differ in their seasonal patterns of discharge, variation in low flow and flood magnitude and frequency, and other aspects of flow predictability and variability. Factors related to catchment (watershed) topology, surficial geology, and climate were found to be strong discriminators of flow regime, and this information is being used in statistical models to predict flow regime type and flow metrics for streams and rivers across the state. The spatial context provided by the hydrologic classification improves understanding of the interaction between hydrology and ecology in rivers of the Pacific Northwest United States, and provides a benchmark against which the response of biological communities to hydrological alteration can be assessed.

Water temperature is also a key component of environmental flows and is strongly influenced by ground- and surface-water hydrology (Olden and Naiman in press). In Michigan, 11 river types have been delineated for the 253,793-km^2 state, based on hydrology, temperature, and catchment size (Michigan Groundwater Conservation Advisory Council 2007).

Plant and animal species may respond differently to flow alteration in geomorphologically distinct reaches of a stream. For example, in a homogenous stream reach, extensive dewatering could cause a stressful habitat bottleneck that induces a threshold-type reduction in fish populations; but if the river has deep pools, then these refuges could make possible a more gradual and continuous (linear) ecological response. Therefore, it is useful to subgroup river types according to geomorphic setting. For example, researchers in Washington State have used channel slope, discharge, stream power, and bankfull width and depth to delineate streams and rivers into geomorphic classes. Streams in several parts of the United States have been similarly subgrouped according to macrohabitats with unique combinations of size, elevation, gradient, geology and connectivity (Higgins 2003).

Computing Flow Alteration

To assess the degree of flow alteration at each control point, baseline hydrology is compared to current hydrology stored in the hydrologic foundation database. This step serves two purposes. First, it standardizes hydrologic impacts, allowing creation of a degree-of-alteration data set to use in combination with ecological data from multiple rivers. This enables data from *individual* rivers to be combined to define flow alteration - ecological response relationships for *types* of rivers. Second, it helps scientists and stakeholders understand the degree to which streamflow has already been altered throughout the region.

Several software packages are capable of conducting this analysis. New Jersey, Massachusetts, and Missouri used the Hydrologic Alteration Tool (HAT) software in the U.S. Geological Survey's Hydroecological Integrity Process (HIP) package (Henriksen et al. 2006) to calculate flow alteration for control points with measured streamflow gauging data. The Nature Conservancy's Indicators of Hydrologic Alteration (IHA) software also analyzes flow alteration (Richter et al. 1996). In addition to traditional hydrologic metrics, IHA calculates 34 Environmental Flow Components that were specifically developed to be ecologically relevant; amendable to water resource management; and intuitive to hydrologists, ecologists, and stakeholders alike (Richter et al. 1996; Mathews and Richter 2007).

To date, statewide analyses of flow alteration have considered only measured data; synthesized streamflow data from the hydrologic foundation have not yet been analyzed at the scale of an entire state or large basin in the United States. However, complete sets of simulated data have been analyzed at a smaller scale, providing the scientific basis for evaluating tradeoffs among management options. In the 770-km^2 Fraser River basin, which supplies water to the City of Denver, Colorado, natural and fully-developed flows were modeled for a 45-year period (1947 – 1991). Hydrologic status of six flow parameters was evaluated for six locations in the catchment using IHA software. The degree of alteration among flow parameters varied both within and among streams (J.S. Sanderson *unpublished data*). Small flood duration was the most impacted across streams, being reduced 37 to 72% in five of six streams. One-day maximum flows were the least impacted across streams, with reductions of 15 to 45% in all but one stream. The greatest percent alteration was in extreme low flow duration, which has increased as much as 482%. The results generated by this analysis were used to evaluate tradeoffs among streams for the management of 'spills' during high runoff periods, in order to identify which parts of the flow regime would be most useful to restore, and in which locations the most ecological benefit could be gained. The conclusion reached was that the greatest ecological benefit of managing spring spills would be achieved by improving flood conditions at those locations where low-flow conditions are either natural or minimally altered, thereby bringing all flow metrics at these streams to a level of minimally altered or better.

Defining Flow Alteration – Ecological Response Relationships

A scientifically challenging, yet crucial step of ELOHA is the development of relationships between measures of flow alteration and particular ecological response variables (Poff et al. in press; see Tharme and Kendy this volume, Fig. 1). For some river types, ample data are available for defining these relationships. In most places, however, data are scarce. In places with limited data, scientists are nonetheless advancing ELOHA through expert judgment, statistical analysis, and modeling. Whether

data are abundant or scarce, scientists must account for confounding factors such as pollution, physical habitat degradation, and invasive species, which may cause substantial impact even with minimal flow alteration (Dunham et al. 2002).

Using expert opinion

Expert judgment is a well-accepted supplement to scarce data in site-specific environmental flow assessment (Arthington et al. 1992; Richter et al. 2006). Likewise, at the regional scale, interdisciplinary expert panels have successfully developed and refined flow-ecology hypotheses for ELOHA. For example, for high-gradient, subalpine streams in Colorado's Fraser River catchment, scientists in a facilitated expert workshop listed ecological attributes associated with streamflow in the catchment; identified the key components of the flow regime that sustain those values; and set preliminary, quantifiable criteria that could be used to make informed management decisions. Results of the workshop were summarized and expressed as explicit relationships between ecological status and flow status for flow metrics. Based on the needs of five biological components of the system (cutthroat trout, amphibians, riparian plant communities, beaver, and aquatic macroinvertebrates) and two abiotic characteristics (sediment and water quality), criteria based on six streamflow parameters were identified as essential for maintaining the health of the system.

In the 8,000-km^2 Verde River basin in Arizona, scientists also conceptualized flow alteration – ecological response relationships through a collaborative expert process. The outcome focused subsequent field studies directly on quantifying the relationships. The fine-tuned relationships are helping water managers interpret separate ground-water modeling results in terms of the ecological -- not just hydrological -- impacts of proposed ground-water pumping (Haney et al. 2008). In the long term, this work is intended to inform the development of linked ground-water, surface-water, and ecological models which can predict ecological responses to water management scenarios. Scientists in the 29,137-km^2 Connecticut River basin in the northeastern United States are taking a similar collaborative approach to hypothesis formulation in preparation for setting environmental flows.

Analyzing existing data

Another approach for formulating hypotheses and identifying hydrologic metrics for ecological analysis is to statistically analyze available data. In the 106,200-km^2 Tennessee River valley, scientists used a multivariate correlation procedure and quantile regression (Cade and Noon 2003) to identify functional relationships between insectivorous fish metrics and three hydrologic metrics -- constancy, frequency of moderate flooding, and streamflow recession rate -- based on data from 33 streamflow gauging stations (Knight et al. 2008).

In a few places where data are ample, actual flow alteration – ecological response relationships have been developed using existing measured data. A pilot study of the 71,250-km^2 Susquehanna River basin in Pennsylvania identified linear relationships between aquatic invertebrate metrics and proportion of water withdrawn from 298 sites. Results indicate that the size of the drainage basin is an important factor controlling these relationships (Apse et al. 2008).

Statistical analysis of existing data was used to define flow-ecology relationships for streams throughout the 268,627-km^2 state of Colorado (T. Wilding and N. Poff, *unpublished report*). Diverse data derived from 149 sources, including journal articles, technical reports and theses, were sufficient to quantify relationships between streamflow conditions and riparian vegetation, fish, and aquatic macroinvertebrates in three types of streams. Comparison of measured ecosystem parameters across a range of flow conditions (varying levels of modification) allowed patterns to emerge that provided a basis for quantifying ecosystem response. Where ecosystem complexities precluded a simple monotonic response to flow change, the best-available flow-ecology response relationship was inferred as the ceiling of the scattered data, as defined by quantile regression (Cade and Noon 2003). Konrad et al. (2008) similarly applied quantile regression to advance understanding of relationships between streamflow and benthic invertebrate assemblages in the western United States.

Ecological modeling

Scientists in Michigan used ecological modeling to quantify how fish guilds in different types of Michigan streams would change in response to decreased base flows, defined as median streamflow in the lowest flow month (i.e., August or September). The model uses habitat suitability information (catchment size, base flow yield, July mean temperature) for more than 40 fish species to predict assemblage structure and characteristic fishes under a range of base flow reductions (Zorn et al. 2008)

Using flow alteration – ecological response relationships to manage environmental flows

There exists a broad range of potential uses of ELOHA. For example, its geographically extensive assessment of flow alteration provides a measure of relative risk for particular ecosystem components. ELOHA can also be used to identify potential conservation areas, to guide water supply operations, as described above for the Fraser River basin, and to set regional flow standards, as described below.

ELOHA informs the setting of flow standards by illustrating the expected ecological consequences of flow alteration. With explicit understanding of consequences, the decision becomes one of determining the desired ecological condition for a river or class of rivers. Like any environmental flow method, the final flow standard is a judgment call and a political decision that relies strongly on scientific, technical, policy, and legal experts and stakeholders. Ideally, this decision is made by local stakeholders and mediated and ratified by government.

In Michigan, first stakeholders and then the state legislature decided to allow no more than a 3% impairment of a lake's or stream's ability to support its characteristic fish population compared to the current condition. Modeled flow alteration – ecological response curves (described above) translate changes in ecological condition into allowable streamflow withdrawals. These, in turn, are linked to a ground-water / surface-water model (the "hydrologic foundation"), which underlies an online decision support system. Prospective water users access the online system to determine whether their proposed withdrawals, combined with the cumulative impacts of all upstream water uses, will degrade fish communities in excess of the allowable amount.

Whereas Michigan applies a uniform ecological standard to every river in the state, other states are establishing goal classes for different rivers to achieve different ecological standards. For example, Maine and Connecticut are adapting existing water quality classes to environmental flows.

3. DISCUSSION

As we have shown, in diverse regions of the United States, an ELOHA-based approach is proving to be a useful framework for assessing and managing environmental flows across geographically extensive areas. However, even where progress has been made, both scientific and political challenges remain.

A key challenge of applying ELOHA is developing the hydrologic foundation, which enables flow alteration to be calculated for every place where ecological data have been collected. Despite the obvious advantages of using the underlying model as a decision support system for water management, governments are reluctant to invest the significant time and money required before being convinced that ELOHA is a viable approach for their jurisdictions. To demonstrate its utility, several pilot projects have mined ecological databases to develop preliminary flow-ecology response curves using only measured flow data. The success of these projects has been hampered by a lack of synthesized hydrologic data to pair with ecological data collected from locations where streamflow has not been measured.

Thus, for example, Knight et al. (2008) used fish data from only 33 of the more than 1,100 sites where samples had been collected in Tennessee. Next, researchers in Tennessee intend to develop prediction

models for the flow metrics they identified based on the 33 sites. Instead of using watershed modeling to synthesize daily flows, they will use regression modeling to predict values of selected hydrologic metrics at the 1,100 fish sites. Although this abbreviated approach will yield flow-ecology response relationships, it will be limited to only a few pre-selected flow metrics. Furthermore, the ability to manage environmental flows in a regional context will be limited by the lack of a decision support system for assessing tradeoffs between management scenarios.

Watershed or water balance modeling, in contrast to regression, accounts for the cumulative impacts of upstream water uses at any control point and therefore makes a useful decision support tool for water managers. A promising hybrid approach, modified QPPQ, uses regression and catchment characteristics to synthesize daily flows without a rigorous watershed model (Waldron and Archfield 2006). This approach has been trialed successfully in humid northeastern states (Apse et al 2008) and is being considered for testing in other regions.

The hydrologic foundation is a particular challenge in arid regions, where ground-water use can significantly affect streamflow. While humid states like Michigan can adequately account for ground-water/surface-water interactions with relatively simple models, arid states like Arizona and Nevada may require major investments to model accurately the timing and location of streamflow depletion due to ground-water pumping.

Developing robust flow-ecology relationships can also be a significant challenge. Only recently has a relatively small handful of researchers explicitly addressed such relationships (Konrad et al. 2008). In the absence of explicit studies, ELOHA practitioners must use existing literature to develop or infer these relationships. Even in relatively well-studied watersheds, existing studies may be of limited use in developing flow-ecology curves. For example, in the Fraser River watershed, the majority of points defining the flow-ecology curves were based on expert opinion or hydrologic approaches such as the Range of Variability (Richter et al. 1997). Nonetheless, preferred flows determined for the Fraser River compare favorably with those developed using site-specific approaches (Tetra Tech et al. 2008), including PHABSIM and a hydrologic events approach (Reiser et al. 1990). In Colorado's Roaring Fork catchment, literature search yielded sufficient data to support flow-ecology curves for cottonwood (*Populus*) forests, fish (trout and a subset of native fish), and invertebrates, yet only one study was found relating woody riparian vegetation to flows above the maximum elevation of *Populus.*

Moving from science to policy presents another set of challenges. Even where scientists are beginning to understand how ecological systems depend on streamflow patterns, they often describe these patterns in terms of hydrologic statistics that are difficult to apply to water management. To regulate water use, water managers need the allowable volumes or levels of water withdrawals at different times of the year. To manage reservoirs, operators need volumetric dam release requirements at different times of the year. Scientists and water managers must work closely together from the inception of ELOHA applications to ensure that scientists analyze flow metrics that water managers can use to mimic, to the extent possible, natural flow patterns. With hindsight, some ELOHA practitioners are revisiting their analyses to derive new hydrologic statistics that combine ecological significance with management relevance.

Political obstacles to sound water management are renowned. Where water is over-allocated, water users may be reluctant to consider changes. Therefore, progress is likely to be made in incremental, politically feasible steps. For example, stakeholders in Michigan agreed to the state's innovative approach to limiting future water withdrawals according to ecological needs, so long as current water uses would be untouched. Although this compromise in effect condones the existing degradation of some of the state's rivers, ultimately it gained acceptance as the most progress that could be made at the present.

In many places, it may not be politically expedient to limit future water withdrawals at this time. Where economic growth depends on water resource development, the political will to limit that development can be weak. Even in these places, however, it is critical that the scientific foundation be laid for environmental flow management. In laying that foundation, ELOHA informs debate about how water

will be managed in the future, focusing discussion away from conflict and onto solutions that integrate economic development with ecosystem health.

Adaptive management is key to both the scientific and the political processes of ELOHA. Long-term monitoring of ecological responses to flow alteration refines the scientific basis for planning and management programs, and measures their success. While scientists routinely reinterpret their findings as new data emerge, rigid regulatory programs are often slow to respond. An ongoing challenge of science-based governance is to adapt flexibly as the underlying science evolves. This is especially true of ELOHA because, by design, the framework establishes interim environmental flow targets using sparse available data until additional data and resources can be obtained. Standards and regulations that implement laws mandating the use of "best available science" may need to be rewritten when the "best" gets better. Thus, for example, the State of Florida's "Minimum" Flows and Levels are now interpreted and managed as minimum as well as maximum flows and levels that vary seasonally and annually according to ecosystem needs (Diffenderfer and Duhy 2006).

4. CONCLUSION

These case studies from the United States show that, despite scientific and political challenges, ELOHA is advancing the recognition, determination, and management of environmental flows in places where they were never before considered at the policy level. They illustrate how this framework can be applied in a range of settings, with varying availability of hydrological and ecological data, across spatial scales, and within different regulatory contexts. Successful efforts to build a hydrologic foundation, characterize river types, compute flow alteration, define flow alteration – ecological response relationships, and use these relationships to manage environmental flows are a cause for optimism.

Despite this noteworthy progress, there remain many regions where hydrologic foundations and/or flow-ecology curves remain insufficient to complete robust ELOHA frameworks, and where politics seem to conspire against large-scale environmental flow protection. It may indeed seem daunting to apply ELOHA as credibly as possible with uncomfortably sparse data and tremendous uncertainty.

In years past, land and water resource development occurred without consideration for environmental flows. Now, through the hard work of river scientists worldwide, policy makers, water users, hydropower producers, and communities understand the urgency of protecting and restoring environmental flows, and they are increasingly asking us to help them do so. If we allow less-than-ideal conditions to paralyze us, then we will miss the opportunity to pass through a door that we ourselves have worked so hard to open. Rigorous, fieldwork-intensive, site-specific assessments for every river will always be the ultimate goal. While we focus limited resources and capacity on rigorously assessing the highest-priority rivers in the short term, ELOHA can fill the escalating need for most rivers in the long term.

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