In: Ecological Management: New Research
Editors: M. S. Alonso, I. M. Rubio
ISBN: 978-1-60456-786-1

Chapter 7

VIRTUAL REFERENCE RIVER: A MODEL FOR SCIENTIFIC DISCOVERY AND RECONCILIATION

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ABSTRACT

Advances in aquatic ecology can be broadly separated into two contrasting approaches, synthetic vs. incremental. Synthesists study rivers at a holistic level and typically describe important processes in relative terms from headwater to river mouth or across regions. Incrementalists typically quantify relationships of stream flow quantity and quality to fisheries response and are often constrained by institutional requirements. The two approaches can be reconciled using the concept of the habitat template and creation of the Virtual River Reference model. This model should build upon the fundamental principles of natural processes and habitat simulation, determining the physical habitat characteristics of reference river systems as a function of landscape attributes. This approach would use the habitat requirements of the native fish community to reconstruct a corresponding hydro-morphological template of a reference river. The template of habitat attributes can be employed to compare impacted systems to natural or relatively healthy systems (the reference condition) across broad temporal and spatial

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scales. The summary attribute set can be adjusted to establish a template describing target conditions which are achievable for managers under current or future circumstances. The Virtual River Reference habitat template will create a simulation platform to investigate natural biophysical processes in riverine ecosystem.

Keywords: ecological modeling, habitat modeling, impact assessment, habitat template, river restoration.

INTRODUCTION

In 1998 Holling observed that there are two philosophical streams in science (analytical and integrative) that created disparity of methodological approaches across many disciplines [1]. Similarly, the advances in aquatic ecology can be broadly separated into two approaches, synthetic vs. incremental, each with its own distinct origin and history of development. In the synthetic approach, which may be considered one of analytical trends, scientists attempt to understand the ecology of rivers at a holistic level and describe how important riverine processes vary over time and space often at the catchment scale. Noteworthy conceptual advances made by this group included the Nutrient Spiraling Concept [2], River Continuum Concept [3], Serial Discontinuity Concept [4], the Flood Pulse Concept [5], the Patch Dynamics Concept [6, 7], the Natural Disturbance concept [8], Habitat Templet concept [9, 10], the Riverscape Concept [11], the Natural Flow Paradigm [12 13], and its corollary, the Normative River Concept [14].

In the incremental approach, researchers tried to integrate suites of tools to quantify and predict the amount of stream-flow required to preserve and maintain local-scale fishery resources, i.e., the instream flow [15]. Incremental approaches were first developed to preserve aquatic resources in western USA streams that were managed under prior appropriation water laws [16]. Under western USA water law, instream flows could be owned as a water right in the same way that land or a mining claim could be owned. Therefore, the incremental method started from the premise that habitat could be treated as a commodity and quantified using a framework of commodity pricing and allocation. Accordingly, methods for determining instream flows had to be consistent with the institutional framework used to manage water rights, as exemplified by the Instream Flow Incremental Methodology (IFIM) [17], but other methods also share this characteristic. The Physical Habitat Simulation Model (PHABSIM), a standard modeling tool of IFIM, estimates aquatic habitat using cells located in river cross sections. This approach is based on the same gauging methods used to estimate stream discharge [18]. In addition, relatively simple hydrologic methods initially used to characterize the probability that a particular river reach could deliver specific quantities of water to support farm irrigation, water supply, or other production-based uses of water were borrowed to estimate the time dynamics of habitat requirements. The close conceptual relationship between habitat duration curves [17] and flow duration curves is clear. These methods, particularly the PHABSIM, have become institutionalized and exported for use in streams throughout the world [19, 20, 21, 22]. In the process, important relationships between application purpose, history of the tools, and underlying assumptions have been obscured. It is important to note that many western US rivers that presently support valuable fisheries might have been completely degraded had the time been taken to fully develop more holistic science-based methods.

Neither the synthetic nor the incremental approaches, separately, are adequate to develop comprehensive science-based management strategies for rivers. Advances made by synthesists have been largely conceptual in nature. Their findings are usually presented in a relative sense because the primary goal was to guide the development of research or to develop broad conservation strategies for complex ecosystems that could not be convincingly reduced to predictive, mechanistic models. Important stream attributes were described as changing from upstream to downstream or across seasons in statistical terms (e.g., long-term averages) rather than in terms of time-varying values characteristic of mechanistic models.

Although useful from a heuristic or theoretical standpoint in having broad general application, the synthetic approach cannot be used to *a priori* address many river management issues where detailed site-specific information is required. However, the synthetic approach can be used *a posteriori* to guide large-scale restoration (e.g., see examples in [12]) or to set general guidelines for conservation action on individual rivers [23, 24]. Implementation of the synthesist approach for river management is typically viewed as "experimental" in an adaptive management context [14, 12, 25].

The foundation for synthesis is often restricted to parts of one watershed or too narrow and fragmented to give useful, broad perspectives on aquatic ecosystems [11]. The assumptions, conclusions and concepts are derived from brief observations of short river reaches (at the scale of hundreds of meters) that are then “extrapolated” to the scale of whole river systems and their supported populations. The landscape context is lost in the process. Most often these observations are not spatially explicit and do not allow for posteriori analysis at the landscape scale. Many important processes that cannot be recognized at the very fine scale (such as edge effects or patchiness) are lost from the synthesis.

Clearly, incrementalist tools have a place in water resources management because they exhibit the potential precision needed to quantify benefits and impacts of alternative plans. However, tools such as the IFIM were criticized for a variety of reasons [26], but primarily for their inability to adequately relate habitat quantity to fish abundance [27 28]. Further, the traditional, narrow application of these tools toward management of single species has been viewed as inadequate in the context of growing concerns over ecosystem integrity [13, 12]. Although spatially explicit, classic applications of the method suffer the same sort of spatial uncertainties as do synthetic analyses [20]. The quantitative nature of incremental methods has great appeal in the regulatory environment; however, the high costs have always limited it application to single (or few) short river sites. Consequently, observations at the scale of tens of the meters, of only few environmental parameters have been extrapolated to much larger spatial units [29]. Furtheremore, the pressure to reduce the costs of application frequently led to oversimplified and therefore inaccurate solutions, such as reducing the habitat description to very few (e.g. hydraulic) attributes [30]. The scientifically questioned precision of instream flow applications, their heavy reliance on simple hydraulic and hydrological summary techniques, and problematic biological assumptions have limited the acceptance of the approach by the synthesists community [31, 32]. This is unfortunate, because recent development of modeling methodologies proved hydraulic habitat simulation approaches to be very valuable for scientific discovery as demonstrated in the example below.

Specialized methods can be used to identify and quantify the scale of features using transect data typically collected during an incremental study [33]. Figures 1A and 1B depict a

Missouri River cross section at KM 1254.3 under high flow (906 m^3 sec^{-1}) in 1964 (shortly after regulation) and 1992 (after about 30 years of regulation). A scale analysis of the before versus post-regulation channel shape (Figure 1C) shows that the historical channel is best described as being self-similar because it was comprised of graded series of features of different scales without dominance by a single scale or small set of scales. In contrast, the 1992 cross section is dominated by features at two scales. At a relatively large scale (~450 m) the 1992 cross section exhibits a large, ditch-like feature (solid oval) (Figure 1B). The scale analysis indicates that the 1992 cross section exhibits no features of smaller scale until a scale of about 50 m (dotted ovals) is reached. Using the historical condition as a reference, the scale analysis shows that the Missouri River at this location has changed from a self-similar to simpler, shape characterized by channel features of predominantly two scales. Further discussion of Missouri River changes can be found in [34].

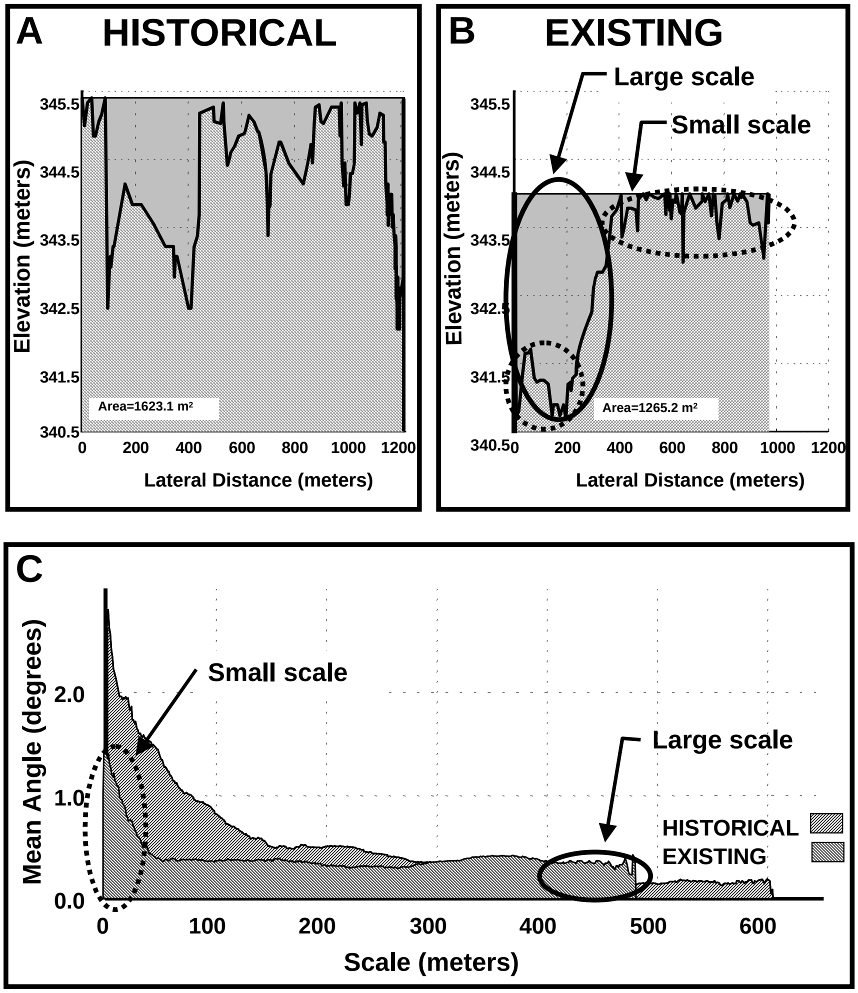

Figure 1. Comparison of river kilometer 1254.3 based on field measurements made in 1964 (A) and 1992 (B) at a flow of 906 m^3 sec^{-1}. Overlay of mean angle by scale plots for A and B.

It is not only important that habitat models can assess the current conditions but also that they can be used to simulate and to better understand the processes and driving forces of riverine ecosystems. With appropriate modifications the quantitative modeling of incrementalists can be used to create virtual reference systems as a tool for synthesists to study aquatic environments and create quantitative feedback for managers. Recent advancements in physical habitat modeling tools [20, 22] as well as in scientific theories about the organization and simulation of complex systems [33, 35] make the creation of mathematical models of virtual reference rivers a viable option.

GOALS AND OBJECTIVES

Our goal in this paper is reconciliation of the differences between the incremental and synthetic approaches and thereby lay the foundation for a development of a comprehensive tool box for water resources management by: 1) describing how the reference river concept can be used to integrate the perspectives of synthesists and incrementalists, 2) demonstrating the concept of Virtual Reference River (VRR) model, which could serve both groups as a research tool and aid comprehensive river management and 3) present the utility of incremental simulation models as a backbone of virtual river representations.

REFERENCE RIVER CONCEPT

The reference river concept was perhaps first used and described by Karr [36] , as a component of the Index of Biotic Integrity, and is widely embraced as a regulatory framework [37] and in quantitative analyses of river management [34 38]. In its broadest context, the reference river represents the maximum realizable future condition of a river targeted for management action. The reference river source information can be formed from reference conditions obtained from a historical conditions, a relatively unimpacted section of the target river, a physical analogue located outside of the watershed, or a numerical construct using a process-based mathematical model. The source for the reference information can affect the resulting model [39]. The template of time-varying attributes used to describe or assess the reference river is the critical component of the VRR concept that bridges the gap between synthesists and incrementalists. The attributes and their scaling used to create the template are based on the knowledge of synthesists. The precision required by incrementalists can be obtained by quantitative comparisons between the reference river and different management alternatives using the template variables.

Two examples, one North American and one European, demonstrate how the idea of the reference river can be used to bridge the apparent divide between synthesists and incrementalists. In North America, the growing recognition of the ecological relevance of flow variation [40] led to the development of the concept of the Natural Flow Regime [12] and tools to characterize it, such as the Indicators of Hydrologic Alteration (IHA) [13] The IHA uses a template of hydrological variables, summarized as indices, thought to influence important natural biophysical processes in rivers (see [41] for a discussion of redundancy among IHA and other hydrologic indices). Deviations in these indices from values expected in relatively unimpacted systems provide insight into possible causes of poor ecological health of river systems and provide a general roadmap for river restoration. A large and growing body of empirical literature showing that alteration of hydrologic pattern leads to ecological modification [12,24] has contributed to the broad appeal of the approach among the synthesists [21]. Recently a subset of the indices has been identified as environmental flow components and created a basis for the proposed Ecologically Sustainable Water Management Approach [42, 43].

In Austria, a "Hybrid Approach" was developed [44] in which key attributes of a relatively undisturbed reference system were quantified using a multivariate modification of PHABSIM to guide restoration actions on a heavily altered reach of the Traisen River. Special emphasis was placed on identifying hydraulic and geomorphological factors responsible for differences between reference and impacted systems. Note that the IHA and the Hybrid Approach use the reference river concept of the synthesists to generate summary variables to understand impact at broad temporal and spatial scales. The tools use concepts of the incrementalists to formulate hydrologic and geomorphology-based indices that are quantitative and easy to interpret for restoration planning and water resources decision-making.

The Hybrid Approach set the stage for development of the MesoHABSIM approach, which uses the concept of biophysical templates to develop river scale habitat models of reference conditions as a baseline for quantification of habitat alteration and improvement actions [20,45,46]. The following example demonstrates a recent applications of the model to rivers in the Pomperaug River watershed, located in central Connecticut. The watershed has a total area of 233 km^2 (90 mi^2) and is made up of three main rivers, the Pomperaug, Nonnewaug, and Weekeepeemee. The river has high quality groundwater and surface waters, and more than half of the basin is forested.

The purposes of this study were to: 1) to evaluate the low-flow related stresses to the physical habitat and fish community and 2) to determine ecologically viable objectives for a management plan for the rivers of the Pomperaug River watershed.

Using a method modified from [47] we created two separate reference fish communities (RFC); one for the upper watershed, the Nonnewaug and Weekeepeemee Rivers, and the second for the lower watershed, the Pomperaug River .

For each RFC we: 1) described species composition, and 2) determined each species' proportions using biological data obtained from field collections from a number of unimpacted sections of similar rivers within the area of investigation. The ranks of the species obviously underrepresented in the samples (e.g. Atlantic salmon *Salmo salar*) were adjusted based on best professional judgment of a regional experts. Species proportions for the RFC were determined by establishing the dominance rank of species in the historic fish samples. The ratio of reciprocal mean rank of each species to the sum of reciprocal ranks is considered the expected proportion of the species in the community [47] The RFC provided baseline against which present fish fauna abundance and composiont could be assessed. The habitat needs of each species were determined by logistic regression analysis of the fish habitat and abundance databases from nine other northeastern rivers supplemented from literature reviews.

Mesohabitat habitat assessment of the three rivers was conducted between 2002 and 2005 using multiple mapping surveys of representative sites at a range of low flow conditions. We developed a GIS model of habitat suitable for each species by integrating information from the RFC and habitat needs with the mesohabitat surveys .

The model was linked to hydrological models of pre-colonial flow conditions, developed using Precipitation-Runoff Modeling System [48], to create a habitat time series. Analyses of habitat patterns in the time series were used to develop flow management recommendations identifying thresholds for the magnitude, frequency, and duration of rare, critical, and common habitat events in each bioperiod using the Uniform Continuous Under Threshold technique [46]. Subsequently, the change in the number of days when the habitat was below these thresholds for periods of time long enough to become persistent or catastrophic, was used as a metric for the comparison of four different scenarios.

FIRST PRINCIPLES AND THE TEMPLATE OF VARIABLES

Tools and concepts used in water resources sciences must accurately characterize important hydrologic and geomorphic processes affected by management actions. In the physical sciences, this requirement would be couched as fidelity to "first principles" [49]. As used by Aristotle, first principles are attained when a problem cannot be decomposed any further, that is, when the problem is irreducible. However, biological theories are based on concepts that arguably cannot be reduced to the laws and theories of the physical sciences [50]. For biological problems, we redefine first principles to mean that aquatic processes are described in ways that are consistent with the fundamentals of biology, physics, chemistry, and geomorphology while maintaining appropriate temporal and spatial scale relationships among all variables. The importance of maintaining fidelity to first principles is eloquently stated by Kalmijn (2000), "…in seeking regularity and focusing on the most salient features in their environment, in order to endure and thrive, animals have empirically discovered the laws of nature." [51]. Therefore, the needs of the organisms may be used as a guiding principle for creation of a physical habitat template representing a reference river, as in the MesoHABSIM application presented above. Defining these needs becomes the most crucial element in such models. The Numerical Fish Surrogate (NFS) is an example of a tool serving this purpose that is based on first principles descriptions of how fish perceive their environment.

This model is developped by coupling together a fish swim path model with the output of a detailed, 3-D hydraulic model using methods described in Goodwin et al. (2006).[52] The scientists use a sensory ovoid to approximate the scale at which a fish of a particular size can acquire information from its surroundings (Figure 2). Information gradients within the sensory ovoid are approximated by line segments originating from the location of a fish and extending to the boundary of the sensory ovoid in the cardinal directions. Information in the form of gradients is fed to a decision-making algorithm programmed to simulate the behavior. Swimming speed can be adjusted to reflect the influences of fish size and water quality or hydrodynamic variables. The output of such a model is depicted in Figure 3, see [52] for details.

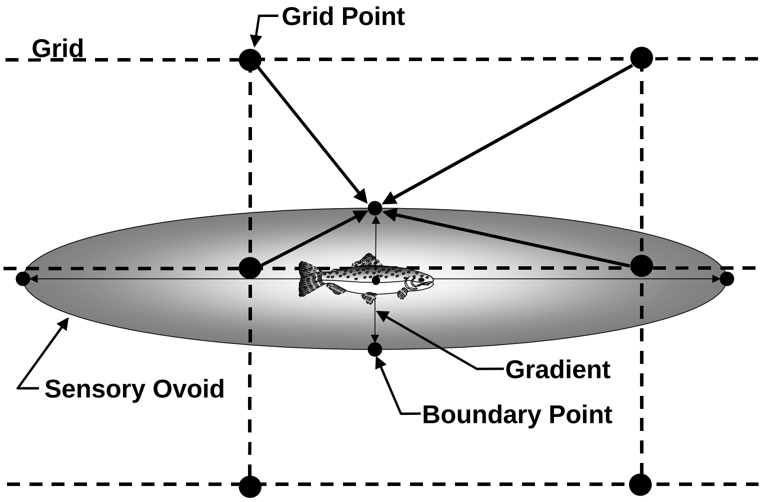

Figure 2. Moving information from node points to interior points of interest to create the sensory ovoid.

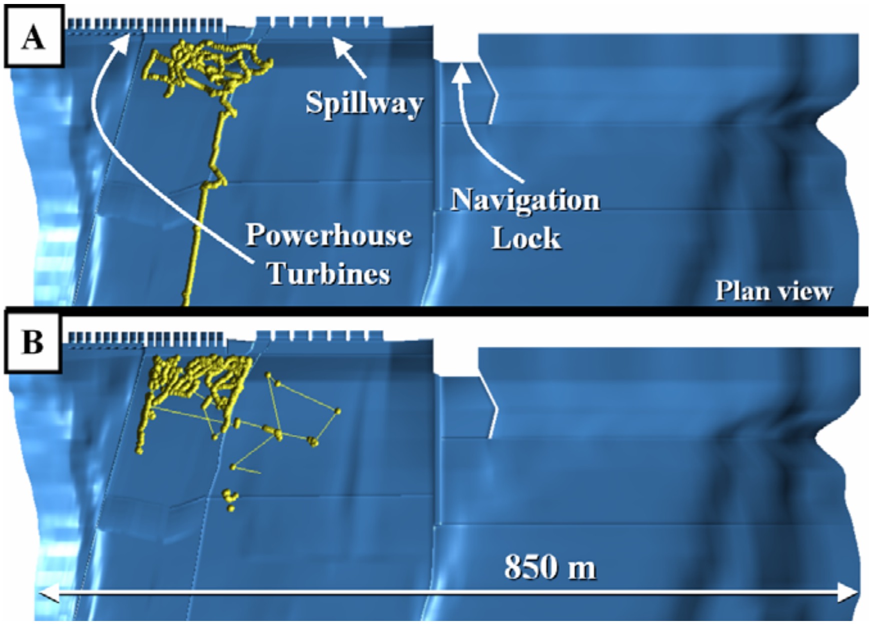

Figure 3. (A) Virtual fish movement output from a Eulerian-Lagrangian-agent method (ELAM) model that integrates high–fidelity CFD modeling, Lagrangian-based particle tracking, and agent-based fish behavior rules. (B) Observed movement of an acoustically-tagged juvenile salmon from [77]. Details on the ELAM model in [52].

This approach provided the evidence for resident [53] and out-migrating juvenile [52] salmon that suggests that the hydraulic variables necessary to understand how fish respond to flow pattern are the 3-D velocity field, the 3-D hydraulic strain (spatial derivative of velocity or gradient of velocity to gradient of depth) field, a measure of scale, and pressure (when water depth is sufficiently large). The first three variables derive from first principles of river geomorphology, fluid dynamics, and scaling limitations associated with the fish mechano-sensory system and are embodied in the Navier-Stokes equations of fluid motion [52].

The relationship between hydraulic strain and velocity is best understood using principles of fluvial geomorphology [54]. In free flowing rivers, flow field pattern results from flow resistance [55]. Without flow resistance there is no force to distort a unit volume of water once it is set into motion by the force of gravity [56]. Flow resistance can be separated into two categories for sub-critical, steady flow in a straight and uniform channel: friction resistance and form resistance. Friction resistance in such a channel produces a flow pattern in which average velocities are lowest nearest a source of friction (such as the channel bottom and edges) with a zero water velocity occurring at or near the water-channel interface. Pattern in the strain field is the inverse of pattern in the velocity field, with lowest strain occurring furthest from a source of friction resistance and highest strain occurring nearest a source of friction resistance.

Form friction is created by large woody debris or rock outcrops projecting into the channel. As in the case of friction resistance, strain rate associated with form resistance increases towards the source of resistance. In contrast to bed friction (where water velocity decreases towards the friction source), water velocity increases towards the signal source for form resistance because of local reduction in conveyance area and increased travel distance of water flowing around an obstruction. A fish approaching submerged wood from the upstream direction will sense an increase in strain and an increase in water velocity magnitude until solid boundary effects very close to the obstruction are encountered. By integrating information between the strain and velocity fields, fish have sufficient information to separate channel structures associated with either friction or form resistance, thereby creating a hydrodynamic "image" of their immediate surroundings. This groundbreaking results allow us to better understand the mechanisms of fish behavior and attributes that define habitat.

DEVELOPING THE CONCEPT OF VIRTUAL REFERENCE RIVER

The idea of Virtual Reference River began with the effort of the International Aquatic Modeling Group (IAMG) [57] promoting and facilitating advances in quantitative assessment of freshwater ecosystems to improve our understanding of biological responses to human actions. This voluntary collaborative group consists of biologists, hydrologists, engineers and geosciences professionals, and experts in the application of physical habitat models as a tool of science and management. During a technical workshop of IAMG in Quebec City in October 2000 it was concluded that:

> "in order to better structure river restoration/conservation practices a broadly applicable, system-scale oriented numerical model of a 'reference river' is a primary need. The model should establish the basis for quantitative analysis of interactive ecosystem structure (water quality, hydrology, geomorphology, biology, multidimensional connectivity) coupled with biological response measures. This approach will create foundation for a comprehensive set of river management methods that fulfill recognized requirements and demands."

The definition of VRR was coined in August 2001 at the technical workshop of IAMG in Ft. Collins, Colorado:

> “The Virtual Reference River concept should be based on the fundamental principles governing natural processes, and would serve to quantitatively describe physical habitats and their variability at various scales. It would allow for the translation of landscape-level descriptors (e.g. climate, geology, zoogeography) into metrics for evaluating the distribution of the target habitat, species composition, hydraulics (depth, flow), etc. at dominant spatial and temporal scales.”

This definition has only limited similarity with the one used for the same name by Wohl (2001).[58]

The attributes of the VRR are as follows: it must be applicable at the ecosystem level, universally valid for all regions and river types and relevant to managers. The foundation of VRR will be build upon biophysical habitat template concepts and corresponding ideas about biological communities [9, 10, 59] to develop quantitative models of the mechanisms that control biota distribution. Physical habitat models will be used as the backbone of the model. Biocomplexity-based models of biological community structure such as the Target Fish Community approach [47] or the landscape-based models [60,61], or coarser scale models such as those presented by Kolasa [62] provide the biological counterpart of the template. The combination of these four models with interfaces to the riparian corridor [63] will allow the VRR to provide reference conditions as a function of landscape attributes and mathematical descriptions of important processes. Ideally, processes are described in a way that is realistic, efficient, accurate, and incorporates the fundamentals of biology, physics and chemistry while maintaining temporal and spatial scale relationships among all variables.

DISCUSSION

Use of the reference river concept acknowledges that the state-of-the-art in aquatic ecology is insufficient to design and manage ecosystems for ecosystem services in the same way that highly commoditized systems, such as farmland, are managed. That is, knowledge of the interactions of critical physical and chemical processes, subsequent biological responses and feedbacks, and the role of multi-scale temporal and spatial variability and biotic dispersal is presently insufficient to adequately "engineer" ecosystem structure and function. The strategy of employing a VRR concept largely overcomes these insufficiencies by focusing on the transfer of knowledge about “healthy” systems (the reference river) to other systems (target systems) through the use of a template of key driving variables and the mathematical approximation of changes caused by human actions. The more the means and ranges (or other measures of dispersion) and seasonal timing of driving variables of the target system resemble the means and ranges and timing of the same variables of the reference system (at some specified scale), then the more likely the target system will exhibit the same potential for resilience and self-sustainability as the reference system.

A properly selected reference condition may overcome common pitfalls of an overly incremental approach. For example, fish may temporarily survive in sub-optimum habitat (refugium) although optimum habitat may be required for recovery. [64] Therefore, incorrect or incomplete habitat information may be developed if habitat information is collected from inappropriate reference systems. Additionally, some species can be restricted to harsh environmental conditions because they are out-competed or subject to predation by other species in more favorable habitat settings [65]. Decline in the abundance of endemic fishes of the Missouri River may be partly explained by the operation of dams that converted a river system characterized by high turbidity, natural extremes in flow, and wide variation in water temperatures to a regulated system exhibiting greater water clarity and less extreme flow and temperature conditions that is disconnected from its floodplain [66]. These more benign environmental conditions are thought to favor non-indigenous North American fishes such as sauger, walleye, and small mouth bass that can out-compete endemic fishes of the Missouri River. Similarly, declines in native fishes in the lower Colorado River Basin has occurred as the historically fluctuating and relatively harsh environmental conditions were transformed into more stable environments that support the proliferation of non-native species [67]. Therefore it is necessary that the Virtual Reference River model will be developed for a cross-scale, system-level analysis and be embedded within the context of Riverscape [11].

Several options exist for selection of a reference river for a target river system. If sufficient data are available, then the most logical choice is to use the target system in its pre-impacted state. If such data are unavailable, then an upstream or downstream reference site may be considered. Alternatively, a similar river but in another basin or region may be chosen. Unfortunately, alteration of rivers in the developed nations generally occurred prior to the systematic collection of data to describe the unaltered condition. For example, in the USA, gauging records in the piedmont of the southeast do not predate deforestation and the large scale planting of cotton. Therefore, any gauge information available to describe the hydrologic patterns of such streams already includes the effects of the large-scale agricultural landscape alteration. In some cases stream channels have been tremendously modified geomorphically by early mill dam operations [68]. In such a setting, it may be possible to use advanced modeling techniques to create a virtual reference condition, e.g., by reconstructing pre-settlement land cover [69]. In the “mega-model” developed for Michigan’s Muskegon River system [70] mechanistic models of groundwater, surface runoff, nutrient, channel hydraulic, and water temperature processes were developed, calibrated, and linked to create an integrated, dynamic modeling environment; this was overlain on a synthetic scale template of habitat segment units [71]. This physical modeling environment was linked to fish and invertebrate populations through both coarse statistical models and detailed time-variant mathematical models. A variety of alternative reference scenarios could be predicted by an added link to forward and backward looking Land Transformation Models.

Another approach is to use the biological needs of desired fauna for reconstruction of channel form that will support appropriate community structure. The MesoHABSIM application described for the Pomperaug River was guided by this principles. The VRR was created using an optimum combination of surveys of the present condition, archived historical information and numerical simulation The physical template is a numerical model derived from biological requirements. However, the historical information describing river modifications (such as dams) and empirical data guided the calibration of this model. Historical land use was also used to synthesize hydrological time series for pre-colonial period. This numeric model allowed us to specify the key habitat deficits of the river and set the foundation for the habitat assessment for rivers at the watershed scale. The model provided quantifiable management criteria on one hand and simulation aided several scientific recognitions such as:

1 restoration of habitat structure is a prerequisite of any prescription of flow management
2 the greatest impact of flow alteration caused by development is on the spawning and summer life stages.

Since the choice of the right attributes should be driven by the analysis of the needs of the end-users of the template i.e. aquatic fauna the precise definition of these needs is crucial. Application of the first principles recognition based models such as the Numerical Fish Surrogate or bioenergetic models [72] is a very promising approaches for this purpose. Through mathematical imitation of the sensory system of the animals and the description of the driving forces of animal behavior we can go beyond the simple correlation of habitat attributes and species abundance. This allows not only for better understanding of why the habitat is suitable or not, but also to better simulate animals behavior in circumstances that could not be observed

The template of attributes is the critical element of the reference river concept that can be used to integrate the historically disparate synthesist and incrementalist approaches in aquatic ecology. In the above discussion we have emphasized primarily hydrological and hydraulic variables for developing the reference river concept, but we acknowledge that many other attributes should also be considered. For example related Michigan work stresses summer water temperature regimes as key to determining fish populations [73, 74, 60]. These attributes span a range of space-time scale and include in-channel hydrodynamic patterns, channel bed forms, floodplain and backwater connections, and watershed influences [75]. The entire assemblage of theses attributes should be sufficient to describe the processes such as sediment transport, nutrient spiraling, carbon (energy) dynamics, and the distribution, abundance, and diversity of aquatic biota.

Ecologists are often accused of having "physics envy" because their concepts often do not clearly and unequivocally lead to specific mathematical formulations, as is the case for many physics and engineering applications. The historical basis for this unfortunate condition is clear in aquatic ecology, where tools and concepts from different disciplines and traditions are borrowed from other fields without considering the inherent limitations and assumptions of these technologies [76]. That is, the connection of these borrowed technologies to the first principles of environmental systems is lost or ignored. We believe that adherence to first principles will help aquatic ecologists derive analytical, statistical, and mechanistic tools necessary to more rigorously characterize reference conditions and thereby help ensure sustainable water resources development.

The concept presented above may appear simplistic as the concept is still under development. It is clear that the complexity of running water ecosystems makes development of Virtual River model a challenge. There are very many river types (large, small, braided, steep, meandering) and ecological settings (climates, zoogeography etc.). It is through applying a wide range of expertise from different fields and by identifying governing equations and basic principles that a universally applicable model can be created. The Virtual River should be a living concept in that it must evolve to accommodate the latest developments in ecological science and management needs. Nevertheless, some important elements necessary for the backbone of the Virtual Reference River Model have been already developed and more are surely to come. Some of them were presented above, but they are not the only ones.

It is not the intention of the authors to enforce development and use of Virtual River Model. This paper should be considered an invitation to collaborate towards the common goal in more concerted fashion. We want to stimulate scientific discussion and thinking processes that could lead to more effective uses of available science and resources. As shown in examples above, the perspectives of the synthesists and incrementalists are not as different as it may seem, and both sides have a lot to benefit from collaboration. Specifically, we believe that numerical modeling techniques offer an excellent opportunity and scientific tool that should not be disregarded easily. In management planning context the numerical simulation is much more cost effective than "try-and-error" strategies. Adaptive management can be more effective if preceded and accompanied by a numeric simulation model. The scientific discovery may be dramatically accelerated with support of Virtual Reference River. Obviously, further improvements of existing models are necessary and possible, but the development alone will create unique scientific opportunities. Simulation models are widely applied in many scientific and engineering disciplines and are central part of scientific discoveries. For example climate science is unthinkable without predictive models. We hope to create consensus among the scientists that this is a valuable approach and greater willingness to contribute their expertise to this long term goal.

ACKNOWLEDGEMENTS

This work is an initiative of the International Aquatic Modelling Group (IAMG) with support of The Nature Conservancy's Freshwater Initiative that sponsored two workshops in Quebec City in October 2000 and in Ft. Collins in August 2001. We would like to thank to the workshops participants: Mark Bain, Ken Bovee, Zack Bowen, Richard Cunjak, Panos Diplas, Mark Gard, Atle Harby, Thomas Hardy, Charles Hendry, Manuel Hinterhofer, Alex Hoar, Tony Ladson, Michelle LeClerc, Steve McAdam, Jean Morin, Kevin Moody, Doug Nieman, Brian Richter, David Scruton, Mike Sale and Rod Wentworth, for their help in forming our thought process and contributed ideas. Thank s to Paul Seelbach and Leszek Bledzki for friendly review of this paper. We hope that our paper will be understood as a contribution to further collaboration within IAMG as well as an outreach to broader scientific community.

Permission was granted by the Chief of Engineers to publish this information.

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