STREAM SYSTEMS TECHNOLOGY CENTER

STREAM NOTES

Rocky Mountain Research Station **January 1999**

Characterizing Hydrologic Regimes in Ecologically Meaningful Terms

by Brian Richter

Hydrologists have long been challenged to document the degree to which human activities and uses of land and water have altered flood regimes and low flow conditions. In recent decades, growing concern for the protection of biological diversity has led to increased scrutiny of the consequences of human-induced hydrologic alteration to natural ecosystems.

However, hydrologists and ecologists are still woefully incapable of answering the question, "How much hydrologic alteration is too much for an aquatic or riparian ecosystem?" This is not to say that we haven't learned a great deal about the influence of hydrologic variation and extreme events on species and natural communities or key ecosystem processes such as nutrient transport and cycling. In recent years, many river scientists have suggested that considerable ecological research supports the premise that healthy aquatic and riparian ecosystems depend upon maintaining some semblance of natural hydrologic regimes (Richter et al. 1997; Poff et al. 1997). But a breakthrough in understanding the degree to which natural hydrologic regimes can be altered before inducing substantial ecosystem damage has eluded us.

Nearly a decade ago, The Nature Conservancy recognized the need to advance our understanding of ways that aquatic and riparian ecosystems depend upon the quantity and quality of the water that flows through them. As a result, they formed a "Biohydrology Program"[1] staffed by a small team of hydrologists and aquatic ecologists.

One of this team's first findings was that hydrologists and ecologists talk about hydrology in fundamentally different ways. For example, hydrologists tend to use statistics like monthly or annual averages, flood frequency distributions, and multi-day (e.g., 7-day) averages to characterize drought conditions. Ecologists, on the other hand, are concerned about the duration of annual flood pulses or low flow extremes, the timing of those conditions, and the rates at which water levels rise or fall. The

[1] The Nature Conservancy defines **biohydrology** as "the study of the influences of hydrologic regimes in biological systems."

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Nature Conservancy's team concluded that these differences in our hydrologic vocabulary were unnecessarily inhibiting collaboration between hydrologists and ecologists, perhaps even retarding our progress in understanding flow-biota relationships. The team decided to construct a common "biohydrologic" vocabulary.

The goal was to compile a suite of hydrologic parameters that would be ecologically meaningful and yet also serve as sensitive indicators of human effects on hydrologic regimes. We wanted the parameter suite to be useful in evaluating hydrologic variability and change in ecologically relevant terms, so that hydrologists and ecologists could use these parameters to:

- explain biological and geomorphic changes,
- assess the magnitude or rate of human-induced change in key hydrologic conditions, and
- use these parameters as river ecosystem management targets.

The team began by exhaustively surveying the ecological literature and compiling a list of hydrologic parameters that aquatic and riparian ecologists were using in their research. We then embellished our list with some additional hydrologic parameters that we felt would be most sensitive to various forms of hydrologic alteration, such as dam operations, diversions, ground water pumping, and predominant land uses. We sent the list to more than 40 river ecologists around the world, and modified parameters in response to their suggestions. The resultant suite of parameters are listed in Table 1.

Because some of these parameters are difficult or impossible to calculate using standard spreadsheet and statistics software, we developed the "Indicators of Hydrologic Alteration" (IHA) software to enable users to quickly compute the full suite of IHA parameters using daily streamflow (e.g., USGS) data. We have also used this method with ground water, lake level, temperature, and precipitation data. A nice feature of the software is that users can measure differences between two time periods, such as before and after a dam was constructed, or assess trends in each IHA parameter. The IHA results are portrayed as both tabular summaries and as graphical plots (see Figures 1 and 2).

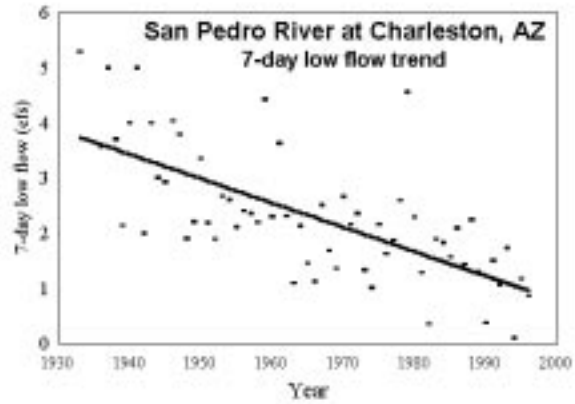

Figure 1. This plot of annual 7-day low flows illustrates a declining trend that has been largely attributed to ground water overdraft in the San Pedro Valley in Arizona.

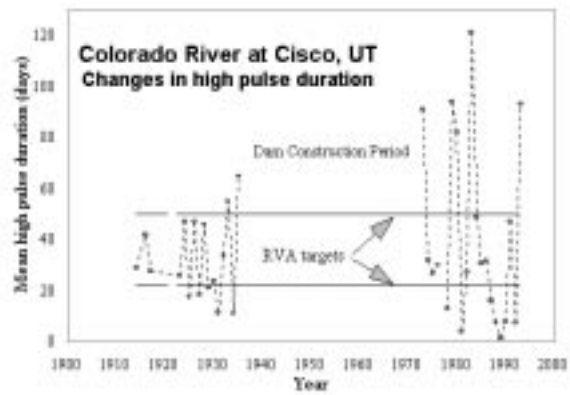

Figure 2. This plot of annual average high pulse duration illustrates increased variability in the duration of high flows resulting from upstream dam operations in the Colorado River basin.

Table 1. Summary of hydrologic parameters used in the IHA, and their characteristics.

General Group	***Regime Characteristics***	***Streamflow Parameters Used in the IHA***	***Examples of Ecosystem Influences***
1. Magnitude of Monthly Discharge Conditions	Magnitude Timing	1. Mean discharge for each calendar month	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and Duration of Annual Extreme Discharge Conditions	Magnitude Duration	1. Annual maxima one-day means 2. Annual minima one-day means 3. Annual minima 3-day means 4. Annual maxima 3-day means 5. Annual minima 7-day means 6. Annual maxima 7-day means 7. Annual minima 30-day means 8. Annual maxima 30-day means 9. Annual minima 90-day means 10. Annual maxima 90-day means 11. Number of zero-flow days 12. 7-day minimum flow divided by mean flow for year	• Balance of competitive, ruderal, and stress-tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3. Timing of Annual Extreme Discharge Conditions	Timing	1. Julian date of each annual one-day maximum discharge 2. Julian date of each annual one-day minimum discharge	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms
4. Frequency and Duration of High/Low Flow Pulses	Magnitude Frequency Duration	1. Number of high pulses each year 2. Number of low pulses each year 3. Mean duration of high pulses within each year 4. Mean duration of low pulses within each year	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate/Frequency of Hydrograph Changes	Frequency Rate of Change	1. Means of all positive differences between consecutive daily values 2. Means of all negative differences between consecutive daily values 3. Number of flow reversals	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility stream edge (varial zone) organisms

The IHA method is described in detail in Richter et al. (1996). The utility of the IHA method for assessing potential hydrologic impacts associated with various water development proposals will be limited unless hydrologic simulation models can be used to create synthesized records of daily streamflow or water table fluctuations under future climate or development scenarios. If potential hydrologic conditions can be simulated using such models, these conditions can then be compared with existing conditions (actual hydrologic measurements or simulation of current conditions) using the IHA method. Management decisions can then be based on the IHA's elucidation of hydrologic regime changes likely to be associated with alternative management scenarios.

As researchers and ecosystem management teams around the world began using the IHA tool, we began receiving requests for further guidance on using the IHA method to determine instream flow needs. In particular, we have been repeatedly asked, "How much flow alteration is too much?" and "Which of these hydrologic conditions is most important in maintaining a healthy river ecosystem?"

We have responded that river ecosystem managers should strive to maintain as much of the natural range of variability in each of the IHA parameters as possible; and the only way to responsibly determine the degree to which natural ranges of variability in hydrologic conditions can be altered is by engaging in a scientifically credible adaptive river management process. Richter et al. (1997) describes a "Range of Variability Approach" (RVA) that lays out recommendations for implementing such an adaptive management program. The proposed approach is derived from aquatic ecology theory concerning the critical role hydrologic variability, and associated characteristics of timing, frequency, duration, and rates of change, play in sustaining aquatic ecosystems.

Brian Richter is the Director, Freshwater Initiative, of The Nature Conservancy. He has served as the Conservancy's National Biohydrologist during most of his 11 years with the organization. His new responsibilities include serving as a liaison to public agencies and other organizations involved in freshwater conservation, and leadership of a staff that includes biohydrologists, aquatic ecologists, educators, and outreach coordinators. He works with science staff and conservation project teams across the United States and internationally to identify key hydrologic processes supporting biotic diversity, assess stresses to these processes, and design conservation strategies for restoring desired hydrologic conditions. He has published numerous scientific papers in *Conservation Biology*, *Freshwater Biology*, *BioScience*, and *Regulated Rivers* on the importance of restoring natural flow regimes.

More information about the IHA software, the RVA, and copies of the papers discussed in this article are available from these web sites:

http://www.freshwaters.org
http://www.freshwaters.org/iha.htm
or by writing to the author at
brichter@theriver.com

The IHA software package which includes a manual and technical support, costs $200 and may be purchased from Smythe Scientific Software, Boulder, Colorado. *Mention of trade names does not constitute endorsement by the USDA Forest Service*.

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Development of an Individual-Based Trout Instream Flow Model

by Russell B. Rader and N. LeRoy Poff

Management of instream flows includes questions concerning the amount of water and pattern of flows needed to maintain healthy trout populations. One approach, the instream flow incremental methodology (IFIM), is rapidly becoming a standard procedure and even a legal requirement in some states. IFIM is a decision-making tool that includes a collection of computer programs called the physical habitat simulation system (PHABSIM). PHABSIM generates predictions of changes in the amount of habitat available for trout (weighted usable area, WUA) for a specific stream reach at various flows (Bovee 1982). Although PHABSIM can be difficult to calibrate, it does offer an easy procedure for quantifying important elements of the physical habitat, such as velocity and depth.

The primary criticism of PHABSIM is that WUA and fish biomass are often unrelated over various increments of flow (e.g. Scott and Shirvell 1987, Gore and Nestler 1988). IFIM assumes that the influence of flow on fish is mediated through velocity and depth. Other variables, such as food availability, competitors, predators, and cover, also influence habitat selection by trout (e.g. utilized current velocities and water depths). Furthermore, other factors, such as scouring or dewatering of redds, stranding of young-of-the-year, and lethal and sub-lethal temperatures, can determine the reproductive success and mortality of trout and consequently population fluctuations as a function of altered flows. In instances where velocity and depth are the primary limiting factors for trout, PHABSIM should perform well in determining instream flow requirements. However, where other factors limit trout populations, a new model is needed that incorporates more biological realism.

This article briefly describes a spatially-explicit, individual-based model (IBM) designed to complement PHABSIM and include much of the ecological information known to influence trout populations at the stream reach scale. We have modified an earlier version of this model designed for electrical power facilities in northern California (Van Winkle et al. 1998) to include processes and factors influencing wild brook, cutthroat, brown, and rainbow trout, as well as hatchery trout in Rocky Mountain streams.

Four criteria are useful in determining the biological realism of any model:

1. the degree to which life cycle complexity is represented,
2. whether resource dynamics (e.g. the physical habitat) are explicitly modeled,
3. the use of natural estimates in representing population abundance, and
4. the extent to which variability of individuals of the same age or cohort is considered.

PHABSIM provides an explicit representation of part of the physical habitat (velocity, depth), but does not include other criteria. Most classical population models (e.g. Lotka-Volterra) rely on some representation of an average individual and also fail to include most of the above criteria. IBMs incorporate each of these criteria, especially individual variation.

Model Description

The IBM model we are developing simulates trout foraging, movement, growth, mortality and reproduction (Figure 1) on a daily time step at the scale of a single stream reach. The physical habitat of the reach is described by a habitat map and depth and velocity cross-sections similar to those used in PHABSIM. The map consists of the actual sequence and length of each habitat unit (riffles, pools, runs, cascades) for the entire reach. As in PHABSIM, depth and velocity cross-sections should be measured at two or more flows. The model uses PHABSIM to simulate the average water column depth and velocity as a function of flow on a daily basis for

cells running the length of each habitat unit. In addition, to depth and velocity, estimates of the percentage of the stream bottom containing cover (rocks, undercut banks, wood, etc.) and substrates suitable for spawning is also made in each unit or a subset of representative units. Access to cover is used in formulations describing foraging, movement, respiration costs, and risk of predation. The fraction of the bottom with suitable-sized gravels is used to assign females to specific spawning areas.

Conceptually, the stream reach is viewed as a two-dimensional surface of mortality risk and growth potential that changes with flow, temperature, prey availability, competition, and predation. Each fish within the population is assigned to a specific cell within a unit having a specified velocity, depth, cover availability, and density of other trout for the duration of a single day. At the start of each day, fish can move and test other cells or units to seek more favorable conditions. Each trout will move if it can locate a feeding territory within a cell with a lower ratio of mortality risk to growth than it encountered during the previous day.

We modeled six risks of mortality for adults as independent probabilities (high temperature, washout from floods, stranding, starvation, angling, and predation) and calculated a single cumulative value for each cell on each day. Bioenergetic equations are used to model growth potential or the net energy remaining after substracting energy costs from consumption for each cell on each day. Consumption is a function of drift density, drift size, velocity, trout size and swimming speed, and temperature. Within each unit and for the duration of a single day, trout are assigned to specific feeding territories within cells based on body size because size determines the dominance hierarchy as trout compete for feeding stations (optimal velocity and depth) and cover.

When all of the feeding territories for a specific day have been assigned within a unit, the remaining trout suffer higher maintenance costs (no access to a velocity shelter) along with lower rates of consumption. The model calculates the condition factor of each fish for each day based on its acquisition of a feeding territory and the difference between consumption minus energy costs. Trout starve to death when their condition factor drops below a threshold (0.75).

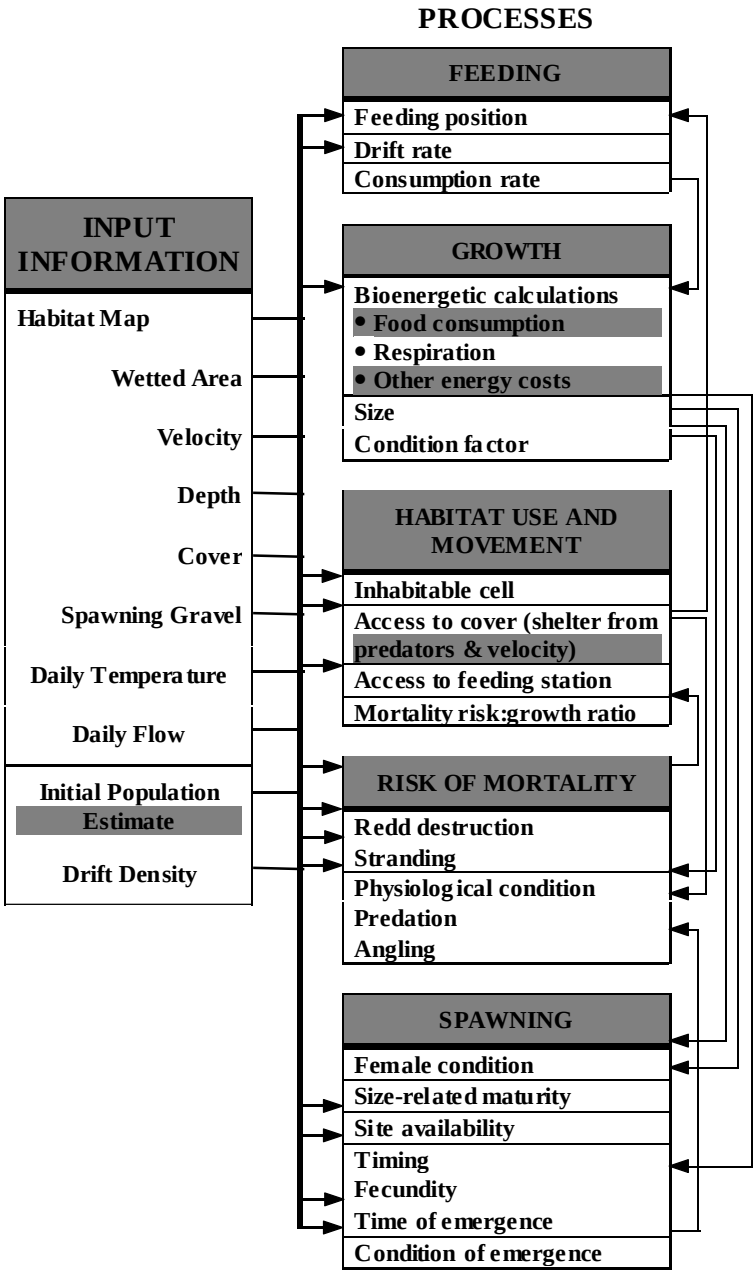

Figure 1. IBM model input information, processes modeled, and process

The IBM model also provides a tool to evaluate the effects of flow, temperature, velocity, depth, and substrate on spawning success. Formulations

were created to determine: 1) age of sexual maturity, 2) timing and order of spawning, and 3) effects of various sources of mortality in the redd on the number of young-of-the-year at emergence.

The input information to run the model are shown in Figure 1. As with any model, quality of the data is important. The model predicts year-to-year changes in trout population numbers as a function of flow and temperature. It can be used to address instream flow questions by running simulations (e.g., 100 years) using different proposed or potential flow regimes for the flow input file and plotting the predicted change in population numbers over time. Flow regimes that result in a steady decline in numbers, population crashes, or even extinction could be regarded as risky. It would be possible to identify threshold flows necessary to prevent model population crashes by incrementally increasing specific aspects of the flow regime (e.g. baseflows) and running multiple 100-year simulations producing a mean and variance for population density for each increment increase in flow. Such simulations can be a valuable tool for identifying stream management options that are scientifically defensible and more likely than other options to minimize adverse effects on trout.

Future Directions

Although a valuable tool, IBMs have limitations. Increased biological realism produces an increase in model complexity. At present, the model is complicated and not user-friendly. Data input and model calibration is a lengthy and often difficult process. Similarly, it is very difficult to modify the code to tailor the model to a specific application. In the future, we hope to create a menu-driven software package that will assist non-modellers in understanding data input and model calibration. This model applies to the spatial scale of a single reach. Recent research suggests that trout move extensively and might utilize habitat at the watershed scale. Scaling-up from a reach to the watershed may be important to some applications but will require extensive modification.

In conclusion, IBM's are presently a valuable, but somewhat cumbersome tool that enhances biological realism and our ability to understand the potential adverse impacts of flow management on trout populations. Over the next few years, we hope to produce a product that can be easily used by resource managers on any desk-top computer.

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Mike Furniss Joins STREAM

Mike Furniss, Forest Hydrologist, Six Rivers National Forest, has begun a one-year detail with the Stream Systems Technology Center. Mike's duties will focus on the hydrologic and water quality effects of wildland roads including how to improve our ability to reduce road impacts to stream systems. Mike is representing the hydrology discipline on the National Roads Analysis Team which is part of the Chief's Road Policy Reform initiative. The Roads Team is charged with devising a scientific analysis process for existing and potential roads on the National Forests. Mike's other duties include working with the National Water/Road Interactions Core team, managing a software project that helps to solve problems of fish passage through culverts, developing a learning framework for the ecological characteristics of small streams, and acting as webmaster for the STREAM website (www.stream.fs.fed.us). Carolyn Cook is filling in for Mike as Forest Hydrologist on the Six Rivers during his absence.

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