Developing Ecological Criteria for Sustainable Water Management in Minnesota

The Nature Conservancy

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THANK YOU!!!

1.0 Background and Need

Managing water to meet current human needs and economic demands without undermining long-term water supplies or environmental quality is one of the most pressing challenges facing many regions in the 21st century. Minnesota is endowed with a wealth of lakes, streams, and rivers, significant aquatic biodiversity, popular game fish resources, and an engaged public interested in aquatic habitat protection and restoration. The state is recognized as a leader in aquatic protection, and has long had one of the more comprehensive water appropriation permitting processes among the states, with a permitting system that dates to 1937. However, like many states around the country, Minnesota faces mounting water management challenges in the face of population growth, land use change, and growing demand for water, combined with an array of water quality impairments and trends. In at least some parts of the state, human use now represents a significant fraction of the renewable supply of water. At the same time, drainage and land use alterations have in many places substantially altered flow regimes, including annual flow volumes, frequency and severity of low and high flow events. For example, analysis of streamflow gages throughout the state suggests that many rivers have been experiencing declining trends in July-August low flows, despite increased rainfall over the same period (Streitz 2011). These changes have the potential to drive significant changes in freshwater ecosystems.

Recently, in pursuit of the goal of water sustainability, the Minnesota state legislature defined sustainable water use in statute as that which that “does not harm ecosystems, degrade water quality, or compromise the ability of future generations to meet their own needs”. At the same time, the Great Lakes-St. Lawrence River Basin Water Resources Compact signed into law in 2008 requires all basin states to implement water withdrawal management programs by December 2012, and establishes as a purpose “to prevent significant adverse impacts of withdrawals and losses on the Basin’s ecosystems and watersheds.” The Compact seeks to “protect, conserve, restore, improve and effectively manage the Waters and Water Dependent Natural Resources of the Basin.” Responding to this challenge, numerous recent reports and assessments--conducted at the behest of the legislature—have highlighted gaps in the state’s water management framework. A consistent theme is the need for a more comprehensive framework for evaluating the ecological and biological impacts of water withdrawals and other sources of flow alteration. In other words, there is a need to quantify how much water can safely be withdrawn without harming Minnesota’s aquatic ecosystems.

The goal of this project was to develop recommendations and indicators for ecological criteria for instream flow protection in Minnesota, with special attention to rivers and streams in Minnesota’s Great Lakes basin. Products were developed through a collaborative process with public agencies in Minnesota and other experts, building on partnerships between the Conservancy and U.S. Geological Survey (USGS) across the Great Lakes.

This report assesses available data, tools and approaches that can be used to establish ecologically-based instream flow protections in Minnesota. To this end, we introduce the Ecological Limits of Hydrologic Alteration (ELOHA) approach, a science and policy framework for organizing the elements of an instream flow protection program and synthesizing available information. Applications of ELOHA that have been implemented in several other states are featured in this report as case studies.

The report evaluates options for developing criteria and indicators for managing flow alterations and preventing adverse resource impacts to the state's aquatic and riparian ecosystems. It recommends next steps for implementing such an approach via management and policy, and identifies gaps in data or understanding that may be filled by monitoring and adaptive management. Specifically, the report:

- Describes the current situation in Minnesota regarding the status of aquatic resources and water management practices that affect ecosystem health (Section 1)
- Outlines the ELOHA framework, highlighting seven case studies and exploring options for Minnesota (Section 2 and Section 4)
- Summarizes work completed to date, including preliminary conceptual models upon which to build flow-ecology relationships (Appendix 3)
- Recommends next steps (Section 3)

1.1 Principles for environmental flow protection

Streams, rivers, lakes, and wetlands depend on natural patterns of hydrologic variability (Bunn and Arthington 2002, Poff et al. 1997). The magnitude, timing, duration, frequency, and rate of change of different flow components or water levels play a major role in maintaining water quality, habitat, nutrient and energy flows, as well as the life support needs of aquatic organisms. The natural patterns of flows in rivers largely determine the life history traits, adaptations and behaviors of riverine species, such as fish, and natural communities, such as floodplain wetlands. Changes in flows or their timing inevitably alter conditions to which aquatic life has adapted, leading to changes in the abundance and condition of fish, wildlife and natural communities that comprise the river ecosystem. Likewise, for humans who benefit from the ecological services provided by lakes, rivers and streams, these changes too are often undesirable. But how much change is too much? When does "change" become "degradation" or "unacceptable adverse impact"? These are questions of both science and social values.

The term **"environmental flows"**, sometimes called ecological flows or instream flows, describes the seasonal patterns of high and low water levels needed to sustain healthy lakes, rivers, streams, and estuaries while simultaneously meeting society's needs for water supply, agriculture, energy, and flood management.

Increasingly, states recognize the importance of environmental flows and have responded with a variety of programs and statutes to protect them. Nearly all states now have legal language that acknowledges the role of instream flows and/or minimum flows in protecting fish and wildlife. However, implementing an effective instream flow protection program requires environmental flow criteria or standards that apply across broad spatial scales, e.g. from small headwater streams and wetlands to large river systems. A variety of methodologies are available for determining *site-specific* environmental flow needs, each with strengths and weaknesses. In contrast, very few scientifically robust methodologies exist, or have been applied, to set environmental flow standards across an entire state or river basin.

In practice, the word ‘standard’ has often become synonymous with a ‘minimum’ flow below which the water is reserved for aquatic life, but above which all water is assumed available for use (Annear et al. 2004). Minimum flow protection continues to dominate state policies, since there is no universally accepted method of setting ecosystem-based standards. For example, Minnesota’s long-held authority to suspend appropriations permits at the “Q90”[1] is an example of such a minimum flow criterion, one that predates many other states’ adoption of minimum protected flows. Many state flow policies focus on some sort of annual or seasonal minimum such as the Q90 or Q95. A widely used minimum flow standard of this type is the 7Q10 flow, defined as the lowest flow for seven consecutive days that occurs every 10 years on average. The 7Q10 was intended to protect water quality by ensuring adequate water for diluting pollution, not to maintain healthy ecosystems. In the 1980s and 1990s, numerous states adopted minimum flow thresholds with a greater ecological basis, such as 30% of mean annual flow (MAF), or minimum thresholds that vary seasonally (Gillilan and Brown 1997, Richter et al. 2011).

The overemphasis on minimum flows can sometimes have unintended consequences. For example, minimum flow rules that require releases from tributary reservoirs ostensibly to protect downstream aquatic life can sometimes negatively impact upstream systems. As water use increases, minimum flow can become the dominant flow in a river. This was the case with the Trinity River in California, where flow diversions to reservoirs designed primarily to support irrigated agriculture in California’s Central Valley resulted in a loss of the seasonal variability that maintained the river’s salmon populations, channel dynamics, and riparian communities (Figure 1.1). Eventually 90% of Trinity River’s flow was diverted for Central Valley Project irrigation. Having lost its natural flow regime, the river evolved into a fast-flowing, uniform channel with a riparian zone dominated by single-age cottonwood stands, and salmon stocks declined to less than 20% of historic levels. Despite years of restoration efforts costing millions of dollars, salmon populations have not recovered to historic levels (Pacific Fishery Management Council 2011, Trinity River Restoration Program 2011).

The “natural flow regime paradigm” (Poff et al. 1997) states that “the structure and function of a riverine ecosystem and many adaptations of its biota are dictated by patterns of temporal variation in river flows” (Arthington et al. 2006). In practice, this leads to a set of principles for environmental flow standards (Acreman et al. 200, Acreman et al. 2006, Annear et al. 2004, Arthington et al. 2006, National Research Council 2005, Poff et al. 2010, Postel and Richter 2003):

1. The goal of environmental flow standards is to protect entire ecosystems, not single species (National Research Council 2005).
2. Environmental flow standards should provide inter- and intra-annual flow variability in a manner that maintains aquatic ecosystem form and function to the greatest extent possible (Annear et al. 2004). This includes protecting natural magnitude, frequency, timing, rate-of-change, and duration of different hydrologic conditions, particularly high and low flow conditions.
3. Environmental flow standards should be based upon information about the species, communities, and ecosystems that occur naturally or that could be expected to occur naturally at a given site.

[1]The annual Q90 exceedance flow value is the stream discharge that statistically was exceeded 90% of the time during the period of record analyzed (MN DNR 2007)

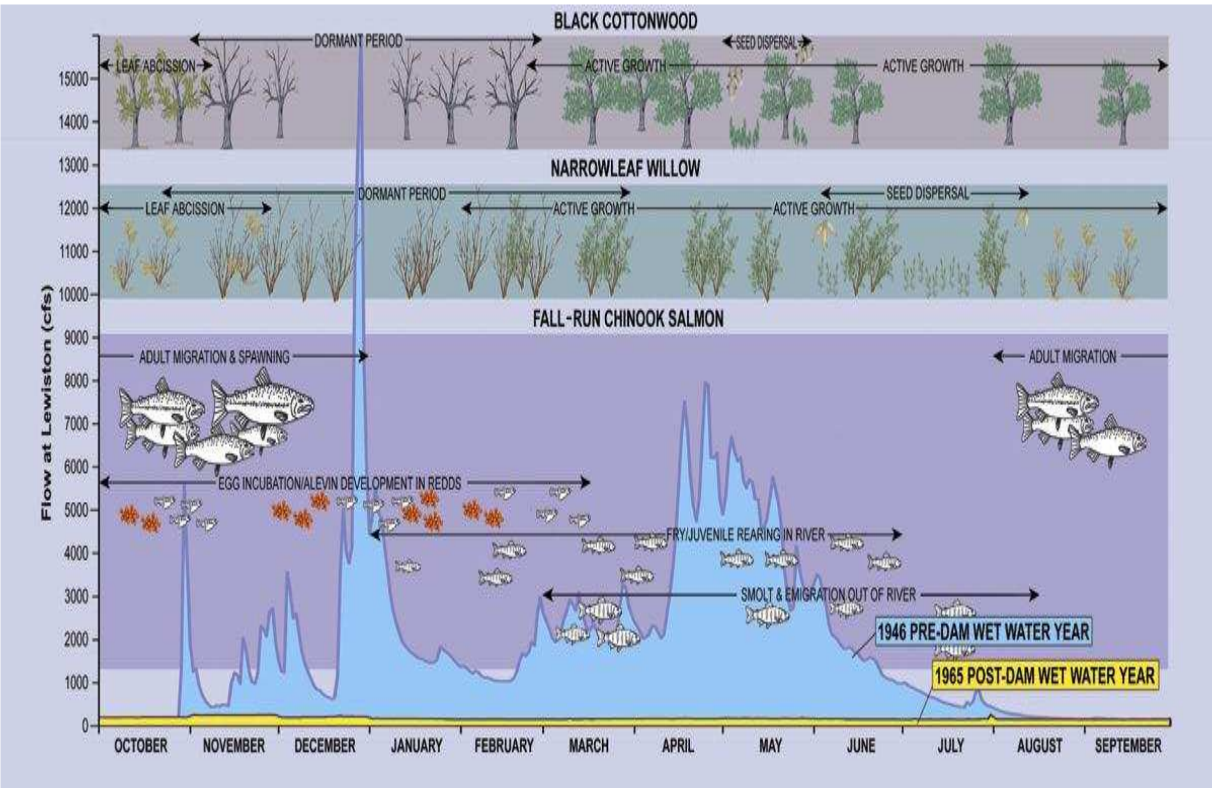


Figure 1.1. The Trinity River in California has been the subject of extensive environmental flows studies in the wake of salmon declines that followed the construction of a major dam in 1965. Prior to dam construction, the natural flows of the river (shown in light blue) created a balance of ecosystem components, including chinook salmon and riparian cottonwoods and willows. High flow pulses from late fall and early winter rains washed away fallen leaves and other debris from the gravelly substrate, allowing salmon eggs to incubate. Low winter flows encouraged growth of juvenile fish. During spring, the melting snowpack triggered high flows that carried young chinook salmon to the ocean, scoured encroaching willows, moved sediment, shaped channels, and formed diverse riffle, pool, gravel bar, and island habitats. As high flows receded in late May and early June, cottonwoods dispersed their seeds, which sprouted and grew roots just fast enough to maintain contact with the declining water table. Late summer low flows triggered adult salmon migration upstream to spawn. Following dam construction, even the wet-year flows (yellow) were depressed all year. Cottonwood recruitment ended; willows invaded the channel, which became straight and homogenous; and the salmon run declined to less than 15% of previous numbers.

4. Adaptive management should be used so that changes in the ecological system can be observed and the management approaches adjusted as necessary to protect and restore ecological integrity.
5. A margin of safety should be included in hydrologic regime management programs.
6. In contrast to pristine flows, environmental flows achieve a balance between a healthy river ecosystem and other management objectives such as supplying water for cities and farms and generating hydropower.

When considering how and whether to limit alteration of surface and ground waters, the "natural flow regime" paradigm provides only general guidance on a methodological approach for setting environmental flow standards. It is well understood that different flow levels provide for ecosystem and species needs at different times of year. However, it can be challenging to quantify those flow levels in a manner that can be practically and meaningfully implemented in a regulatory framework. This report and recommendations build on relevant experience of minimum flow protection programs, but expand on this foundation ton include protections for other aspects of flow that are critical to aquatic resources and provides a framework for implementing environmental flows in Minnesota.

1.2 Status of Aquatic Resources in Minnesota

1.2.1 Ecological and hydrologic status of Minnesota's freshwater ecosystems

The primary anthropogenic factors affecting freshwater biodiversity in Minnesota include dams, channel alterations, surface and subsurface drainage systems, and land use/land cover changes that have cumulatively altered river and lake flows, degraded water quality, and fragmented habitat (Minnesota Statewide Conservation and Preservation Plan 2007, Rankin and Armitage 2006). Combined with overexploitation in the early days of European settlement, recreational use impacts, and the spread of aquatic invasive species, these alterations have driven significant changes in native freshwater communities in terms both of ecosystem structure and function as well as in populations, species composition, and relative abundance. In Minnesota as throughout the country, hundreds of dams have been constructed on rivers and streams to control lake and river levels and facilitate navigation (Aadland et al. 2005). These dams interfere with natural movement of aquatic species, and at times significantly alter natural patterns of river flows. In southern and western Minnesota, extensive wetland and drainage have greatly modified the hydrology of the landscape and watershed function, resulting in increased nutrient transport, elevated runoff, and flashier stream and river flows. Many watersheds have more than 80 or 85% of their area in annual row crops, much of which is underlain by subsurface tile drainage, and have lost more than 90% of wetlands and 99% native perennial prairie, altering seasonal evapotranspiration and water budgets.

In southern Minnesota, many studies have accumulated evidence of significant hydrologic change as a result of landscape and drainage modifications made over the past century. Land use changes have increased the effective drainage area, increased linear miles of headwater habitat with corresponding reductions in wetland habitat (TerHaar and Herricks 1989). The net effect of these changes has been to reduce the evapotranspiration (ET) component of watershed budgets, increase the hydraulic conductivity and conveyance capacity, and increase the "flashiness" of the system. The pattern generally observed in landscapes intensively drained by tile drainage has been increased baseflows and annual water yield (Schilling and Libra 2008, Blann et al. 2009). Increased total discharge and transport of nutrients to the Mississippi River Basin and the Gulf of Mexico have been attributed primarily to hydrologic changes associated with agricultural development in the upper Midwest over the past century (Donner et al. 2004, Alexander et al. 2008, Raymond et al. 2008).

In the Minnesota River Basin, Miller (1999) used a model to demonstrate increases in annual water yield and peak flows associated with 1.5- to 50-year return periods. Changes in landscape hydrology on the Little Cobb River increased average annual runoff from 1.9" to 6.8", discharge/ precipitation ratios from 5% to 19%, and average annual peak discharge from 0.19 cfs/mi2 to 3.86 cfs/mi^2. Magner et al. (2004) also found increased peak flows in the Blue Earth River Basin, associated with high nitrate-N loads and concentrations. Peak flows for the 1-2-yr recurrence intervals increased 20% - 206% when comparing 1940-1960 to 1974-1998. Over the past 10-15 years, a range of assessments in the Minnesota River Basin, conducted to understand and address impairments due to turbidity, TSS, BOD, and phosphorus, have increasingly recognized the importance of altered hydrology and drainage modifications in driving water quality and biological impairments (TetraTech 2008, Wilcock 2009). Increased flows have driven channel incision in post-settlement alluvium (Fitzpatrick et al. 1999, Knox 2001, Magner et al. 2004), and are part of a growing body of evidence suggesting much of the sediment in streams draining Minnesota's agricultural region is derived from channel banks and bed erosion (Wilcock 2009).

Lenhart et al. (2011) used the Indicators of Hydrologic Alteration (IHA) software (see Figure 1.3 below) to analyze responses of Minnesota watershed flows in response to observed climate patterns, and showed that flows in southern (agricultural) Minnesota show higher degree of alteration than flows in northern (mostly forested) parts of Minnesota. In watersheds with more than 67% agriculture, they reported significant increases in mean annual flows, median monthly flows, low flows, annual discharge-to-precipitation ratios, and seasonal discharge-to-precipitation ratios for all seasons except summer. A greater proportion of precipitation is being routed to streams as streamflow, leading to percentage increases in streamflow that are generally disproportionate to increases in rainfall (Lenhart et al. 2011). These changes were attributed at least in part to increased subsurface and/or groundwater flow created by artificial subsurface tile drainage. In addition to carrying elevated loads of nitrate, phosphorus, and some contaminants to downstream receiving waters, unnaturally large or frequent streamflow events in late winter and spring transport excessive amounts of sediment and contribute to habitat degradation, channel and bank erosion, sedimentation and/or scour of instream habitats.

As small headwater channels (ditches) have been expanded and entrenched to accommodate additional drainage, natural streams have also incised significantly, creating laterally confined channels that are disconnected from the riparian corridor (Magner et al. 2004). In some places, groundwater and surface

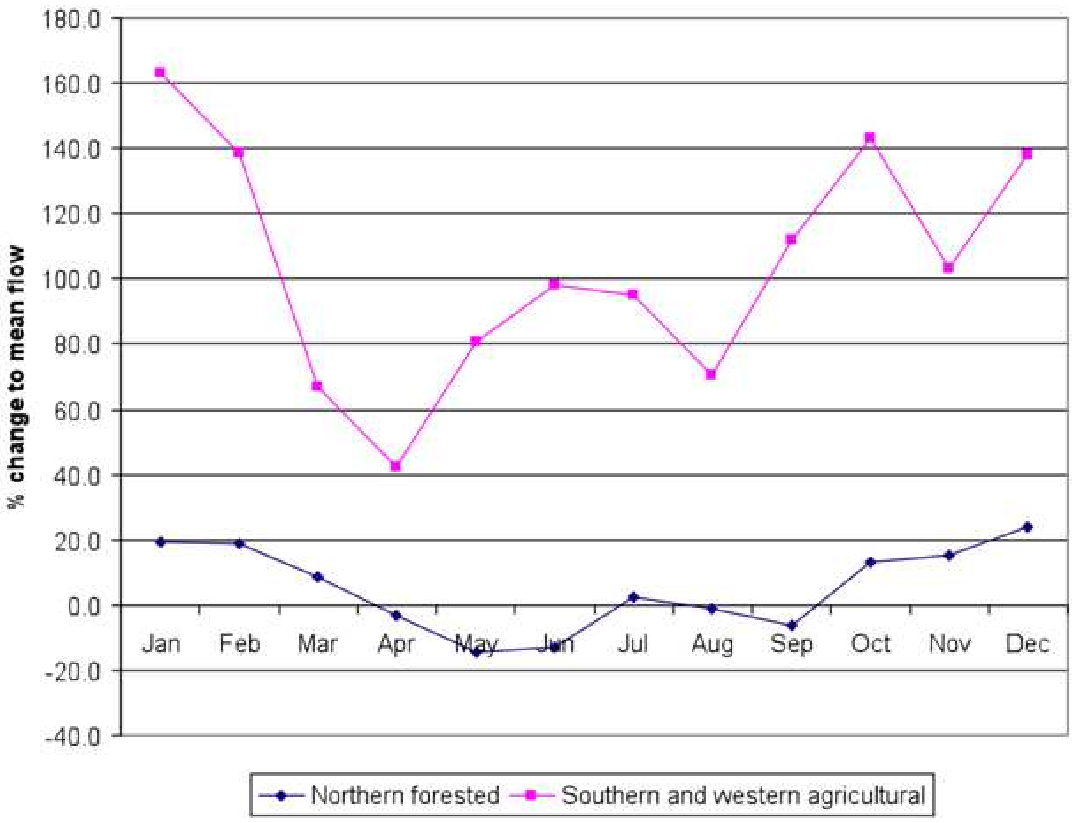


Figure 1.3. Differential response in flows of northern forested versus southern and western agricultural portions of Minnesota to recent climate trends. [Source: Lenhart et al. 2011].

water withdrawals combined with altered patterns of runoff and recharge exacerbate summer low flows (Streitz 2011), reducing habitat and water quality for fish and other aquatic species, and creating critical physiological "bottlenecks". For example, in the Des Moines till region, Laing and colleagues (in press) have shown that during prolonged dry conditions, tile drainage can reduce the shallow aquifer reserves to near zero in selected headwater areas, depressing baseflows.   Where tile drainage reduces the water table, adjacent wetlands can also be affected (Bullock and Acreman 2003; Smakhtin 2001).

Fish and other communities across Minnesota have changed significantly in concert with these hydrologic alterations and other major modifications of the landscape. As a result, every recent statewide, regional and/or national aquatic habitat assessment have classified aquatic biodiversity and habitat conditions in the agriculturally dominated portion of the state as moderately to severely impacted or threatened (Figure 1.4) (Minnesota Statewide Conservation and Preservation Plan 2007; MN DNR 2008; National Fish Habitat Board 2010; MN DNR Watershed Assessment Tool). In the remainder of the state where row crop agriculture is less dominant, changes in fish and other aquatic ecological communities that have been linked to altered hydrology have been driven additionally by construction, operation and maintenance of dams for flood control, recreation, and hydropower (Aadland et al. 2005); by forestry and timber harvest operations (Verry 1986, 1988, and 2000); and by urban, residential and recreational development (Wang et al. 2000, Meador and Goldstein 2003, Konrad and Booth 2005, Minnesota Statewide Conservation and Preservation Plan 2007).

Relationships between altered hydrology and ecological response have also been clearly established in Minnesota's Great Lakes basin.   Many studies have documented declines in stream ecological conditions as impervious surface increases, regionally (Wang et al. 2001, Baker and King 2010)) and in particular along the "North Shore" or Lake Superior (Johnson et al. 2010, Niemi et al. 2006). Along the North Shore, urban rather than agricultural development is the most significant driver of altered hydrology and water quality in terms of severity, whereas the land use impact with the greatest scope is forestry/forest management (Deserae Hendrickson, MN DNR Regional Fisheries Manager, pers. comm.; Brazner et al. 2004; Verry 2000). For Lake Superior basin streams, Brazner and colleagues (2004) found mature forest cover to be one of the most important landscape characteristics affecting fish assemblage characteristics, along with watershed storage (measured as the percent of the watershed upstream in lakes and wetlands). Significant thresholds of change in flow metrics occurred at between 50-65% mature forest and between 18-26% watershed storage. Thresholds for detecting response of fish assemblages to watershed storage was lower, at 11%; and even lower for nonpoint source pollution impairments, where impairment thresholds were detected at 5-10% storage.

In lakes throughout the state, excessive nutrient loading from developed or agricultural watersheds and/or extensive shoreland alteration associated with lake homes and recreational facilities can drive changes in lake nutrient cycling and food webs that can negatively impact water clarity, native plants, and fish populations (Radomski and Goeman 2001; Radomski 2006; Valley et al. 2004, 2006, 2010). Likewise, many of the state's shallow lakes and wetlands have been highly modified by flow alterations and nutrient loading (Dietz and Engstrom 2011), as evidenced by major shifts in species composition and dominance by tolerant or invasive species (Zimmer et al. 2009, Herwig et al. 2010).

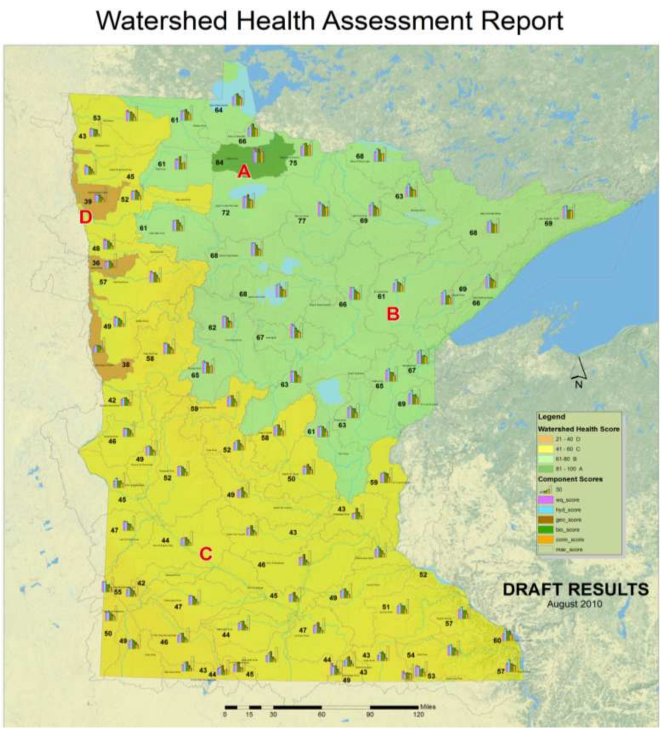
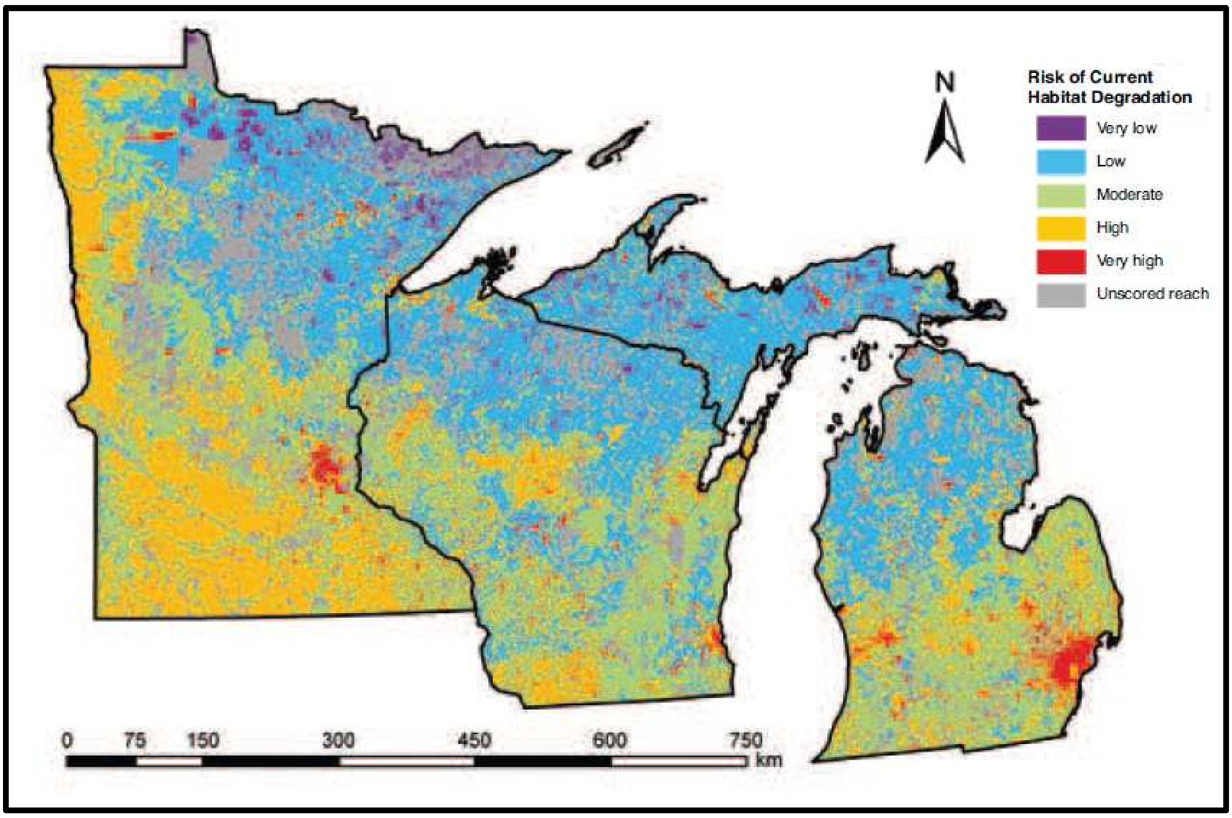


Figure 1.3. Watershed Health Assessment recently completed as part of the Minnesota DNR Watershed Assessment Tool. [Source: MN DNR Stream Habitat Program 2010].

Figure 1.4. National Fish Habitat Assessment scores for upper Midwest states. Similar patterns can be observed. The NFHAP assessment can be examined at reach and subwatershed scales [Source: National Fish Habitat Board 2010].



1.2.2 Water management in Minnesota

Minnesota has long been recognized as a leader in aquatic protection. The state water appropriations permit program was established in 1937. It was amended in 1973 to establish a priority system for water use, and revised again in 1989 in response to the drought of the 1980s. Trout streams have been afforded special protections since 1979. The Wetlands Conservation Act of 1991 provided for protection of calcareous fens, a unique type of groundwater-fed wetland that supports many rare and endangered plants.

Over time, state water management policy has been amended to meet evolving needs and emerging issues. In 1993, Minnesota Statutes 103 (M.S. 103G.265, Subdivision 1) gave the Commissioner[2] the authority to "develop and manage water resources to assure an adequate supply to meet long-range seasonal requirements for domestic, municipal, industrial, agricultural, fish and wildlife, recreational, power, navigation, and quality control purposes from waters of the state." Public water suppliers serving >1,000 individual users are required to prepare and submit emergency water supply and conservation plans for Department of Natural Resources (DNR) review and approval. Public water suppliers have the authority to implement demand reduction measures for new well construction or requests for volume increases. The Twin Cities Metro Area has also been subject to special measures.

Currently, responsibility for surface and groundwater management in Minnesota is distributed widely among different state agencies and departments each with different roles. Minnesota Department of Agriculture (MDA), Minnesota Department of Health (MDH), and Minnesota Pollution Control Agency (MPCA) all have overlapping obligations and authorities to protect water quality, while DNR is responsible for water quantity.

Water Appropriation Permits. Minnesota requires a permit for water withdrawals that exceed 10,000 gallons per day or one million gallons per year[3]. Permits also are subject to a number of restrictions, caveats, and contingencies, including protection of existing users, ecological and water resource protection limits (including low flow protections), specified conditions under which permits may be limited or suspended, and requirements for contingency plans in the event of such suspensions.

Surface waters in Minnesota are subject to several protections (MNDNR 2010). The "no-net-loss of wetlands" policy was developed following passage of the Wetland Conservation Act in 1991, and is currently regulated under Minnesota Administrative Rules Chapter 8420. Calcareous fens are protected by Minnesota Statute 103G.223 from being "filled, drained, or otherwise degraded, wholly or partially, by any activity" (MN DNR 2000).

DNR also is charged with maintaining natural flows and water levels (MNDNR 2000, Fairbairn 2010). Interbasin transfers (MN Statute 103G.265), appropriations from water courses during low-flow periods (MN Statute 103G.265), and appropriations from basins less than 500 acres (MN Statute 103G.265) are

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[2] The Commissioner of the Department of Natural Resources and, by delegation, staff

[3] For comparison purposes, a well that continuously pumps 10,000 gpd yields 11.2 acre-feet of water in one year. In a typical year in which recharge from precipitation averages 6 inches, this would equal 100% of the recharge occurring on 22.4 acres.

all subject to specific management or permitting requirements. Statutes and rules also designate water use priorities in order to protect higher priority surface and groundwater users from interference by other users (Leuthe 2010). "Water Use Priorities" are described in Minnesota Statute 103G.261.

> **Resource Protection Limits**
>
> **Surface Waters**
> - Protected Flows - Streams
> - Protected Elevations – Water Basins
>
> **Groundwater**
> - Withdrawals that impact surface waters are subject to surface water protection limits
>
> **Special Protections**
> - Trout Streams
> - Endangered Species

Trout ("coldwater") streams, as designated by Minnesota Administrative Rule 6264.0050, Subpart 4, are protected under Minnesota Statute 103G.285, Subdivision 5 and Minnesota Administrative Rule 6115.0670, Subpart 3 B. Only temporary water appropriations during high-flow periods are allowable. However, the rules allow the Commissioner to issue exemptions in cases where justified on the grounds of reasonable beneficial use. For example, Lutsen Mountain Corporation (LMC) was recently granted temporary permission to increase appropriations from the Poplar River for snowmaking, despite the fact that the volume appropriated potentially represents a substantial percentage of winter baseflow in the Poplar River (located along the North Shore of Lake Superior), particularly during low flow conditions such as have been experienced by the North Shore throughout the fall of 2011.[4,5] The exemption was granted in the wake of legislative action to override permit restrictions on LMC's use of Poplar River water, on the grounds that preventing the resort from making snow would have a substantial deleterious impact on the local economy, given that the resort is one of that community's major employers. However, the current permit requires LMC to develop an alternate water supply (i.e., Lake Superior) within 5 years[6]. Several other cases can be documented where surface water appropriations from designated trout streams have been permitted (Minnesota Surface Water Use database, 2008). Such cases underscore the importance of political support for existing protections; however, they do potentially provide an opportunity to test hypotheses about the anticipated impacts of flow reductions.

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[4] Data on recent appropriations http://files.dnr.state.mn.us/waters/watermgmt_section/ appropriations/index-county-location-active.pdf show that prior to the 2011 legislation, appropriations by LMC from the Poplar River had exceeded existing permit levels in every year reported. The new permit allows withdrawal at a rate as high as 8 cfs. Although most of the time this does not represent a very high percentage of winter flows, in low-flow years, the percentage could be quite high (40% or more). The USGS flow record for the Poplar River from 1912-1961—though incomplete—reports daily flows below 22 cfs approximately 10% of the time. More recent flow data for the Poplar can be found at http://www.dnr.state.mn.us/waters/csg/index.html. Flow in the Poplar River has dropped below 10 cfs several times in recent years (e.g. 2006, fall 2011).

[5] See for example, Minnesota Public Radio report 5/11/2011 http://minnesota.publicradio.org/collections/special/columns/statewide/archive/2011/05/lutsen-bill-pits-anglers-against-alpine-skiers.shtml

[6] Minnesota Public Radio report 6/20/2011 http://minnesota.publicradio.org/display/web/2011/06/19/lutsen-dnr-water-permit/

Groundwater permits are reviewed by DNR on a case-by-case basis. Multiple recent reviews have concluded that current practices for permitting groundwater withdrawals should be changed to ensure consistent consideration of ecosystem needs as well as the anticipated cumulative impacts on all protected uses (MNDNR 2010b; WSF 2011).

Groundwater protections. Permit applicants must also develop a contingency plan that describes supply alternatives that will be utilized if appropriations are restricted due to low flows or water levels (M.S. 103G.285, Subd. 6).

Water conflicts –real and potential—have historically been handled on a case-by-case basis. For example, in cases of well interference (e.g., where one user's well has negative impacts on that of another), the solution is generally to fix or replace the well. However, as use and the number of wells increase, it is increasingly untenable to handle these issues individually, and there is a need to understand limits and thresholds on long-term sustainable yield from aquifers, groundwater and surface waters (Jeanette Leete, Groundwater Supervisor, MNDNR, personal communication; Michelle Walker, Regional Hydrologist, MNDNR, personal communication).

In cases where a proposed groundwater or surface water permit application has the potential to impact surface water resources, the state has the authority to require the permittee to conduct well tests or aquifer tests, or to commission a site assessment by internal DNR technical staff. The regional groundwater hydrologist has the authority to limit or deny the permit based on anticipated impacts to protected resources (Leete 2011).

The authority to protect specified low flows is established in *M.S. 103G.285, Subd. 2*: "If data are available, permits to appropriate water from natural or altered watercourses must be limited so that consumptive appropriations are not made from the watercourses during specified flows. The purpose of the limit is to safeguard water availability for instream uses and for downstream higher priority users located reasonably near the site of appropriation."

As adopted in Minnesota Rules 6115.0630, Subp. 12, "protected flows" are defined as "the amount of water required in the watercourse to accommodate instream needs such as water-based recreation, navigation, aesthetics, fish and wildlife habitat, water quality, and needs by downstream higher priority users located in reasonable proximity to the site of the appropriation. Consumptive appropriations may be limited provided that adequate data are available to set such limits." Furthermore, the rules specify that considerations in adopting protected flows may include historic streamflows, frequency of high and low flows, hydrological characteristics of the watershed, as well as biological communities, riparian vegetation, and existing fish and wildlife management within the watercourse.

DNR may suspend surface water appropriation permits as determined by its Surface Water Appropriation Permit Issuance and Suspension Procedures. The annual Q90 flow is used as the specified low flow threshold for suspending certain surface water appropriations "until specific watershed protection levels are established". In practice, specific watershed protection levels other than the Q90 have not been established. Suspension procedures are activated within a major watershed when the average daily flow at the designated monitoring gage is at or below Q90 for 120 hours (MNDNR 2007).

Appropriations from individual public waters basins are subject to suspension if the major watershed in which they are located is suspended. Appropriations from an individual public water (e.g. lake basin) may be suspended even though the major watershed containing the basin is not suspended, if water levels reach or fall below the protection elevation specified in applicable permits. If no protection elevation is specified in the applicable permit(s), the protection elevation is either the basin's runout elevation (i.e., the elevation at which water begins to flow out of the basin for basins with a functioning outlet below their ordinary high water level (OHW)); or 1.5 feet below the OHW for landlocked basins (basins without a functioning outlet below the OHW) (MNDNR 2007).

For the purposes of low flow permit suspension, the designated monitoring gage is the best available gage for reflecting local flow conditions within a major watershed. Because of significant gaps in Minnesota's stream flow monitoring network, the "best available" monitoring gage may be located in a different major watershed. Furthermore, even if the gage is located in the same major watershed, headwater watersheds may be experiencing low flow conditions during earlier or later periods than that reflected by the gage. In recent decades, Minnesota DNR has initiated permit suspension procedures in response to drought multiple times.

Because groundwater withdrawals can potentially impact surface waters or streamflows, groundwater permits also require review, typically involving the regional hydrologist or groundwater specialist(s). However, there is a lack of consistent data and criteria for screening. The staff and personnel burden imposed on the agency from this case-by-case approach to permitting prompted the Water Sustainability Framework's 2011 recommendation that the state of Minnesota revise the water withdrawal appropriations permitting process and adopt a screening tool similar to that being used in Michigan. Until recently, funds and staff time had not been dedicated to creating a working integrated statewide database; however, individuals in the Division of Ecological and Water Resources had established the rudimentary working elements of such a database (Jeannette Leete, Groundwater Supervisor, MN DNR, pers. comm.) In addition, during the time this report was in preparation, state clean water funds were appropriated to initiate development of electronic water permitting.

DNR Stream Habitat Program. In Minnesota, the state DNR stream habitat program is the program responsible for making flow recommendations and ensuring that the state has the information it needs to comply with resource protection limits established in statute. The goal of the MN DNR Stream Habitat Program (SHP) is to protect, maintain and restore the health of river ecosystems in Minnesota. The statewide program was designed to establish protected flows based on flow-related needs of fish, wildlife, and recreation, and to provide a foundation for setting biologically valid protected flows for water appropriation permits, reservoir and hydropower operations, local water planning and resource enhancement. As part of this effort, the Stream Habitat Program is periodically called upon to assess potential impacts of ground or surface water withdrawals on freshwater resources. The program was also historically responsible for developing instream flow recommendations for rivers representing Minnesota's 81 major watershed basins. It has also been called upon to make flow recommendations for hydropower and other dams subject to relicensing under the Federal Environmental Regulatory Compliance (FERC) standards.

Program Overview. To protect the necessary range of river processes, the SHP (Division of Ecological and Water Resources Stream Habitat Program) has adopted the goal of establishing a protected flow regime suitable to the river or basin in question. This flow regime is intended to target each of the five components of a healthy river; including the natural flow variability (hydrology and connectivity), the riparian zone and geomorphology, as well as water quality and habitat (biology). The approach differs from the historical SHP approach of identifying a single seasonal flow (the Community Based Flow, or CBF) to be used as the aquatic habitat protection level. The assumption under the historical approach was that high flows needed for channel maintenance and formation were seldom impacted by water or land management practices; in essence there was no need to include higher flows in the management plans. However, as population and land use dynamics have changed, this assumption is no longer valid.

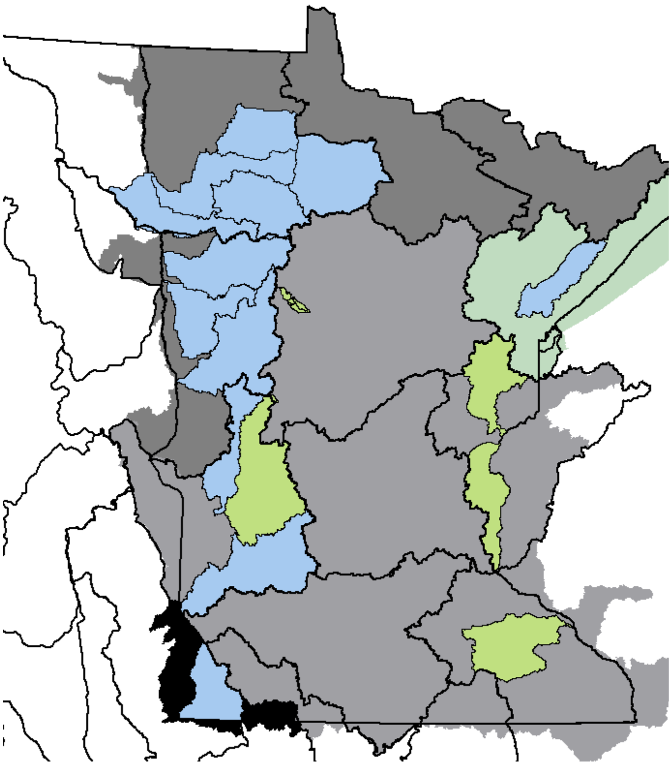
To assess the adequacy and effect of suggested habitat-based flow protection standards on aquatic habitat, the SHP considers the Instream Flow Incremental Methodology (IFIM) (Bovee et al. 1998) approach the preferred standard. A critical aspect of the IFIM methodology is having accurate, site-relevant habitat preference curves. The SHP continues to develop empirically based habitat suitability criteria; at current there are comprehensive flow related criteria for 147 fish species-life stages and 9 mussel species (Aadland and Kuitunen 2006).

Historical Approach. Under the historical approach, the SHP began an assessment of habitat versus stream flow conditions at riffle pool reaches near established stream gages with the intent of developing protected flows that met the flow related needs of Minnesota's fish, wildlife, and recreation. The identified assessment reaches were considered representative critical reaches in the basin of interest. At one time, recommendations for streamflow and habitat protection were intended to be developed for each of Minnesota's 39 major watersheds. Physical Habitat Simulation studies (habitat-flow relationships) have been developed for the river basins below shown in the light blue and the green colors, as well as for the Rainy River (northern border with Canada), representing approximately 15% of Minnesota's 81 major watersheds (Figure 1.5). Some analysis and surveys have also been done for the St. Louis and Cloquet (Great Lakes drainages) rivers (Ian Chisholm, Stream Habitat Program Supervisor, MN DNR, pers. comm). Otherwise, Physical Habitat Simulation studies have not been developed for the remaining river basins.

To develop flow recommendations for a specific river basin using habitat-flow relationships, a subset of representative target life-species stages known or expected to occur in that river basin are selected from a range of habitat preference guilds and seasons. Habitat suitability criteria for fish, mussels and macroinvertebrates have been developed for 147 fish species-life stages and 9 freshwater mussels (Aadland and Kuitunen 2006). Habitat availability is then modeled in relation to discharge for each site (based on intensive and extensive field surveys of stream morphology/cross-sections). The amount of habitat available, or Weighted Usable Area, is plotted for each species-life stage at each discharge. The Community Based Flow (CBF) is then determined based on the intersection of habitat curves at the flow that provides the most habitat for all species-life stages in that season. The CBF is adjusted for a given reach based on the drainage area relationship to the gaged site from which the CBF was determined[7]. Flows are then bracketed based on the CBF adjusted to the gage as follows:

- 150% of CBF – full appropriations permitted
- 50-150% CBF – upstream appropriations limited to 20% of the CBF or total permitted appropriations, whichever is less
- < 50% of CBF – suspend upstream appropriations

This approach provides an initial model for transferring habitat-based recommendations to other streams within the same river type.



1. Cannon River
2. Lower St. Croix
3. Kettle River
4. St. Louis River
5. Cloquet River
6. Red Lake River
7. Clearwater River
8. Pomme de Terre
9. Yellow Medicine
10. Upper Minnesota River

Figure 1.5. River basins (8-digit HUC) with flow recommendations shown in light blue and green. For the Great Lakes Basin, instream flow studies have been done for the Cloquet River and to support FERC relicensing of the hydropower facility on the St. Louis River.

<u>Recent Advances.</u> The Stream Habitat Program now advocates a more comprehensive flow regime approach to balance water use with the need to maintain a natural flow regime for long-term river health. Under this new approach, two protection levels must be identified: 1) a cap on total water use for a basin, and, 2) a protected flow designed to reduce additional impacts to habitat and water quality. The flow regime approach still requires managers to identify the cap and protected flow levels. The effect of these levels on aquatic habitat and other riverine components should be assessed using the appropriate habitat criteria and flow-function relationships. The connection between ground and surface water remains a difficult factor for which current management systems still do not fully account.

[7] Note that according to Harvey et al. (1997), drainage area alone explained 97% of variance of mean annual flow, 96% of Q90 and 97% of Q10 in Minnesota.

The Clearwater River- A Case Study in Streamflow Protection Gaps in Minnesota

The Clearwater River is a tributary to the Red River via the Red Lake River, located in Northwestern Minnesota (west of Upper and Lower Red Lakes). The hydrograph in Figure 1.4 shows a variety of flow duration statistics for the Clearwater River based on the period of record for the gage at Red Lake Falls.[8] The Community Based Flow recommendation from the DNR instream flow study (Harvey et al. 1997) is shown in the dashed red line. To maximize habitat for characteristic aquatic communities, the CBF recommends an “optimum” flow of 166 cfs as measured at the Red Lake Falls gage (05078500) for most of the year, or 286 cfs during the spring spawning season from April 17 to May 29. The report recommends suspending appropriations when flows are below 83 cfs, and making appropriations conditional when flows are within the range represented by the dotted pink line. Full appropriations would be permitted when flows are more than 150% of the CBF. In practice, however, these seasonal flow recommendations are neither enforced through suspension of surface water permit appropriations permits (as with the Q90), nor do they appear to have substantially impacted terms or conditions for surface water uses that have been permitted since they were published in 1997. Nor, in practice, are they explicitly factored into considerations for groundwater permits.

Recent analysis by Andrew Streitz of MPCA suggests that July and August low flows on the Clearwater River and other rivers in the state appear to be exhibiting a statistically significant declining trend, despite the fact that recent years have seen higher than normal precipitation. The analysis implies that surface and groundwater withdrawals in the vicinity of the river—more than two dozen high capacity surface water wells plus a number of groundwater wells with a total capacity representing a potentially significant percentage of long-term July and August Q50—***are*** having an impact on late summer low flows (Figure 1.7).

The current structure of streamflow management is not well positioned to address this scenario. Once streamflow recommendations are published, there is no formal program or staff person responsible for routinely monitoring to evaluate how frequently streamflows fall within CBF recommendations or depart from historic flows (as a percentage or a duration statistic). Therefore, outside of drought conditions, it falls largely to the initiative of individual agency staff or independent researchers that an issue such as declining trends in summer low flows would be identified and detected.

[8] Initially, it might appear that overall flows in the recent time period are significantly higher than in the earlier period. However, this is an artifact of the fact that this gage contains incomplete information and the later period reflects flood flows in 2007 and 2008.

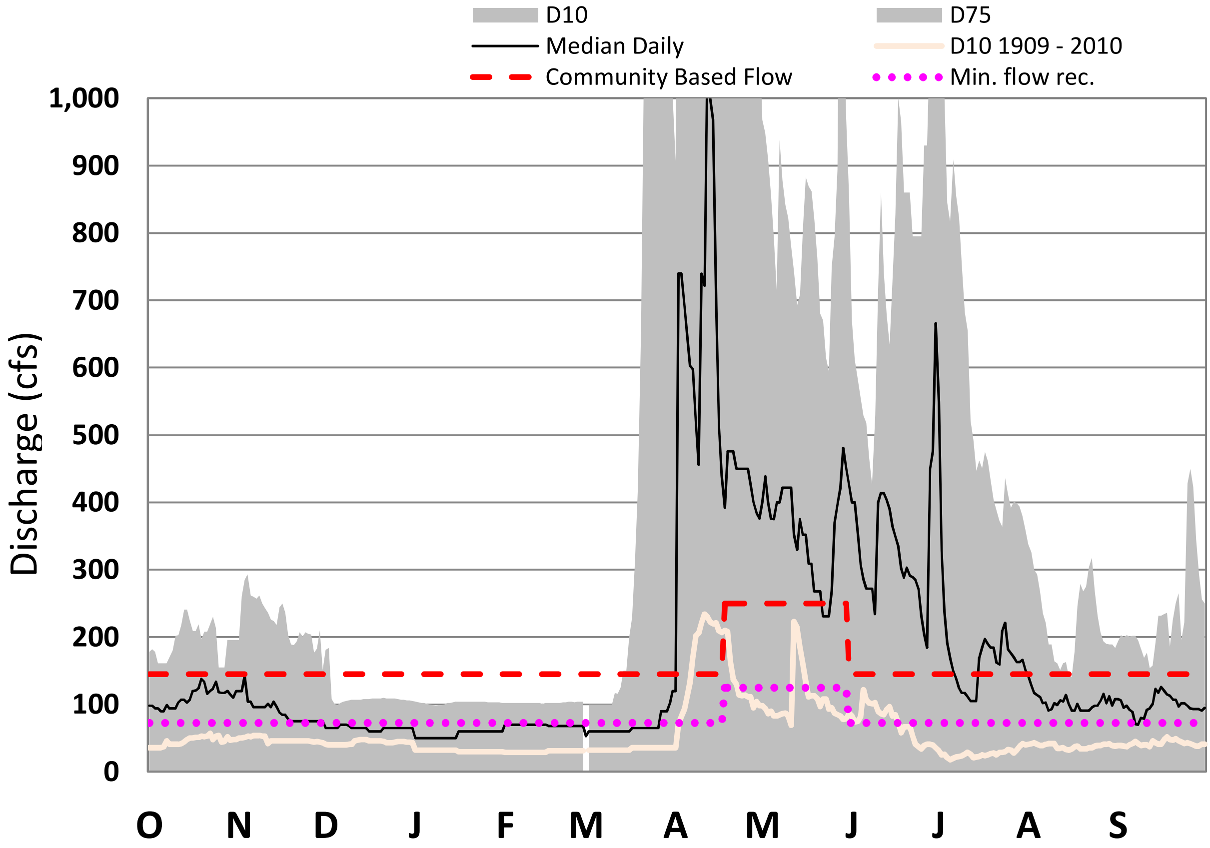


Figure 1.6. Clearwater River hydrographs and daily flow statistics over the period of record in relation to the MNDNR Stream Habitat program's Community Based Flow (CBF) bracketed recommendations.

<u>Altered timing and pattern of streamflow.</u> The Clearwater River is an unusual case for another reason--the bulk of agricultural instream water withdrawals are for wild rice production rather than irrigation. In many years, the seasonal pattern of water use by wild rice producers actually results in a shift in the timing of peak flows (Figure 1.8). A special water allocation plan for wild rice growers has been developed and approved by MN DNR as provided for in Minnesota Rules, part 6115.0740 (MN DNR Waters 2007).

Statewide, there is no consistent statewide policy or standard addressing the ecological impacts of shifts in timing due to water appropriations or lake level management. Altered timing and pattern of streamflows, in particular subdaily variation in flows caused by peaking operations to produce electricity at hydropower dams, has been addressed by the [streamflow and habitat] program largely in the process of providing input on relicensing of hydropower facilities under FERC. For example, the DNR conducted streamflow recommendation studies and reports for the Rainy and Cloquet Rivers to provide input on FERC relicensing (O'Shea 2000). As a result, most hydropower dams in Minnesota have altered their management and operations to more closely mimic run-of-the-river (Ian Chisholm, MN DNR, personal communication). However, many of the best-known recreational lakes of Minnesota's lake country, such as the Gull Lake chain of lakes in the Mississippi headwaters area extending from Leech

Lake to Brainerd--have had dams built at the lake level outlet to enable downstream flood protection and lake level management. Many of these lakes have been managed for decades in ways that have altered the timing and pattern of downstream river flows, as well as timing and pattern of seasonal lake levels—primarily for downstream flood control and to maintain more stable lake levels desired by shoreland property owners and recreational boaters (USACE 2009). As part of the Upper Mississippi Headwaters Reservoir Operating Plan Evaluation (ROPE) study, operating scenarios and alternatives were evaluated using the Indicators of Hydrologic Alteration to compare impacts of different alternatives (including a "natural flow regime" scenario) on lake levels and downstream flows. Results showed that current operating rules at some of the reservoirs do result in significant shifts in timing and distribution of flows and lake levels (USACE 2009). However, the alternatives proposed in the first draft to restore more natural flow regimes were overwhelmingly opposed by the majority of stakeholders commenting on the plan, most of whom expressed concerns about potential aesthetic impacts or impacts on recreational access of reduced late summer lake levels, and the final selection of alternatives reflected this input (USACE 2009).

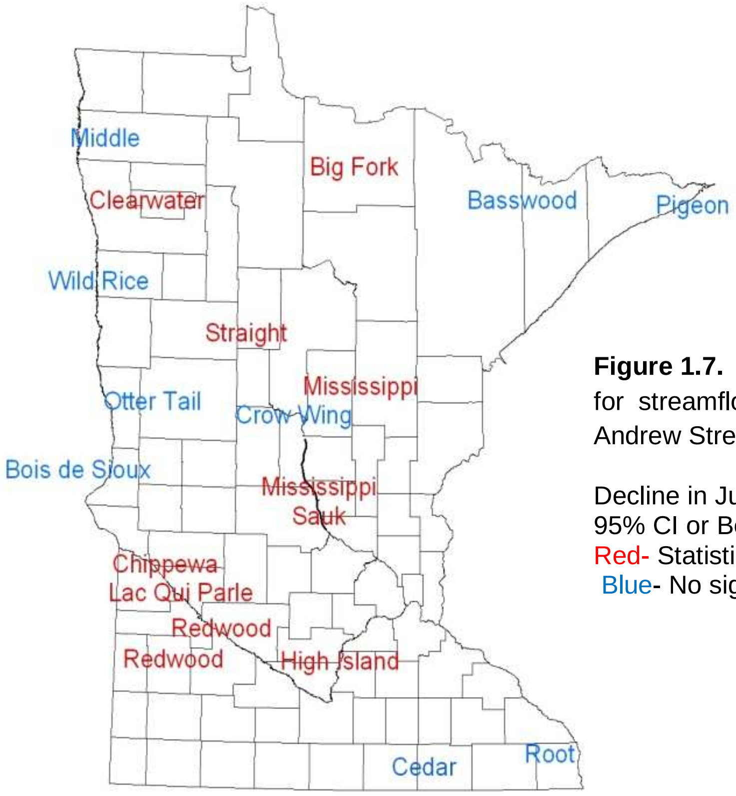


Figure 1.7. River basins analyzed for streamflow trends. [Source: Andrew Streitz, MPCA]

Decline in July and August Flows at 95% CI or Better.
Red- Statistically Significant
Blue- No significant trend

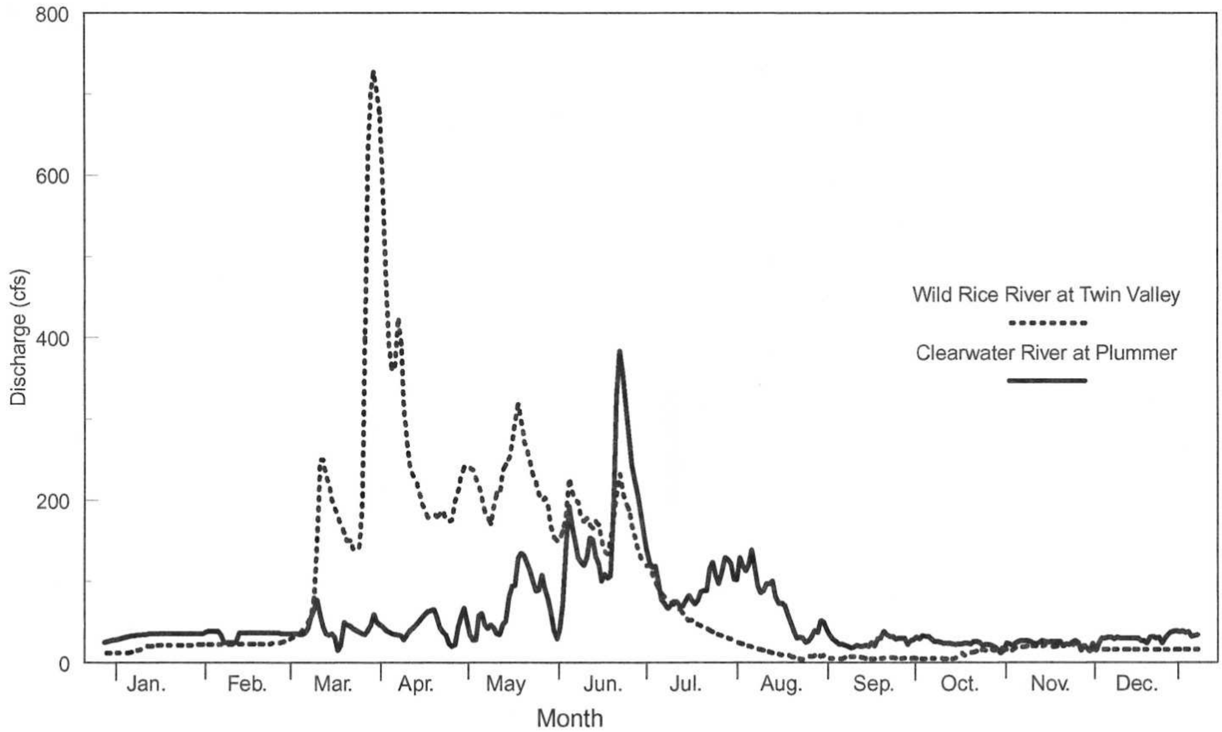


Figure 1.8. Hydrographs of mean daily discharge for 1990 showing transposition of normal high and low flows on the Clearwater River as a result of water appropriation for wild rice production. [Reprinted from Figure 28 of Harvey et al. 1997.]

Recent Developments with Implications for Environmental Flow Management in Minnesota

*Great Lakes-St Lawrence River Basin Compact ("Great Lakes Compact") of 2008***.** The Great Lakes Compact, to which Minnesota is one of 8 signatory states, was driven largely by the need to establish interstate governance to prevent large diversions and protect the Great Lakes from impacts of cumulative withdrawals.[9] The Compact allows signatory states latitude in setting the threshold levels for their withdrawal regulation programs. Threshold levels will be consistent with the Compact if they: (1) assure an effective and efficient water management program, (2) ensure that uses overall are reasonable; (3) ensure that withdrawals overall will not result in significant impacts to the physical, chemical, and biological integrity of the source watershed [for Ohio, the Lake Erie Basin]; and (4) do not interfere with the objectives of the Compact (Section 4.10.1). Many other Great Lakes states are also currently working to meet requirements of the Compact, and elements of their approaches may be of interest to Minnesota (Martin 2010).

Clean Water, Land, and Legacy Constitutional Amendment. In 2008, Minnesotans reaffirmed their desire for clean water, healthy functioning ecosystems, and the high quality of life these amenities support through the passage—by ballot initiative—of the 2008 Clean Water, Land, and Legacy

[9] . www.cglg.org

Amendment to the state constitution. A series of statewide assessments, plans, and reports on water sustainability, water availability, groundwater protection and management, and surface water protection and management conducted by the State of Minnesota over the past decade was designed to lay out frameworks and plans for sustainable management of both water quality and quantity, including protecting ecosystem needs (MN EQB 2007, MN EQB 2008, Groundwater Technical Committee 2010, MN DNR 2010).

Water Sustainability Framework (WSF), 2010- 2011. In response to these identified needs and concerns, as well as the passage of the constitutional amendment, the state legislature in 2009 directed the state to address water sustainability issues under MS 103G.265, "assurance of supply". At that time the legislature also defined water sustainability: "Water use is sustainable when the use does not harm ecosystems, degrade water quality, or compromise the ability of future generations to meet their own needs."[1]

At the behest of the legislature, the University of Minnesota's Water Resources Center then convened a broad stakeholder process to develop a 25-year Water Sustainability Framework (WSF) for the state. The process involved dozens of meetings with stakeholders, a survey to solicit input from thousands of state residents, 8 project "teams" composed of 10-40 experts, each providing input into the overall framework, a synthesis team, a Citizen Stakeholder advisory committee, and a Headwaters Council of advisors. The Water Sustainability Framework represented the "first-ever, comprehensive report designed to protect and preserve Minnesota's lakes, rivers and groundwater for the 21st century and beyond." The final report, presented to the legislature in January 2011, was intended to serve as a roadmap—with clear signposts on how, when and on what initiatives to invest public and private dollars —based on scientific research, expert opinion, and input from citizens around the state.

The WSF made a number of recommendations related to protecting ecosystem needs for water and flows. For example, under the first heading of the report "The Need for a Sustainable and Clean Water Supply" (i.e. desired Minnesota future of protecting high quality and sustainable supply for future generations), the top strategy recommended was to "Determine the state's water balance and improve water appropriations permitting". In fact, revising water appropriations permitting and modeling the state's water balance—along with integrating land and water use planning-- were highlighted in the Executive Summary as two of the top 5 Essential Actions for water sustainability.

Specifically the framework recommended that the state develop full knowledge of water balance, including flows, storage, and recharge rates of major aquifers and surface water, and amend the water appropriations process to account for surface-groundwater interactions and ecological needs, acknowledging that different aquatic system classes may have different needs. As part of the action plan, the framework specifically called for development of a web-based, water extraction permit screening system (similar to Michigan's Water Withdrawal Assessment Tool; see Michigan case study) that would consider existing permits in assessing effects of cumulative withdrawals for a given permit (i.e., consider new withdrawals in the context of existing withdrawals), and that would identify thresholds of increasing ecological risk. These thresholds would help to ensure that increasing probability of ecological risk is paired with increasing degrees of scientific and political scrutiny.

1.2.3 Synthesis—Environmental Flow Needs in Minnesota

The state of Minnesota has the authority in both statute and rules to go beyond minimum flows to protect the full range of ecological flows, including consideration of seasonal flow needs and special protections for trout waters, calcareous fens, and endangered species. The state has an established ground and surface water withdrawal permitting system, requiring permits at a relatively low use threshold. The state also has extensive ecological data and understanding of habitat needs of more than 100 aquatic species at varying life stages, and has developed bracketed flow recommendations applicable to 10-15 of the state's 81 major river basins. The state has the authority to suspend permits --by priority use—during drought conditions, defined as the annual Q90, and this authority has frequently been invoked on numerous occasions over the past 30 years.

However, in practice, evaluation and management of permits on a case-by-case basis leads to potentially inadequate protections for the resource, and may be viewed as somewhat unpredictable to users. Furthermore, the state lacks a number of elements acknowledged as needed for long-term sustainable water management with respect to effective long-term protection of ecosystem needs. It has no formal institutional database for assessing cumulative impacts of withdrawals at the time of permit request review. The current decision support system relies primarily on staff expertise and knowledge to identify potential concerns. Area and regional staff may at times be overwhelmed by the volume of requests on their time and expertise. The state also currently lacks a comprehensive water accounting system that would enable screening level assessments of proposed groundwater withdrawal impacts on streamflow/basin levels (except where site-specific studies have been done). Because groundwater and surface water permits are treated separately, there is a risk that cumulative impacts of existing groundwater withdrawals may simply fall "under the radar". Lag times between groundwater and surface water connections means that by the time monitoring detects there may be a problem, there is little opportunity to be proactive.

Although the state has the authority to protect the full range of ecosystem needs, in practice it does not have a system for protecting environmental flow components (EFCs) other than the Q90 minimum flow protection. Nor does the state have clear and consistent criteria for communicating impacts and defining what constitutes an unacceptable adverse resource impact.

Furthermore, there is widespread acknowledgment that the current use of "index gages" to determine when conditions are at Q90 for suspension of permits during drought is an imperfect system. Conditions upstream from those gages in small headwater streams or basins may be experiencing severe drought conditions far in advance of downstream gages; likewise, conditions in the headwaters may even have improved by the time river flows at index gages reach drought conditions. For this reason, the state also allows for local suspension of permits based on established water level elevations in smaller protected basins; however, these must be set based on individual water body monitoring. Numerous warmwater streams lack stream habitat and flow recommendations, and most lakes and wetlands do not have established protected water level elevations.

Finally, like most other states, Minnesota handles water quality standard setting and planning through a process that is largely separate and independent of management of flow and water quantity, even though the two are integrally linked. Land use planning rarely addresses impacts of land use on quantity and timing of flows.

For all of these reasons, a variety of recent statewide water plans have recognized the need to improve the streamflow protection framework and to develop and expand the use of empirical ecological criteria. For example, in the 2008 Minnesota Environmental Quality Board (EQB) report *Managing for Water Sustainability,* recommended that the state "identify defensible criteria for assessing the critical water levels or flow conditions required to support ecosystems." The report noted that the criteria should consider ecosystem-sensitive practices that protect critical components of the hydrograph, including:

- A habitat- and population-based minimum flow
- A high flow protection standard that protects critical habitat forming and silt flushing high flows
- Protections for downstream needs
- Protections for the natural variability of flows over time (hydrograph shape)

The Ecological Services Team report of the Water Sustainability Framework also emphasized the need to "define ecosystem needs for water" and reiterated that "a single protected flow level is inadequate to protect instream resources."

Responding to acknowledged and identified gaps in the current water management framework, many individuals and agencies have recently been engaged in efforts to improve interagency coordination, communication, planning and management with respect to water resource sustainability, including developing data and monitoring priorities and sharing agreements. One potential tool is Water Appropriation and Use Management Plans, now being referred to as "**Groundwater Management Area Plans**" or "**Aquifer Management Plans**", for which a process is described and outlined under MN Rule 6115.0810. Meetings of the interagency Drinking Water / Ground Water committee, the Groundwater Technical Committee, and other formal and informal interagency problem-solving groups have been working to improve communication and coordination among the agencies about issues, scales, and priorities. Progress is being made in achieving interagency consensus on priorities and next steps. In the meantime, characterizing interaquifer and surface/groundwater interactions and implications for local stream, river, lake and wetland ecosystems is an acknowledged task that falls under proposed GWMA assessment and planning.

To be ecologically sustainable, water management must look beyond just permitting to understand the full water budget and the impacts of other land and water use decisions on flows and water levels. Land use management decisions need to consider water availability and sustainability. Furthermore, water management must move beyond minimum flows to address seasonal variation, timing, duration, frequency, and other ecological components of flow and water levels. There is an acknowledged and compelling need for coordinated development and implementation of federal, state, and local land and water management plans that address water quality, water quantity, and habitat issues simultaneously. Interagency staff and scientists are currently working on a number of initiatives to establish a groundwater management area planning process in Minnesota that would address many of these challenges.

Good process and leadership are as critical to the success of this as good science. Many of the implementation challenges the state has faced over through the years are due as much to institutional barriers between science and policy as to lack of good science or even lack of political will to protect ecosystems on the part of managers or the general public. Although the state has skilled scientific and technical staff and a long history of excellent, high quality science on instream flows and methodologies, there is an acknowledged need to engage users and other partners to develop critical mass for implementation of "protected flows," especially going beyond minimum flows. The state needs a process that can develop the capacity to bridge from science into effective policy and implementation, and to ensure that there is broad recognition and acceptance amongst the public and stakeholders of the importance of ecological flow and water level protections.

2.0 Step-by-Step ELOHA: Approaches, Examples, and Options for Minnesota

The Ecological Limits of Hydrologic Alteration (ELOHA) was developed to meet exactly the types and scope of challenges that Minnesota is now facing. ELOHA is a scientific framework for setting ecological criteria for streamflow management on a statewide basis using existing biological and hydrologic information. The outcome of ELOHA is a decision support system that helps water managers minimize ecological impacts of new water developments, direct water development to least-sensitive water bodies, and prioritize flow restoration efforts.

ELOHA extrapolates relevant information from water bodies for which site-specific studies have been conducted to those that have not. Therefore, ELOHA rests on the premise that rivers and other water bodies can be grouped according to their flow-ecology relationships (figure 2.1). That is, although every river is unique, many exhibit essentially the same ecological responses to flow alteration. Furthermore, within every group of ecologically similar rivers, there exist individual rivers under various degrees of hydrologic – and corresponding ecological – alteration. If, for example, a different quantity of water is diverted from each river among a group of similar rivers for which fish species data exist, then by plotting each of these rivers on a graph of percent of water withdrawn versus percent of native fish remaining, a flow-ecology relationship can be quantified for that *type* of river. ELOHA assumes that this relationship holds for all rivers of that type.

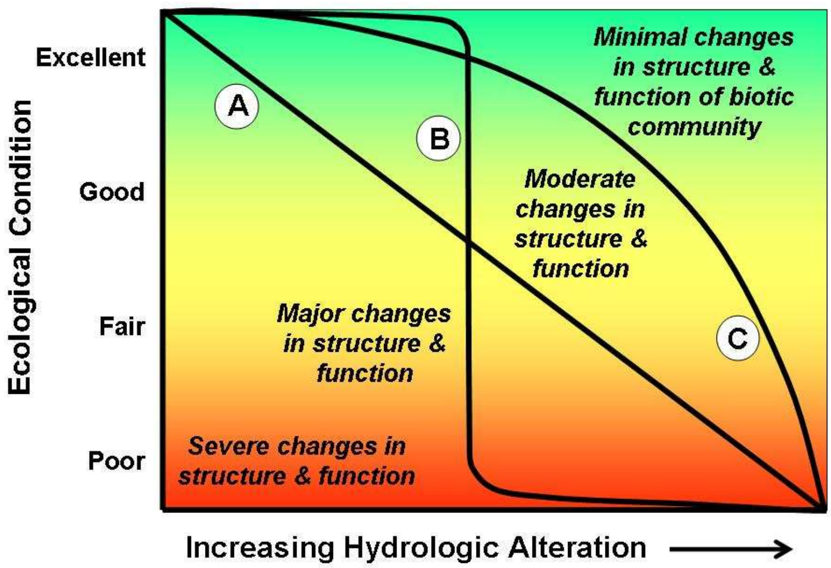


Figure 2.1 Conceptual flow-ecology curves showing possible forms of the relationship. A: linear, B: threshold, C: curvilinear. The graph represents one river type. After Davies and Jackson (2006).

A social process such as lawmaking, regulatory rulemaking, or broad stakeholder engagement determines ecological condition goals for each water body. Flow-ecology curves then equate these ecological goals to specific flow targets.

Figure 2.2 illustrates a simple flow-ecology curve that relates mid-summer water withdrawals (flow alteration) to fish community structure (ecological condition) for one type of river in Michigan[10]. A technical advisory committee recommended, and the legislature then codified, a state map showing all the water bodies expected to achieve "acceptable" ecological condition, which they defined as maintaining at least 90% of their native fish species. Based on the flow-ecology curve developed by scientists, the water managers tasked with achieving this goal now manage water withdrawals and dam operations such that no more than 45% of natural mid-summer flows are diverted from these rivers. Scientists periodically monitor the fish community to ensure that the flow standard achieves its ecological goal.

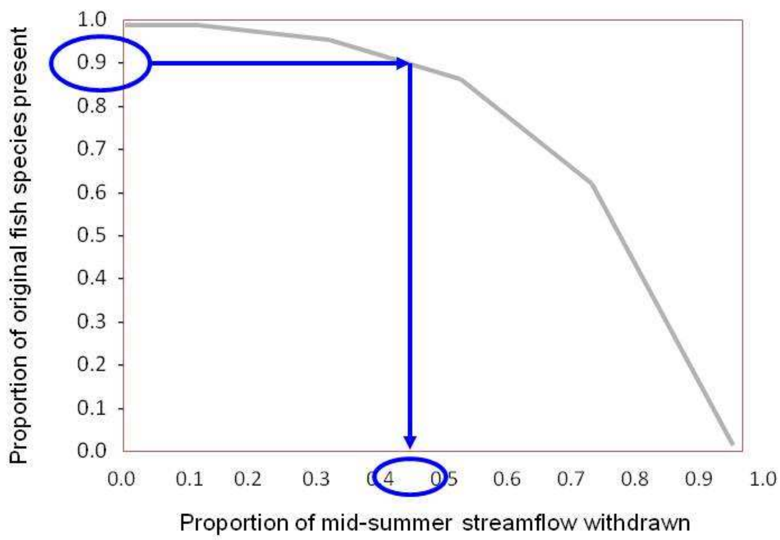


Figure 2.2. Using a simple flow-ecology curve to set an environmental flow standard.

The above overview reflects the original conceptualization of the ELOHA framework and its application. As described by Poff et al. (2010), ELOHA involves essentially 5 steps: 1) build a hydrologic foundation, 2) develop and apply a river classification, 3) select hydrologic statistics and assess hydrologic alteration, 4) develop spatially explicit models of the flow ecology-response relationship, and 5) apply environmental flow criteria in permit decisions (Figure 2.3). For more information, we refer the reader to Poff et al (2010), which introduces the conceptual framework, and Apse et al. (2008), which provides more details and examples of how it *could* be applied.

In practice, ELOHA has taken many forms. The following subsections of the report outline each step of the framework and explain how different users have adapted these steps to conform to their unique needs and constraints, citing relevant aspects of the full case studies that are presented in Section 4. Each subsection concludes with an evaluation of viable options and specific recommendations for Minnesota.

[10] For more detail, see Michigan case study.

The purpose of this report is not to guide practitioners stepwise through the process, but rather to inform them of how others have adapted the framework to different situations, and to provide references for obtaining more in-depth information. Case studies in section 4 illustrate how four states and three interstate river basins have combined various approaches described in this section into effective processes for setting and implementing environmental flows across large regions.

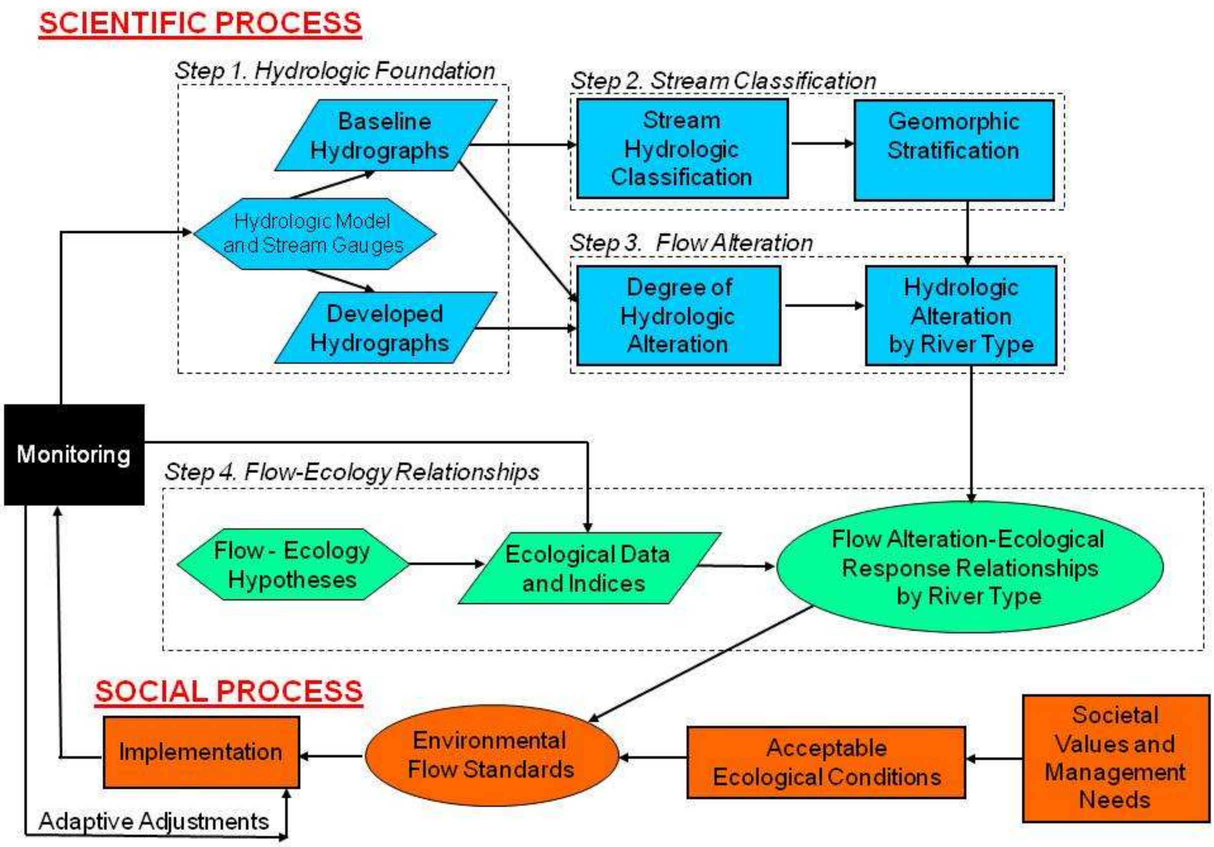


Figure 2.3. Steps of the ELOHA framework (Poff et al. 2010).

2.1 Building a Hydrologic Foundation

ELOHA is built on a "hydrologic foundation" of streamflow data[11] within a region. This information is used to assess flow alteration, classify river types, quantify ecological responses to hydrologic alteration, and evaluate the status of sites relative to environmental flow standards. It is the foundation of ELOHA, and as such is considered the first step of the ELOHA process. In practice, few if any places have such a

[11] This report refers to streamflow data. Although current ELOHA applications use flow data to assess rivers and streams, ELOHA is equally applicable to lakes and wetlands, in which case water level data would substitute or supplement flow data.

foundation in place at the onset, and building it usually requires considerable time and thought. To maintain the momentum generated at the early stages of the project, many ELOHA projects have successfully advanced other parts of the framework while the hydrologic foundation is being developed, rather than awaiting its completion before proceeding with successive steps.

2.1.1 What is the Hydrologic Foundation?

The hydrologic foundation envisioned by Poff et al. (2010) consists of two databases of daily streamflow time series representing *baseline* and *current* conditions for every *analysis node* over a common time period of at least 20 years to represent climate variability. For planning purposes, databases of future streamflow scenarios also may be created.

Analysis nodes are located where ecological data have been collected, where flow management actions such as water allocation may be taken, where streamflow will be monitored to ensure compliance with flow standards, and above and below major river confluences.

Baseline conditions refer to minimally altered conditions before major dams and diversions affected hydrology. Depending on management and restoration goals, baseline conditions also may represent prior land cover and drainage conditions. Whether "baseline" conditions reflect only changes due to direct water use, or also account for land and river channel modifications depends on data availability, feasible restoration options, and political expediency.

Understanding baseline flow conditions and their natural range of variability is fundamental to understanding ecological flow needs and the response of ecosystems to hydrologic changes (Apse et al. 2008, Poff et al. 1997).

Current conditions account for cumulative effects of dams, surface-water diversions, groundwater withdrawals, return flows, and other existing causes of flow alteration. Current-condition flow data can be compared with baseline flow data to calculate flow alteration at any analysis node.

Future conditions also may be modeled. For example, in the Middle Potomac River basin[12] (see case study 4.5), scientists are modeling streamflow under five potential future scenarios, in addition to baseline and current conditions. This way, stakeholders can evaluate how different water management policies, population growth patterns, and climate change are likely to affect environmental flows.

Some adaptations of ELOHA use only current conditions, relying on spatial variation across watersheds to infer the range of potential conditions from least to most altered. This allows for development of flow-ecology curves, but limits the ability of researchers and decision makers to understand the degree to which flows have already been altered. Michigan and Ohio (see case studies) based their flow-ecology curves exclusively on current flow conditions.

[12] The "Middle Potomac River basin" refers to a project area delineated specifically for the environmental flows study described here. It does not have political boundaries.

Modeling flows under baseline, current, and/or future scenarios provides the ability to assess hydrologic change under different past and future scenarios (if desired) to predict effects of anticipated water use or other management changes. At every site or analysis node, at least half of the data must be simulated, since no site can experience both baseline and current conditions simultaneously. At many gaged sites, existing time series need to be extended, and at ungaged sites the entire time series for both baseline and current conditions need to be simulated. Therefore, hydrologic modeling provides a more robust and powerful foundation.

2.1.2 Criteria for Method Selection

ELOHA does not dictate the approach used to model hydrology. The model chosen depends on the project budget and schedule, data availability, hydrology, ecology, and modeler expertise.

The finer the temporal and spatial scale, the more useful the model is likely to be for management. The databases generated by hydrologic modeling need to have enough spatial detail to resolve reaches with different streamflow characteristics (e.g., because of an intervening tributary) and small streams that nonetheless provide significant habitats. The reach scale of the U.S. Geological Survey's National Hydrograhy Dataset (NHD+) meets these criteria; moreover, the NHD+ provides a consistent spatial platform for routing flows and for compiling and processing other relevant data. Ideally, the model generates daily or even sub-daily flow data. Daily flow data allow for the calculation of ecologically relevant flow statistics (Henriksen et al. 2006, Mathews and Richter 2007). Where daily flow synthesis is impractical, the model may generate weekly or monthly time series. If groundwater discharge provides significant baseflow to surface water, then it must be accounted for in the model. Likewise, if rivers discharge into estuaries, then estuarine flows also should be modeled. In some applications (e.g., Michigan and Ohio case studies), ecologically relevant flow statistics have substituted for time series; however, this approach limits the ability to analyze hydrologic alteration and to compare various management scenarios.

As a general rule of thumb, the period of record modeled should be at least 20 years to account for normal climate variability. Kennard et al. (2009) provides more rigorous guidance on selecting a period of record for estimating hydrologic metrics for ecological studies.

Individual and cumulative impacts on streamflow of surface-water diversions, groundwater withdrawals, return flows, dam operations, and land use changes should be modeled. To be useful for future planning, the model should be able to simulate hydrologic impacts of climate change as well.

To summarize, an adequate hydrologic foundation for ELOHA should:

- be spatially comprehensive to capture regional-scale hydrologic variability and to include locations where water management decisions will be made and where ecological data have been collected;
- have the smallest time step possible;
- represent baseline (minimally altered), current, and potentially future streamflow conditions;
- address groundwater and estuarine flows where appropriate;
- be able to simulate new and improved water uses and reservoir operations;

- include the range of ecologically relevant flow characteristics; and
- simulate individual and cumulative effects of water use, reservoir operations, and potentially land use and climate change.

The last two points are especially important. Every model has limitations: some excel at modeling high flows, others simulate low flows better, others capture annual variability particularly well, and so on. The choice of hydrologic model depends largely on the flow components to which the subject ecosystems are most sensitive. For example, Michigan and Ohio (see case studies) modeled only August or September flows, because those are the months when their aquatic ecosystems are most sensitive to water withdrawals, and their water withdrawal permitting is designed to address these sensitive periods.

In contrast, for the Susquehanna and Connecticut River basins (see case studies), the purpose of the hydrologic foundation is to evaluate the relative difference in flows between scenarios. In these cases, consistency and accurate water accounting may be more important than obtaining absolute flow values.

2.1.3 Components of the Hydrologic Foundation

The basic components of a hydrologic foundation of daily streamflow data are hydrologic simulation and water accounting. Below we provide brief overviews of each component and examples of their application to ELOHA.

Hydrologic Simulation

Hydrologic simulation is used to estimate streamflow conditions. Two general approaches to hydrologic simulation are regression modeling and process modeling. Regression modeling tends to be the faster and simpler of the two to complete, whereas process modeling enables evaluation of land use and climate change scenarios.

Regression Modeling. Various regression techniques have long been used to estimate flow data. The most simple regression approach is the drainage area ratio method, which scales the quantile for an ungaged site by the ratio of drainage area above that site to that above a gaged index site (Stedinger et al 1992, page 18.54). StateMod, the hydrologic foundation for ELOHA in Colorado (see case study), uses the drainage area ratio method -- weighted by precipitation -- to calculate streamflow at ungaged sites.

Michigan and Ohio (see case studies) used multiple linear regression and quantile regression, respectively, to estimate low-flow statistics for their flow-ecology models. Michigan added flow routing and a program that calculates time-varying streamflow depletion due to groundwater pumping (Barlow 2000), creating an online decision support system for water withdrawal permitting. Apse et al. (2008) describe other statistical approaches used to estimate ecologically relevant streamflow statistics in Pennsylvania, Tennessee, western United States, the United Kingdom, and elsewhere.

For decades, USGS hydrologists have developed and published simple regression equations for estimating selected hydrologic statistics of local interest for water management. In recent years, they have populated StreamStats, an online application, with these equations, allowing the user to download selected flow statistics for any location. StreamStats is being developed on a state-by-state basis as funding becomes available. In Minnesota, for example, StreamStats uses regression equations (Lorenz et al. 2009) to estimate instantaneous peak flows with recurrence intervals of 1.5, 2, 5, 10, 25, 50, 100, and 500 years. In Minnesota, as in other states, equations for any flow statistic that can be estimated can be added to StreamStats. The Massachusetts StreamStats includes equations for median daily August flow that biologists used for flow-ecology analysis (see Massachusetts case study).

Generally, regression modeling is a relatively inexpensive approach for reliably estimating baseline conditions statewide. It can generate a wide range of flow statistics, often with low standard errors of prediction. However, their versatility is limited. Apse et al. (2008) discuss caveats regarding simple regression models, including their limited ability to simulate extreme high and low flows and extremely large and small catchments. More fundamentally, regression-generated statistics indicate only flow magnitude, and not flow frequency, duration, timing, or rate of change. Sanborn and Bledsoe (2005) developed a modified regression approach that generates ecologically relevant flow statistics. Furthermore, regression alone cannot generate daily flow series; regression only calculates certain statistics that characterize flow over a long time period. In contrast, with a time series of data, hundreds of flow statistics can be calculated and systematically reduced to those with the most ecological relevance for a particular river type.

To overcome this limitation, Archfield et al. (2010) developed a method that uses regression to estimate flow duration curves, which are then transformed into daily flow series for ungaged sites. Massachusetts, Pennsylvania, and the Connecticut River basins (see case studies) use this technique to generate baseline flow series for the Sustainable Yield Estimator (SYE), their hydrologic foundation for ELOHA. As mentioned above, current-condition flows are calculated by adding water use and, in the case of the Connecticut River basin, reservoir release data to the baseline flows.

AFINCH (Analysis of Flows in Networks of CHannels) is a new computer application that uses regression and water accounting to generate monthly time series of current-condition flows at the National Hydrography Dataset Plus (NHD+) reach scale. Flows are accumulated and conserved downstream through the NHD+ streamflow network (Holtschlag 2009). Although AFINCH has not yet been used for flow-ecology analysis, its fine spatial resolution is amenable to coupling flow data with biological sampling sites. AFINCH currently is being developed for the Great Lakes basin through Great Lakes Aquatic GAP[13]. Like all regression-based approaches, AFINCH is limited in its ability to model land-use and climate changes, to represent areas with karst or mined hydrogeology, and to simulate intermittent headwater streams.

[13] http://cida.usgs.gov/glri/projects/accountability/watershed_modeling.html

Process Modeling. Physical process modeling, also known as rainfall-runoff, watershed, or hydrologic process modeling, tracks the flux of water through the entire hydrologic cycle, accounting for surface and subsurface watershed properties and weather. Although these models can be complicated to construct and calibrate, they can be used to simulate many different types of scenarios, including climate and land-use change. However, because of their complexity, process models typically are applied to sub-watersheds that are smaller than ELOHA's intended geographic scope or at a coarser scale than is needed for ELOHA. Hydrological Simulation Program Fortran (HSPF), Precipitation Run-off Modeling System (PRMS), Soil and Water Assessment Tool (SWAT) and MIKE SHE[14] are commonly used hydrologic process models.

Scale issues notwithstanding, process models have generated hydrologic data for some ELOHA applications. The Middle Potomac River basin project (see case study) and the Commonwealth of Virginia (see Commonwealth of Virginia Flow-Ecology website) built their hydrologic foundations for ELOHA from an existing HSPF model, the Chesapeake Bay Program Watershed Hydrology Model. (Kennen et al. 2008) used a process model called TOPMODEL to simulate daily streamflow under baseline and current conditions for 856 mostly ungaged biological monitoring sites in New Jersey. An empirically-based algorithm was added to improve simulation of runoff from impervious surfaces. The biological and hydrologic databases are now poised for analyzing flow-ecology relationships.

Water Accounting

Water accounting uses simple addition and subtraction to route streamflow through a watershed, accounting for water withdrawals and return flows. It is essential to a complete hydrologic foundation, regardless of the approach to hydrograph simulation. The Middle Potomac River basin (see case study) and Virginia (see Commonwealth of Virginia Flow-Ecology website) used process modeling to estimate current-condition flows, then added and subtracted withdrawals and discharges to generate baseline-condition hydrographs. In the Potomac case, baseline conditions also account for land-use changes such as deforestation.

Coming from the other direction, Massachusetts and the Susquehanna River basin (see case studies) used regression to estimate baseline flows, then added and subtracted withdrawals and discharges to generate current-condition hydrographs. Moreover, the routing function of the water accounting module enables regression-based models to calculate cumulative effects of upstream water uses at any site.

Hydraulic flow routing and reservoir operation modeling improve model accuracy by accounting for the time delays of downstream water movement due to channel characteristics and dams, respectively. The WOOOMM model (see Middle Potomac River basin case study) includes hydraulic flow routing. The U.S. Army Corps of Engineers HEC-RAS (see Connecticut River basin case study) is a reservoir operations model.

[14] http://www.crwr.utexas.edu/gis/gishyd98/dhi/mikeshe/Mshemain.htm

General observations and summary

Table 2.1 summarizes some of the main strengths and limitations of the approaches for developing a hydrologic foundation discussed in this section.

Table 2.1 Strengths and limitations of selected approaches for developing a hydrologic foundation, listed in approximate order of effort and expense. All approaches listed include water accounting. Case studies (section 4) elaborate on the examples listed.

Approach	Examples	Strengths	Limitations
Drainage-area ratio method	StateMod (Colorado)	Low cost, easy to generate.	Limited accuracy.
Regression – generated monthly statistic	Median August flow (Michigan), mean September flow (Ohio)	Low cost, easy to generate, widely accepted.	Current-condition only. Not a time series. Represents only one environmental flow component.
Regression with water accounting and flow routing	U.S. Geological Survey (USGS) AFINCH (No ELOHA case study)	High spatial resolution; linked to NHD+.	Monthly time series only. Has not been tested outside Great Lakes basin.
Duration-curve regression plus water accounting	USGS Sustainable Yield Estimator (SYE) (Massachu-setts, Pennsylvania)	Relatively low cost, easy to generate. Daily time step.	Has not been applied outside eastern U.S..
Duration-curve regression plus dam ops model	USGS SYE plus US Army Corps of Engineers HEC-DSS (Connecticut River basin)	Same as above, with ability to model dam releases.	Relatively time-consuming (several years) to develop; requires two federal agencies.
Hydrologic process model plus water use accounting and channel routing	WOOOMM (Watershed Online Object Oriented Meta-Model)[15] (Potomac River basin)	Can model land-use and climate change.	Resolution typically too coarse or area too small for regional application without modification.

A hydrologic foundation need not be completed at the onset of the project. For the Susquehanna and Connecticut Rivers (see case studies), scientists recommended environmental flow ranges based on conceptual models extracted from literature, professional judgment, and analysis of flows at existing, minimally-altered gages to determine baseline flow variability. However, daily flow data eventually will be needed to implement their recommendations. In the Susquehanna, proposed withdrawals and dam operations will be evaluated to determine whether they could alter streamflow beyond the recommended ranges. In the Connecticut, streamflow and environmental flow targets feed into a model that compares different multi-dam operation scenarios. Therefore, both projects currently are building hydrologic foundations of baseline and current-condition daily streamflow series.

[15] WOOOMM (Watershed Online Object Oriented Meta-Model is a decision support system developed by the Virginia Department of Environmental Quality. It has three components: Output from Chesapeake Bay Program HPSF Phase 5.2 hydrologic process model, USGS channel morphology model, and a channel routing routine. It can access water use and other environmental data online . . For more information, see http://sifn.bse.vt.edu/sifnwiki/index.php/WOOOMM_Modeling .

Regardless of the approach ultimately selected, the hydrologic foundation can only be as accurate as the water-use data that go into it. Ideally, accurate water use reporting is mandated. In practice, there is a great need to improve techniques for estimating the locations and timing of water withdrawals and return flows. Withdrawal and discharge permits usually are poor surrogates for actual water use. Periodic USGS water use reports (e.g., Kenny et al. 2009) are equally unreliable, as they compile *reported* monthly or annual data from counties. Furthermore, disaggregating these data by day and by stream reach requires assumptions about actual water use patterns. For regional applications like ELOHA, the most practical approach is to research individual large water users to obtain the most accurate data possible, and estimate the smaller water uses. Likewise, reservoir operation rules and actual releases are best obtained directly from dam owners. As the Connecticut River case study shows, the time required to get this information can be considerable.

The treatment of interactions between groundwater and surface water depends first on the type of model and second on the hydrogeology. Most process models incorporate groundwater flow, and do not require additional programming to simulate interaction with surface water. Regression-based and simple water-accounting models may warrant additional programming. In bedrock-dominated systems, where runoff is the main control on streamflow patterns, groundwater may not need to be modeled. In narrow alluvial valleys, groundwater withdrawals may be assumed to deplete nearby streamflow directly and immediately. That is the default assumption of the Massachusetts SYE, and regression-transform approaches in Pennsylvania and the Connecticut River Basin. Between these two extremes, the surface-water hydrologic model can be linked to a groundwater model as simple as STRMDPL (see Michigan case study) or as comprehensive as MODFLOW (Harbaugh 2005). Massachusetts SYE users have the option of linking to existing STRMDPL models in certain parts of the state.

2.1.4 Options for Developing a Hydrologic Foundation for Minnesota

Existing data, models, resources, and expertise

Minnesota does not currently have a comprehensive approach for understanding water budgets to support water sustainability planning and estimating water availability. This was one of the primary findings and conclusions of the 2011 WSF. However, numerous studies attempting to characterize water availability have been undertaken in recent years. The 2007 and 2008 EQB reports on water sustainability and the 2010 background paper on water availability for the Water Sustainability Framework (Fairbairn 2010) all reported approaches to estimating water availability after accounting for use, precipitation, groundwater sources and aquifer characteristics, annual net groundwater recharge, and ecosystem needs. Minnesota's hydrogeology is also well characterized in a general sense, in terms of the hydrogeologic characteristics of the various bedrock and Quaternary geologic formations (Fairbairn 2010). MN DNR has developed descriptions of groundwater availability by groundwater provinces as well as identifying issues surrounding long-term availability and management of ground water. However, there is great spatial variability of the bedrock and Quaternary aquifers, both between and within regions. Historically, accurate characterization of aquifers in terms of characteristic groundwater yields has required extensive data collection and analysis from numerous well logs. If adequate existing well logs are not available, the cost of drilling many wells in order to characterize the hydrogeology of an area can be significant. The state does not currently have adequate well logs to generate comprehensive descriptions of regional or smaller-scale hydrogeology throughout the state (Fairbairn 2010). The state has begun the process of developing county and regional hydrogeologic atlases, designed to be complete within 25 years.

MPCA is continuing to invest significantly in process modeling approaches for TMDL planning and implementation, typically developing HSPF models for 8-digit HUC watersheds. Where developed, hydrographs and flow duration curves can be simulated at approximately the 12-digit HUC scale. Although it may be unlikely in the near term that the state of Minnesota will develop HSPF for the entire state, development of HSPF models to support TMDL basin planning purposes might allow use of HSPF to define baseline and current conditions at the spatial scale of the existing model (approximately 50-square-mile and larger basins). SWAT and HSPF models for watersheds in Minnesota (generally at approximately the 8-digit HUC scale) have been developed at different times for different purposes (Figure 2.4). Adapting and re-calibrating these models for the purposes of generating daily flow statistics for a statewide analysis is possibly a non-trivial undertaking; however, Minnesota might find it useful to assess the cost and feasibility of doing so.

Assessments of water availability and estimation of components such as recharge have been conducted in Minnesota at the state, regional, and watershed level. The University of Minnesota has developed and applied a watershed characteristics method that estimates renewable water flux at multiple scales statewide (Ruhl 2002, EQB 2007, Nieber et al. 2010). This method treats surface and groundwater as a single resource. Potential availability is assessed based on runoff measurements and characteristics in concert with physical watershed characteristics of the landscape and subsurface relevant to the hydrologic cycle at the scale of interest. The analysis estimates the amount that might be safely pumped from ground water based upon long-term minimum flows in the month of lowest stream flow, making it possible to estimate sustainable use values to a land area or a parcel of land.

At the statewide level, USGS compared estimates of recharge using five methods: 1) as a percentage of precipitation, 2) automated analysis of stream-flow recession displacements, 3) graphical analysis of groundwater fluctuations, 4) age dating of shallow groundwater, and 5) statistical analysis of groundwater characteristics . The Environmental Quality Board compared present and projected estimates of water use and supply for Minnesota in 2007 (EQB 2007). Supply estimates were made by taking the mean of the middle three values obtained from: 1) the regional regression recharge method (two values, from USGS), 2) watershed characteristics method (see Nieber et al 2010), 3) net available precipitation, and 4) fractional precipitation deemed available for recharge. Demand estimates were based on average reported county per capita use, plus estimates of unpermitted uses, and incorporated projected population changes for future demand estimates. Present and future percentage estimates of water demand versus available supply were reported for each of Minnesota's counties.

More recently, DNR and PCA are investing in a statewide model to estimate recharge using the modified Soil Water Balance model of Thornthwaite and Mather (Andrew Streitz, MPCA, pers. comm.; Westenbroek et al. 2010).

More detailed water availability assessments have been conducted where concerns have been identified, such as the Twin Cities Metropolitan Area and the Red River Basin of the North. The water availability assessment was conducted by USGS for the Red River of the North used information on aquifer area, saturated thickness, and porosity to estimate aquifer storage (Reppe 2005). Water budget estimates were constructed for each aquifer system using results from steady-state aquifer simulations; published water-budget estimates that were based on precipitation data, hydrograph analysis, and infiltration capacities of soils; and published recharge and discharge components. While noting that each surficial aquifer is unique, and citing results of a North Dakota study[35] that suggest that between 1 and 8 percent of stored groundwater may be available for withdrawal without adverse consequences, USGS authors state that the amount of groundwater in the Red River of the North Basin's surficial aquifers that is available without adverse ecological effects is likely a small percentage of the estimated storage volume.

The Metropolitan Council used population forecasts and water use data provided by the DNR, as well as projected changes in demand due to increased efficiency and reductions in demand for certain uses, in order to project metropolitan water demand increases to 2030 and 2050.

Statewide, USGS staff at the Minnesota Water Science Center currently have unfunded proposals to develop daily time series of ungaged flows using a more sophisticated regression approach that combines elements of the Sustainable Yield Estimator (SYE) approach with the networking capabilities of AFINCH.

2.1.5 Recommendations for Minnesota

We recommend that Minnesota implement a phased approach to developing <u>hydrologic models and data from which ecologically relevant flow statistics can be derived.</u> The state needs to define "reference" or "unaltered" flow and hydrologic conditions for the state's full range of aquatic system types as the basis for assessing hydrologic alteration. Not only water appropriations, but other water resource management applications in Minnesota would benefit from a better understanding of baseline hydrology and how that relates to existing ecological conditions. For example, TMDL implementation planning, point source discharge permitting, and antidegradation rulemaking at the MPCA could all benefit from a fuller and more accurate understanding of existing baseline conditions, as well as the ability to characterize natural, unaltered hydrology and simulate hydrologic response under future management and climate scenarios.

To enable comprehensive and quantitative flow ecology analyses based on existing biological assessment data, data and methods are needed to estimate streamflow and water levels at sites where biological sample data are available. The majority of quantitative approaches to developing ecological flow criteria reviewed in this report require such an empirical hydrologic foundation. This foundation should include the ability to accurately represent a range of environmental flow components; therefore a time series of streamflow estimates derived at a daily (or smaller) time step is most likely to provide the greatest flexibility. The time period for which these flow statistics should be derived should include the time period when biological data were collected and should extend for at least 20 years, to include natural climate variability. Selection of flow statistics can begin by facilitated expert consensus, based on literature review and professional judgment. The initial set of flow statistics can then be refined using a multivariate statistical approach capable of separating out the portion of independent and shared variance contributed by flow variables versus other factors, such as water quality, urbanization/impervious surface, suspended sediment load, and channelization.

The USGS Minnesota Water Science Center at Mounds View, MN has been working in partnership with TNC and state agencies to help ensure that adequate resources will be appropriated at the state level over the next several years to meet the data and monitoring needs for establishing ecological flow criteria.   An approach initially proposed by USGS to achieve the hydrologic foundation based on regionalized flow duration curves (FDC)s in Minnesota is outlined below (initial cost and timeline estimated at 3 years, $100K per year):

1. Select the rural, unregulated gaged basins with at least 10 years of record and compute FDC quantiles from 1% to 99% exceedance probabilities over the period-of-record and the entire water year (“annual” FDCs).
2. Compute base-flow recession rates for all of the selected gaged basins. These data will be useful to help model the behavior of the lower end of the FDCs
3. Following approaches used in previous peak-flow regionalization studies in Minnesota (Lorenz et al. 2010) and FDC studies in other states (e.g. Archfield et al. 2010) determine and compute, by means of GIS, the basin characteristics that will be used to estimate the FDC quantile regression models.
4. Following results of previous studies defining the physiographic regions of Minnesota, define the initial regions to be used in the analysis. The multiple regressions must be evaluated by statistical significance as well as by physical and hydrologic criteria. The regression results will be used to check and refine regions.
5. Using an iterative process, develop new FDC estimates for these ungaged locations near the gaged sites that generated the original regression equations using drainage-area ratios or other generalizations.
6. Use the map-correlation method to create synthetic hydrographs at ungaged locations. Extend these results to create a mass-balance, flow-network approach to creating synthetic hydrographs representing baseline conditions,.
7. Where available, use current condition SWAT and HSPF model outputs (based on a daily time step) at modeled pour points to calibrate and improve distributed upstream flow estimates derived from regression

For rivers and streams, we recommend daily natural hydrographs be modeled using the regression approach described above. Additional new tools will need to be developed to assess impacts of water and land use on lake and wetland basin hydrologic and ecological indicators, both for screening-level applications and site-based assessments.

For watersheds that have had SWAT or HSPF models developed for TMDL or flood management planning purposes (Figure 2.4), Minnesota should explore the potential of retrofitting/recalibrating the models to simulate daily flows under scenarios designed to simulate reference (“baseline” or “ natural”), current, and potential future climate, land use, and water use conditions. The opportunity to develop such a land and water planning decision tool might be most feasible in the context of a specific pilot Aquifer Management Area planning process, such as the Bonanza Valley Groundwater Management Area.

Water Accounting: Estimating Groundwater Withdrawal Impacts on Streamflows and Water Levels (Groundwater- Surface water interactions)

A key need for Minnesota in evaluating potential effects of proposed groundwater appropriations is the ability to understand the impacts of groundwater withdrawals on nearby streamflows, lake or wetland basin water levels. The state currently lacks the capacity to do this efficiently in the context of risk-based screening / triaging permit requests statewide. As part of the groundwater management area planning process, DNR Division of Waters has developed methods for estimating gradient changes in aquifers that have the potential to cause interaquifer and groundwater/surface water impacts. Although some local and regional groundwater flow models and databases have been developed for specific applications, these models are data, monitoring, technical, and resource intensive, and are not practical in the short term for use in permit review. A coupled surface - groundwater model is ideal, but these are difficult to do unless the spatial extent is very limited and adequate hydrogeological data is available, and the level of detail is often beyond what is needed for a simple screening tool.

To thoroughly characterize future effects of withdrawals or changes in recharge on ecological flows, a working understanding of water budgets is needed at nested scales from the smallest protected ecosystem class to the scale of large, downstream rivers and lakes. Rather than focus entirely on streamflow, we recommend defining the ranges and uncertainties of all sources and sinks (ET, precipitation, groundwater) and changes in storage so as to develop scenarios that explore how

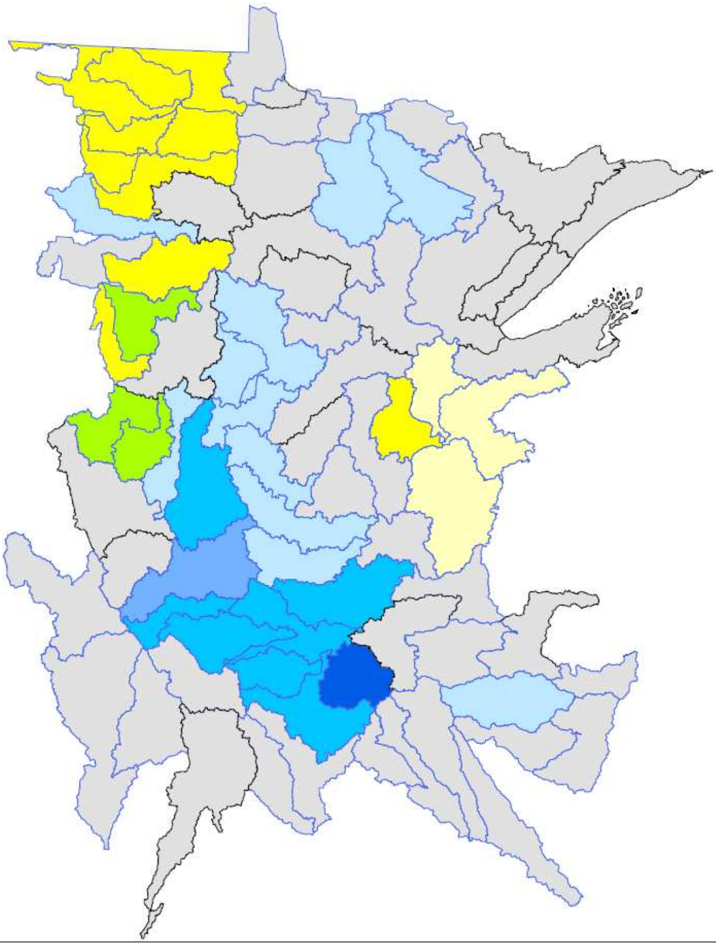


Figure 2.4. Huc 8 watersheds for which HSPF (blue), SWAT (yellow), or both (green) models have been developed. Darker colors indicate greater level of completion / calibration. [Source: Charles Regan, MPCA]

diversions may alter overall water balance. Several different methods have been proposed for estimating water budgets at a statewide scale. One option would be to expand the raster-driven data behind StreamStats to account for statewide net recharge information along with a script to compute wetness index. High values of wetness index would roughly indicate areas of groundwater discharge and could be roughly calibrated / quantified using the net recharge data) (Phil Gerla, TNC, pers. comm). As an alternative to wetness index, areas of groundwater recharge and discharge across the landscape could be mapped using a DEM, known elevations of the water table, and a finite difference flow model with a simple algorithm or model (according to MODFLOW could work with some modifications). In other words, the DEM would be completely filled with water and then allowed to drain incrementally. Once the step is reached where the model water levels best match the observed water-level elevation, a water budget would be run on the DEM cell model. Inputs and outputs not explained by cell-to-cell flow would be attributed to either recharge or discharge, respectively. MPCA also recently began a statewide recharge modeling effort based on the Soil Water Balance (Westenbroek et al. 2010), a method for calculating spatial and temporal variations in groundwater recharge that can in theory be used to estimate streamflow and water level impacts due to groundwater pumping (Andrew Streitz, personal communication). Regardless, temporal resolution is still needed to estimate daily pattern of discharge for purposes of predicting ecological response of streams, wetlands, or lakes.

Incorporating Land Use Impacts

In Minnesota in particular, a major complication of estimating unregulated conditions is the effect of land use and artificial drainage on hydrology. Few if any USGS gages can be considered to have "natural" land use (i.e., pre-settlement). All gages have various levels of upstream impervious surface and loss of forest cover due to ongoing forestry practices, agricultural and urban/suburban land use. Landscape hydrologic modifications in Minnesota were already significant by the mid-19th century, and in the agricultural regions of the state, few if any USGS gages reflect true pre-development conditions.

Making a provision for assessing land use impacts when estimating current or future condition is a critical step, also recommended in Minnesota's 2011 Water Sustainability Framework. Clearly, land use can be difficult to regulate in the statewide water management context and assessing its impacts accurately without watershed modeling is extremely challenging. As noted earlier, even with regression equations to define baseline flow conditions that eliminate land use parameters, most index gages in the state will reflect some hydrologic impacts from land use.

Ideally, a statewide GIS-based computer application would be developed capable of estimating alteration due to both land use and withdrawal scenarios simultaneously. The ability to estimate baseline (i.e., "minimally impacted") and current/future time series at any point location, both gaged and ungaged, throughout the state. This application would allow for the relative contribution of land versus water use and would therefore facilitate more integrated land and water planning. Flow time series could be used to calculate various flow statistics of ecological significance at a range of time steps (from daily to inter-annual). Hydrologic statistics would not be limited to magnitude, but could also include duration, frequency, timing, and rate-of-change. Calculating the differences between values of these flow statistics under baseline and current conditions will yield an assessment of hydrologic alteration. Initially, generating a daily flow time series for streams and rivers statewide could be done via a statistical, regression-based approach that estimates flow duration statistics to construct flow duration curves at any point location of interest based on a baseline period of record (e.g. 1960-2000). As noted earlier, where hydrologic process models have been developed, baseline or reference condition statistics developed from regression could be improved or updated with results from model scenarios designed to generate best achievable "natural" or "restoration" estimates.

We recommend further evaluation for Minnesota –via this project's ad hoc Hydrology Technical Advisory Committee, or a formalized future iteration—of how general land use impacts can be addressed within the hydrologic foundation and incorporated into a Decision Support System or Screening Tool. In areas in which land use issues are of major concern, current or future condition estimates should be developed using estimated impacts from both water use and land use.

Such an effort could build on existing efforts including the Lower Minnesota River model (http://www.metrocouncil.org/environment/water/LMRM/), the Seven Mile Creek watershed study (http://www.cfans.umn.edu/Solutions/Fall2011/Sustainability/index.htm), the Red River Basin Land and Water Investment Decision Support System (http://www.redriverbasincommission.org/ Projects/projects.html), and/or the Prairie Pothole Region Integrated Landscape Conservation Strategy (http://www.fws.gov/midwest/hapet/PPRILCS.html).

2.2 Classifying Aquatic System Types

In this section, we discuss the classification of river types, depicted as "stream classification" in Figure 2.3. According to Poff et al. (2010), this is a strictly scientific classification based on baseline (pre-development) river characteristics. Ideally, river type classification should result in a relatively small number of river types that capture the major dimensions of streamflow-related biological variability within a region. River classification for the purpose of identifying natural systems is distinguished in ELOHA from classification for the purposes of management or establishing standards. Section 2.5 describes the role of defining river condition classes to facilitate management, and/or to express future condition goals for setting and implementing flow targets.

2.2.1 Why classify aquatic systems for ELOHA?

Conceptually, river type classification extrapolates understanding of ecohydrologic conditions at sites that have been studied to similar sites that have not. This is the critical assumption of ELOHA that enables regionalized development and application of flow criteria.

Flow-ecology relationships are developed for each river *type*. Thus, the first reason to classify river types is to strengthen the statistical significance of flow-ecology relationships using information from rivers that have been sampled or studied. The second reason is to extend those relationships to other rivers of the same type in order to define their environmental flow needs.

Poff et al. (2010) highlighted river type classification as a critical step of ELOHA. Subsequently, researchers have developed classification systems for Australia (Kennard et al. 2010, Pusey et al. 2009), Washington (Reidy Liermann et al. 2011), Canada (Monk et al. 2011), New Jersey (Hoffman and Rancan 2007, Kennen et al. 2007), Missouri (Kennen et al. 2009), Texas (Hersh and Maidment 2007), Pennsylvania (Apse et al. 2008), and elsewhere, all intended to meet the needs of ELOHA.

In practice, river type classification has not always been found to be necessary. In some case studies, such as Massachusetts, a statewide regression relationship was created linking fluvial fish relative abundance to watershed characteristics that can be calculated at a small watershed scale. These same watershed characteristics (watershed size, gradient, etc) would likely drive a classification of aquatic system types. In others, such as the Connecticut River basin, flow recommendations are being made by river reach, so small differences between rivers within the project area do not warrant their being grouped by type. Although the Middle Potomac project team is still studying flow-ecology relationships, recent analyses indicate that segregating rivers by type does not significantly increase statistical relationships, and in fact could weaken them by reducing the number of data points per analysis. Thus, classifying watersheds may help reduce variability, but classification also reduces sample size, which increases uncertainty.

Other researchers have found river type classification to be useful. In New Zealand, Snelder et al. (2011) report that flow-ecology relationships (represented by weighted usable area) vary among major river types defined by morphology and flow regime. In Michigan (see case study), classifying rivers according to water temperature and catchment size protects the fish communities that are most sensitive to streamflow depletion. The Middle Potomac River project used river type classification to reduce natural variation in flow-ecology relationships caused by the influence of regional physiographic differences on flow metrics and on biological metrics.

2.2.2 General Approaches to Classification

River type classification for ELOHA tends to be either intuitive or iterative. The iterative analytical approach is well-illustrated in the Middle Potomac River basin project (see Case Study 4.5). The first iteration, based on hydrologic analysis and on the Northeast Aquatic Habitat Classification System, classified river reaches according to watershed size and karst geology. In the end, biological and hydrologic metrics were normalized so that data from all sites could be combined, thereby maximizing the size of the datasets used to quantify flow-ecology relationships.

The Susquehanna River basin project team likewise refined its initial suite of river types, based not on statistical analyses but rather on literature review and expert input. In both the Susquehanna and the Potomac basins, the river classification process extended over many months, and strengthened the resulting flow-ecology relationships.

The Colorado case study illustrates the intuitive approach. Rivers simply were classified by ecoregion, a process that took only minutes because the classification system already existed. Literature review and flow-ecology analyses confirmed that this simple typology sufficiently captures eco-hydrologic variability of Colorado’s river systems, especially considering the very limited databases with which the analysts had to work.

Using an existing classification system not only saves time, but also may help link streamflow management to regulatory programs that are already in place. By adopting aquatic life use classes from an existing water quality program, the Ohio project team (see case study) deflected water users’ concerns that biological flow criteria would create another layer of regulation. Moreover, the Ohio researchers were able to use extensive biological databases associated with the existing water quality program to develop flow-ecology relationships. The final river types for the Susquehanna River basin also borrowed from existing classification systems developed for other purposes, specifically conservation planning and water quality regulation.

In addition to intuitive and iterative approaches, a third general approach might be termed “a priori.” This refers to sophisticated, time-intensive river classification systems that are fully developed for ELOHA before being tested by flow-ecology analysis. For example, Reidy Liermann et al. (2011) used Bayesian-mixture modeling, a recursive partitioning algorithm, random forests, and a geomorphic classification to create a 14-tier hydrogeomorphic classification for Washington, in preparation for flow-ecology analysis.

2.2.3 Parameters Used for Classification

River classification for ecohydrologic analysis is becoming increasingly sophisticated, a trend apparently accelerated by publication of Poff et al. (2010). Olden et al. (2011) provide an excellent review of the full spectrum of approaches and their respective applications. Here, we focus on the parameters and approaches that our case studies have used to support flow-ecology analyses and flow criteria development.

Hydrology

As shown in Figure 2.3, Poff et al. (2010) recommend classifying rivers initially according to their hydrology. This is easily accomplished using hydrologic statistics calculated from daily streamflow data with Indicators of Hydrologic Alteration (IHA; The Nature Conservancy 2009), Hydroecological Integrity Assessment Process (HIP; Henriksen et al. 2006), or similar software. HIP not only calculates the statistics, but also uses them to classify river types. Briefly, principal components analysis eliminates redundant statistics, and cluster analysis then groups the remaining data by river type.

A HIP classification was conducted for Pennsylvania (Apse et al 2008). Of the five river types that HIP delineated, the project team incorporated one (baseflow-dominated streams) because it represented a hydrologic type that was considered to be important and was not captured in other existing classifications. They combined it with river types based on watershed size and drainage area from other existing classification systems to define rivers types for their study (See Susquehanna case study). Our other six case studies did not adopt hydrologic classifications.

Hydrologic statistics that are used to classify river types need not be the same metrics used to express environmental flow criteria.

Water Temperature

Olden and Naiman (2010) make an argument for using water temperature in environmental flow assessments, especially where reservoir releases greatly alter natural temperature regimes. Water withdrawals, too, can affect water temperature to the extent that biological communities completely transform. This is certainly the case for coldwater streams in the upper Midwest; both Michigan and Ohio captured this phenomenon by incorporating water temperature into their river type classifications. Michigan's new water withdrawal permitting system is designed intentionally to keep coldwater streams cold by maintaining sufficient (cold) groundwater discharge into their channels. Many state water quality programs routinely monitor water temperature, so ample data may be readily available. Water temperature is routinely measured in Minnesota as part of state and local monitoring programs; however, because water temperature varies significantly with flow, groundwater inputs, and air temperature, understanding stream thermal regime requires integration of many variables. MPCA and MN DNR designation of streams as "cold" or "warm" water is based largely on a streams' ability to support trout or other coldwater species.

Ecoregion or Habitat

Freshwater ecoregional classification seeks to identify critical areas for conservation by capturing representative components of freshwater biodiversity (Higgins et al. 2005). Although not developed expressly for ELOHA, ecoregional classification is based on many of the same factors that influence flow-ecology relationships. In Colorado, a coarse, high-level ecoregional classification (CEC 1997) proved adequate for distinguishing river types for ELOHA. In the Susquehanna River basin, the Northeast Aquatic Habitat Classification (Olivero and Anderson 2008) informed river type classification. In both cases, applying pre-existing classification systems accelerated project timelines.

Watershed characteristics

Relationships between flow-ecology and river size are well established (Vannote et al. 1980, Higgins et al. 2005). Michigan, Ohio, and Susquehanna River basin classifications incorporate catchment area. Other watershed characteristics that may usefully define river types include land cover, geology, climate, geomorphology, topography, and elevation. The deciding factor is whether the resulting river types strengthen the significance of flow-ecology relationships.

2.2.4 Options for Classifying Aquatic Ecosystem Types in Minnesota

This section discusses some options and issues and potential initial approaches to aquatic ecosystem classification, including both lotic and lentic ecosystems.

In Minnesota, as in Florida and a few other states, traditionally instream flow protections have been interpreted on a case-by-case basis based on site-specific assessments and studies. Compared to a regional approach, this tailored ecosystem or site-specific approach allows for greater precision and greater ability to account for ecological complexity and may result in more locally appropriate assessments and recommendations. However, it has some disadvantages. The most prominent of these is cost and staff time—with the result that in Minnesota the majority of streams, rivers, and lakes still lack specific studies and flow/water level prescriptions. Also, site-based flow prescriptions create challenges in articulating the basis for decisions, and may appear to users or regulated communities to be inconsistent, arbitrary or at least unpredictable.

Below we briefly describe several classification approaches that either could serve as a model for Minnesota or have been completed for streams or watersheds within Minnesota and could be adapted for or incorporated into a hydrologic classification.

Wolock (2003) grouped watersheds in the United States into hydrologic landscape regions (HLRs) according to their similarity in landscape and climate characteristics, representing factors demonstrated to affect hydrologic processes. Hydrologic landscape regions in the United States were delineated by using GIS tools and statistical methods including principal components and cluster analyses.

MN USGS defined “hydrologic regions” in Minnesota (Figure 2.5) for the purposes of estimating peak flows on ungaged to aid regulation and planning of water resources and for design of bridges, culverts, and dams along Minnesota’s rivers and streams. Estimates of peak-flow magnitudes for 1.5-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year recurrence intervals were developed for 330 streamflow-gaging stations in Minnesota and adjacent areas in Iowa and South Dakota based on data through water year 2005. The peak-flow frequency information was subsequently used in regression analyses to develop equations relating peak flows for selected recurrence intervals to various basin and climatic characteristics.

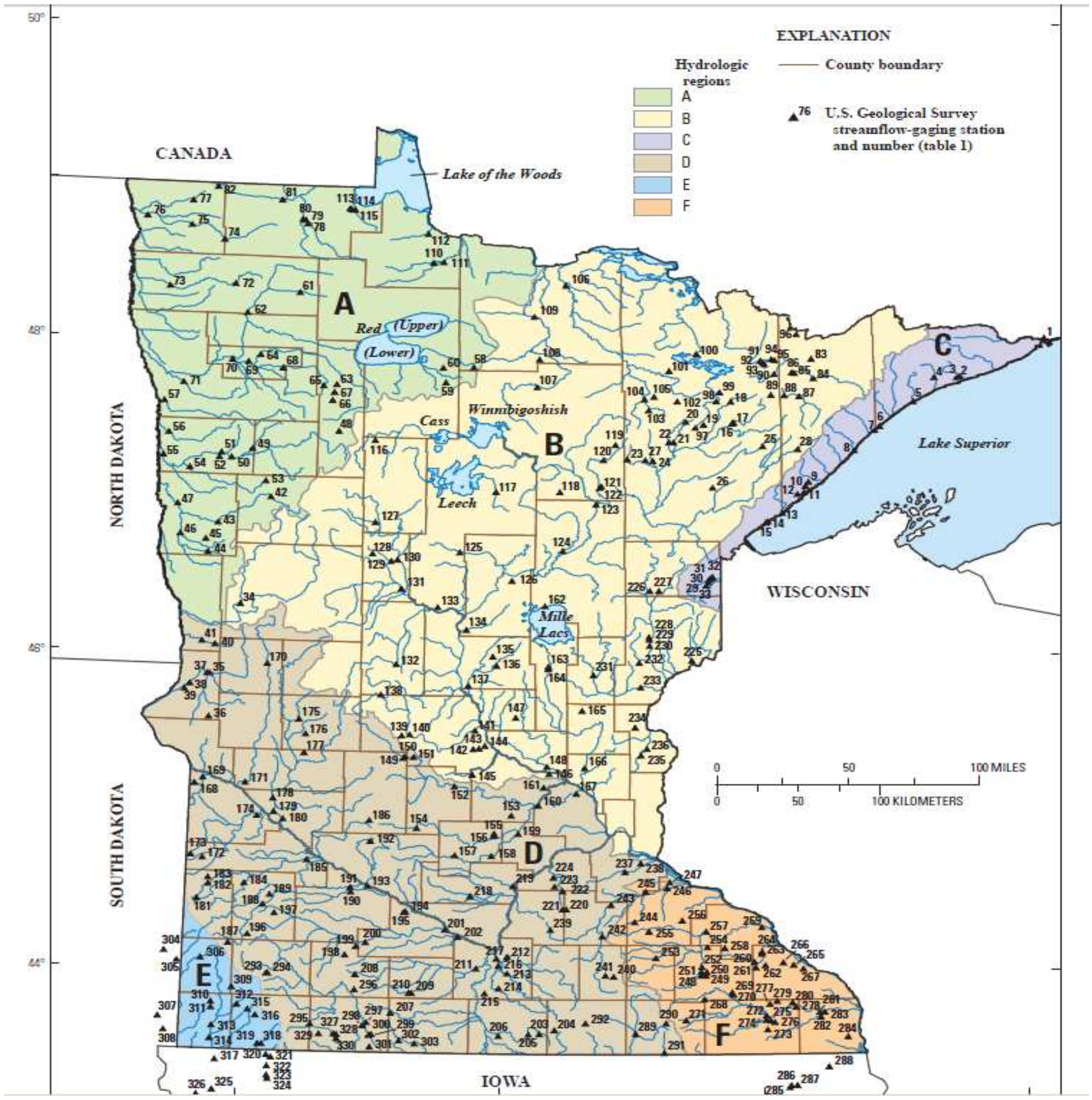


Figure 2.5. Hydrologic regions used to develop regional peak flow regression estimates by MN USGS (Lorenz et al. 2010).

The method developed by USGS essentially recognizes that watershed hydrologic response varies regionally, and therefore regression relationships designed to estimate peak flows will be more accurate if they reflect these general patterns in regional variation. Two statistical techniques were used. Regional regression equations were developed for each recurrence interval in each of the six regions in Minnesota: A (northwestern), B (north central and east central), C (northeastern), D (west central and south central), E (southwestern), and F (southeastern). The region of influence (ROI) technique defines a new set of regression equations for each ungaged site by selecting gaging stations with characteristics that are similar to that ungaged site, based either on similarity or proximity. The ROI technique allows use of a potentially unique set of gaging stations for estimating peak flow at each site of interest. Where regions are relatively homogenous, using hydrologic landscape units and possibly other drainage characteristics is a useful technique to define regions. All regression methods involved calculation of upstream drainage area. Peak flow regression estimates were improved in some regions by including watershed storage (a measure of lakes and wetland) and other covariates. ROI however was determined to be inappropriate for regions C, E, and F because the interrelations of some characteristics of those regions do not agree with the interrelations throughout the rest of the State.

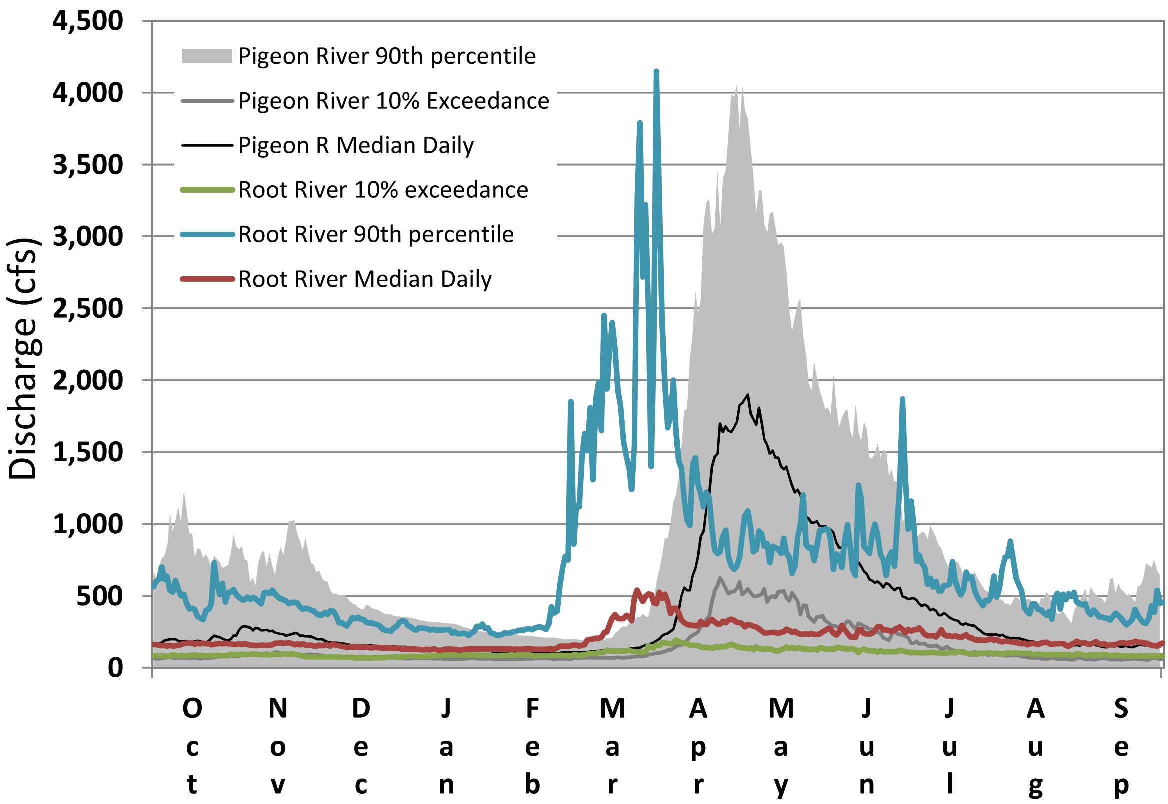


Figure 2.6 Mean annual hydrographs and daily flow statistics for two similar size rivers in Minnesota , illustrating differences in seasonal flow patterns. The Pigeon River is a 609 square mile watershed located along Minnesota's North Shore (Lake Superior basin) with a mostly forested, bedrock dominated watershed, whereas the Root River is a Mississippi River tributary located in southeastern Minnesota, with a 615 square mile watershed above the gage at Lanesboro characterized by significant agriculture as well as karst geology.

The Nature Conservancy has developed **hierarchical classifications of rivers and streams** for each of its ecoregional plans in Minnesota, as well as a **statewide hydrogeomorphic lake classification** (Blann and Cornett 2008). These classifications reflect nested stratified classifications based at the broadest level generally on ecoregion and system size. Underlying geology or natural physical watershed characteristics are also often part of the highest level classifications.

Minnesota DNR uses the Minnesota Ecosystem Classification System and system size as the basis for its conservation planning classifications, including the state wildlife action plan *Tomorrow's Habitat for the Wild and Rare* and the Statewide Comprehensive Conservation and Preservation Plan. These include small, medium and large rivers, as well as lakes stratified by 2 size (large, small) and 2 depth classes (shallow and deep).

Biological Classifications of Minnesota Rivers and Streams

The Minnesota Pollution Control Agency (MPCA) has developed a statewide stream and river classification approach based on the Index of Biotic Integrity (IBI) to support development of biological assessment under Clean Water Act. The goal of the IBI classification was to describe stream types for the purposes of developing appropriate IBI criteria. The basic strategy was to identify a set of physical/chemical stream features that could best predict the occurrence of fish and invertebrate assemblages. This stream classification framework is based on stratification of streams by region (Northern vs. Southern), stream size, and thermal regime, with one separate class for "low gradient" streams. Classification and IBI development is now complete for both coldwater and warmwater streams for the entire state of Minnesota including the streams of Minnesota's Great Lakes Basins. The coldwater classification was completed this spring (2011). An initial map of the classes is shown in the Figure 2.7 below. The classification—based primarily on stream size and thermal regime—yields ~9 types (7 warmwater and 2 coldwater) and is analogous to the approach used in Michigan for development of the fish flow response curves to support the WWAT, as well as the approach that Ohio has proposed.

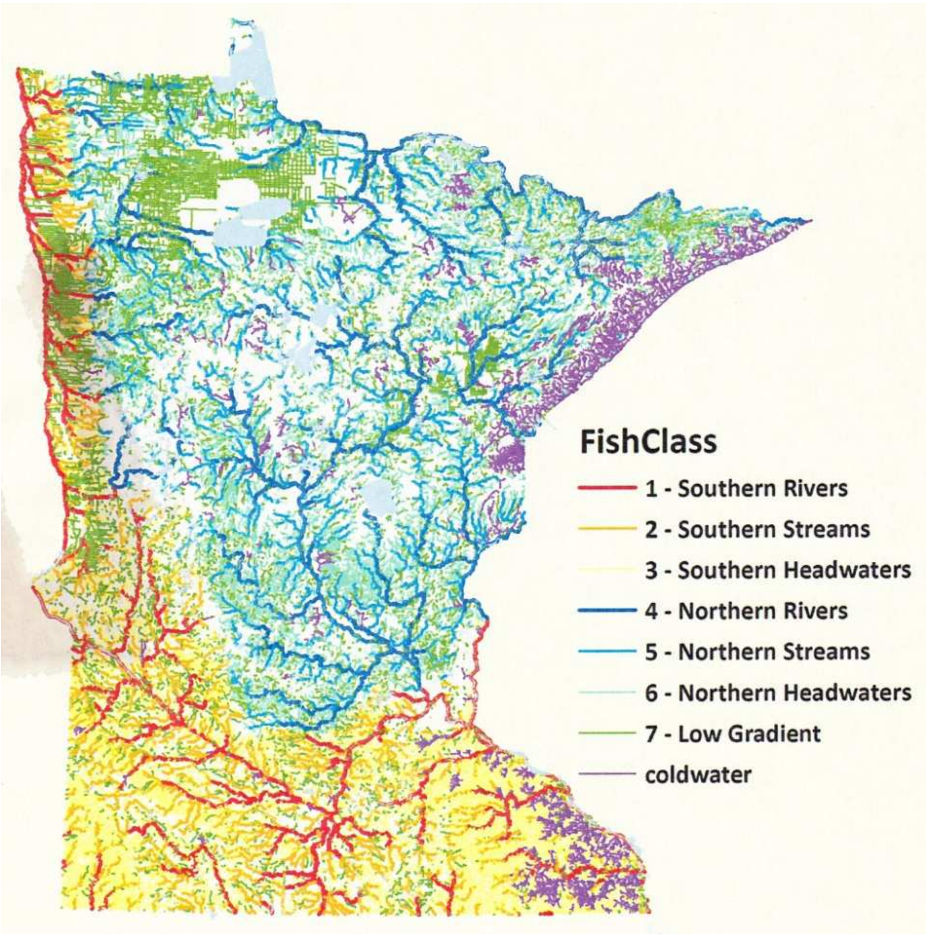


Figure 2.7. Stream classification framework developed to support the implementation of the Minnesota Index of Biotic Integrity (IBI) [Source:J.Sandberg and S. Niemela, MPCA, Draft report.

2.2.5 Recommendations for Minnesota

Developing and Applying an Appropriate River Classification

The goal for developing and applying a river classification in ELOHA is to strengthen flow-ecology relationships. By grouping rivers and streams that have similar hydrology, we assume we account for the dominant patterns and distribution of aquatic ecological communities in response to flow.

We suggest that Minnesota initially adopt the MPCA IBI classification as the basis for an initial exploration of characterizing flow ecology response in Minnesota, focusing on developing and exploring fish and macroinvertebrate response curves. Other factors may ultimately prove to be important to classification in Minnesota; e.g. for establishing aquifer, lake, and wetland protections, a watershed or ecoregional approach might be appropriate. However, selection of the IBI classification for an initial study does not preclude an adaptive management approach that would allow modification of this classification using other river characteristics (e.g. hydrology) or for other classifications to be explored later.

2.3 Describing Flow-Ecology Relationships

Relationships between flow alteration and ecological response are grounded in the biological condition gradient approach (Davies and Jackson 2006), in which increasing degrees of anthropogenic stress lead to decreasing ecological condition. Flow–ecology relationships may be expressed in various forms, depending on the information available and the interpretations required: as an ecosystem attribute (E) as a function of the change in hydrologic condition (Q) from natural ($\Delta Q/E$), as an expected departure of an ecosystem attribute from a reference condition as hydrologic conditions depart from natural ($\Delta Q/\Delta E$), or as an expected status of an ecosystem attribute as a function of the value of a hydrologic metric (Q/E). Sanderson et al. (2011) used both of the latter forms to build one decision support tool (see Colorado case study).

Ecological data used to develop the flow-ecology relationships - for example, aquatic invertebrate species richness, riparian vegetation flow response guilds (Merritt et al 2010), or life-history traits of fish - ideally are sensitive to existing or proposed flow alterations and can be validated with monitoring data (Poff et al 2010). For use in an ELOHA process, flow criteria setting efforts often seek to identify response indicators that are both representative of the range of species responses within an ecological system type, as well as of clear and recognized value to society.

Poff et al. (2010) prescribe a progression from hypothesis development to data assembly and analysis to build these relationships (Figure 2.3). In practice, projects generally follow this progression, with the information available and the implementation mechanism influencing the relative emphasis on quantitative versus qualitative approaches.

2.3.1 Hypothesis Development

Regardless of the analytical approaches ultimately used, flow-ecology relationships should always begin with hypotheses derived from the literature and expert input about how each environmental flow component (Mathews and Richter 2007) influences physical, chemical, and particularly biological processes within a river type. Subsequent quantitative analyses are designed specifically to test these hypotheses.

The Susquehanna River basin e-flows project team introduced a structured approach for developing consistently worded hypotheses in an expert workshop setting (DePhilip and Moberg 2010). The Connecticut River basin project has since adopted this approach, as well. The objective is to capture systematically the entire spectrum of taxonomic groups and physical processes across the entire flow regime. Experts are asked to express hypotheses that answer the questions:

- Who (species or group of species)
- What (flow magnitude or event)
- When (month or season)
- Where (river type and habitat)
- Why/how (ecological response)

For example, "If summer (*when*) low-flow magnitude (*what*) decreases in baseflow-dominated streams *(where)*, then water temperature will increase (*why*) and salmonid populations will decline (*how*)."

To facilitate hypothesis development, project scientists displayed flow-dependent life stages of native species for each river type superimposed on "typical" hydrographs (e.g., case study, figure 1).

In the Susquehanna, as in every large region, insufficient quantitative data were available to test every hypothesis. Yet, the literature conveyed that every ecosystem and flow component in the Susquehanna is important for maintaining ecological integrity, and no single data-rich species or guild could adequately represent the others. The experts agreed that to be scientifically defensible, their recommendations had to preserve both the inter- and intra-annual flow variability needed to protect the entire ecosystem. The only way to do that in the limited time allotted was to base environmental flow recommendations primarily on the literature review and their best professional judgment. The resulting recommendations are linked explicitly to their underlying hypotheses so that they may be tested quantitatively in the future (case study, figure 2).

2.3.2 Quantitative Analysis

The Michigan, Ohio, Massachussetts, and Middle Potomac project teams decided that scientific defensibility requires rigorous quantitative analysis of extensive databases. All four had large biological databases with which to work, and carried out systematic processes for selecting the parameters that ultimately would define their flow-ecology relationships.

For ELOHA, ecological metrics should be:

- sensitive to flow;
- meaningful indicators of river health;
- broadly distributed spatially in a variety of watershed types and sizes, along a gradient of flow alteration; and
- recently sampled (to pair with current flow conditions).

Hydrologic metrics calculated from daily streamflow data should:

- represent natural variability in the flow regime;
- be sensitive to change and have explainable behavior;
- be easy to calculate and replicable;
- have conceptual and empirical linkages to ecological response
- be easy for non-hydrologists to understand; and
- be non-redundant.

An ideal set of parameters represents natural flow variability by:

- including all environmental flow components (e.g., low flow, freshets, floods);
- characterizing the magnitude, timing, duration, frequency, and rate of change of all flow components; and
- representing inter- and intra-annual flow variability.

The Susquehanna River basin project is our only case study that meets this standard for reflecting natural flow variability. This was accomplished through quantitative *flow* analysis and qualitative flow-*ecology* analysis. The ten flow statistics used to describe the magnitude and frequency of large and small floods, high flow pulses, median monthly flow, and monthly low flow conditions in the Susquehanna River basin are: magnitude and frequency of 20-year (large) flood, 5-year (small) flood, and bankfull (1-2 year high flow) events; frequency of high flow pulses in summer and fall; high pulse magnitude (monthly Q10); monthly median (Q50); typical monthly range (area under monthly flow duration curve between the Q75 and Q10); monthly low flow range (area under monthly flow duration curve between Q75 and Q99); monthly Q75 and monthly Q95. The flow-duration metrics allowed for flow recommendations based on the seasonal ecosurplus/ecodeficit concept (Vogel et al. 2007) .

Appendix 1 lists hydrologic and ecological metrics that have been used in selected studies of ecological response to flow alteration.

Statistical analysis

Ecological condition of a river is the result of many factors, of which flow is only one. A focus of recent research is to isolate the influence of flow alteration from other environmental stressors, and then to identify the flow and ecological metrics that best describe ecological response to flow alteration. Several statistical techniques facilitate this analysis.

Multivariate statistical analysis can identify the environmental parameters that most strongly correlate with observed variation in ecological indicators. When indicators of hydrologic alteration are among the parameters analyzed, their importance relative to other stressors can be evaluated. This preliminary analysis greatly reduces the universe of flow statistics for subsequent flow-ecology analysis and builds confidence that these relationships will be minimally obscured by other factors.

Kennen et al. (2010) used multivariate methods to identify a subset of eight ecologically relevant hydrologic variables describing streamflow magnitude, frequency, duration, timing, and rate of change that explained variation in macroinvertebrate assemblage composition across the 339,290-km^2

northeastern United States. The study used physical, chemical, and biological data collected as part of the National Water-Quality Assessment Program and landscape characteristics from the National Land Cover Database. Principal component analysis (PCA) and partial collinearity assessment reduced 527 environmental and land-use variables initially analyzed to a subset of 52 variables that accounted for the most variance in macroinvertebrate assemblage, while minimizing redundancy and reducing the effects of natural variation. Conditional multiple linear regression was then used to quantify relationships between the remaining 52 variables. From this analysis, significant bivariate relationships were developed to depict relationship between macroinvertebrate assemblage structure and the 8 hydrologic variables.

Several other studies have similarly used multivariate statistical analyses to select hydrologic statistics. Using generalized linear modeling, Armstrong et al (2010) quantified fish response to several hydrologic statistics (see Massachusetts case study). Using multiple regression analysis, Kanno and Vokoun (2010) showed that water withdrawal rate was more important than other natural and anthropogenic factors (e.g. land cover and stream size) in explaining several fish assemblage metrics. After using multivariate analysis to eliminate hydrologic parameters associated with anthropogenic disturbance, Kennen and Riskin (2010) found significant linear and curvilinear bivariate flow-ecology response relationships for fish and invertebrate assemblages in the New Jersey Pinelands. Kennen et. al. (2007) combined watershed modeling and indirect ordination techniques to identify components of the hydrologic regime that have the most significant effects on aquatic-assemblage structure across a disturbance gradient. Important variables included the average number of annual storms producing runoff, ratio of 25-75% exceedance flow (flashiness), diversity of natural stream substrate, and the percentage of forested land near the stream channel (forest buffer). Knight et al. (2008) analyzed hydrologic time series to identify three hydrologic metrics essential to habitat suitability and food availability for insectivorous fish communities in streams of the Tennessee River Valley: constancy (flow stability or temporal invariance), frequency of moderate flooding (frequency of habitat disturbance), and rate of streamflow recession. In Georgia, Roy et al. (2005) quantified relationships among fish assemblage metric response, hydrologic variables, and imperviousness in small streams and their subcatchments (see Table A.1)

Classification and Regression Tree (CART) and Boosted regression tree (BRT) are statistical methods that identify threshold values for explanatory variables that serve to separate groups of response variables. Carlisle et al. (2010) used CART to relate two indicators of altered hydrology-- streamflow *depletion and* streamflow *surcharge*--and aquatic biological community impairment across the conterminous US compared to eight other covariates (water temperature, specific conductance, pH, total nitrogen, total phosphorus, channel gradient, agricultural land cover, and urban land cover of the riparian buffer). The degree of alteration (depletion and surcharge) was estimated based on regression models using landscape and watershed variables to predict flows at reference gages versus gages with highly modified upstream conditions.

The Middle Potomac River basin case study illustrates a systematic, iterative approach similar to those described above for selecting non-redundant hydrologic and ecological metrics that define statistically significant flow-ecology relationships.

After flow and ecology metrics have been selected, **quantile-regression modeling** can be used to quantify bivariate flow-ecology relationships from large datasets that represent sites affected by multiple stressors. The premise is that scattered flow-ecology data are bounded by "ceilings" that represent the maximum ecological condition that could be achieved at any given flow value if all other stressors were absent (Cade and Noon 2003, Konrad et al. 2008). Regression is used to quantify the decline in maximum ecological condition as flow alteration increases. The 90th percentile accounts for some uncertainty. The Colorado, Massachusetts, Middle Potomac, and Ohio case studies illustrate the use of quantile-regression modeling to define flow-ecology relationships.

Modeling

In Michigan, scientists studied large fish and flow databases, along with other habitat suitability information (catchment size, base flow yield, July mean temperature) to develop predictive models of fish assemblage structure under a range of base flow reductions (Zorn et al. 2009). These models then generated flow-ecology curves for water withdrawal permitting (see Michigan case study).

2.3.3 Being Resourceful: Hybrid Approaches

Relying on large existing biological databases limits flow-ecology analyses to a subset of a complex ecosystem. Likewise, relying on a single flow metric limits analyses to a subset of a complex hydrologic pattern. Conversely, basing flow recommendations on conceptual models may pose credibility issues in a controversial political milieu. The Colorado case study illustrates a novel approach for blending the best of both.

Lacking large ecological databases, the withdrawal thresholds that populate Colorado's Watershed Flow Evaluation Tool are based on literature review and expert input. In this case, the experts not only helped develop flow-ecology hypotheses, but they also suggested how to use the very limited data found in the literature to test those hypotheses. Analytical approaches ranged from categorical threshold delineation to quantile regression, depending on the form and quantity of data available. Ultimately, flow-ecology relationships were quantified for warmwater and coldwater fish, invertebrates, riparian vegetation, and recreation. Many of those were based on only a handful of sites, which are assumed to represent their entire river type. Camp Dressser & McKee Inc. et al. (2009, Appendix B) document the specific approach used to quantify each flow-ecology relationship that they generated.

2.3.4 Options for Defining Flow-Ecology Relationships in Minnesota

The following section summarizes data, analysis, and peer-reviewed literature published pertaining to flow ecology response relationships in Minnesota's Great Lakes Basin (the original subject of the pilot study) as well as statewide.

Published studies documenting quantitative responses to specific measures of flow alteration are largely unavailable for most species or communities in Minnesota, but studies documenting quantitative responses to variables that relate to hydrologic alteration as well as drainage basin size help establish weight of evidence. Many studies described qualitative ecological responses to flow alteration that are consistent with the qualitative hypotheses and quantitative relationships developed in other states and in Appendix 3. Although these studies do not provide quantitative thresholds, they provide empirical support for flow ecology hypotheses and reinforce the acknowledged the need to protect low, seasonal, and high flow components.

Indicators of Hydrologic and Ecological Condition--Minnesota's Great Lakes Basin

Several initiatives, studies and datasets relate to the establishment of ecological criteria to support environmental flow protections for Minnesota's Lake Superior basin streams. The Natural Resources Research Institute and the EPA Mid Continent Ecology Lab have collaborated on a number of ecosystem indicator and assessments. For example, the Great Lakes Environmental Indicators (GLEI) project was a multi-year project funded by an EPA STAR grant to develop multi-metric indices of ecological health for Great Lakes coastal ecosystems (Danz et al. 2005). GLEI examined several different types of indicators of ecological health, ranging from species richness, habitat indicators, indicator species, and other metrics. Indicator species (e.g. walleye, Hexagenia, unionid mussels, exotics) respond predictably and consistently to gradients of environmental condition, such as the health of the system or the presence and severity of a particular type of stressor. Trophic status indicators-- such as the proportion of predators or insectivores, or benthic feeders for fish, and shredders, filter-collectors, grazers, or predators for macroinvertebrates--are often used as a measure of community structure. Taxonomic and/or life history trait indicator metrics (e.g. feeding, reproduction, locomotion) are frequently included in fish IBIs. For example, Brazner et al. (2005) included metrics of body shape and swimming speed for fish, as well as feeding, spawning, and habitat guilds, in evaluating response of fish assemblages to watershed hydrologic indicators in watersheds of Lake Superior. Multimetric indices such as the Index of Biotic Integrity (IBI) score sites based on robust sets of metrics developed at known least-impacted reference sites (e.g. fish IBI, benthic IBI). Higher scores indicate greater ecological health based on comparison to the appropriate reference condition. Multivariate approaches develop relationships between indicator and stressor datasets, and allow for some degree of variance partitioning to determine which relationships are dominant. The GLEI project also examined multimetric versus multivariate approaches to see whether they provide consistent results. It provides another potential source of data to assess ecological metrics specifically in response to measured or modeled flow statistics.

Table 2.2 lists selected landscape variables found to be related to watershed ecological and hydrologic response in watersheds of the Lake Superior Basin. Table 2.3 shows fish indicator variables found to be significantly related to landscape hydrologic variables (e.g. mature forest cover, watershed storage) in the EPA led studies (Detenbeck et al. 2004, Brazner et al. 2005). Indicator Species Analysis suggested that the best indicator species of fragmentation and watershed storage were brook trout and slimy sculpin for least degraded forest conditions, and common shiners and mottled sculpins (*Cottus bairdi)* for more degraded conditions (higher fragmentation). For third order streams, brown trout and salmon were significant indicators of lower watershed storage. Most of the indicator metrics listed in Table 2.3 above, as well as other potentially flow sensitive fish guild or functional trait metrics, could be derived from the extensive datasets collected by the MPCA as part of statewide IBI development and watershed monitoring efforts (Niemela and Sandberg 2010). These could form the basis for a robust regional or statewide quantitative flow ecology analyses, evaluated in response to selected hydrologic statistics or watershed hydrologic indicators as available.

Decades of MN DNR fisheries reports and management plans also support the importance of natural flows for aquatic community health on Minnesota's North Shore. In addition, some North Shore streams listed on the impaired waters list have been extensively surveyed in preparation for development of TMDL plans. For example, fish surveys have been conducted to support the

Table 2.2. Selected landscape indicator variables found to be significantly related to hydrologic response in Lake Superior Basin watersheds

Driver of Hydrologic alteration	**Hydrologic/ecological response**	**Location/ region**	**Reference**
Fragmentation of forest cover	Higher peak flows, more variable flows	Northern Minnesota	Verry 2000, Poff and Ward 1990
	Increased erosion		Everest and others 1987; Hartman and others 1996
	Changes in fish assemblage traits		Brazner et al. 2005
Lower mature forest cover	Altered thermal regime, higher life-stage diversity; changes in fish functional traits prevalence of streamlined body forms and silt-tolerant fish	North Shore streams	Brazner et al. 2005
	Increased temperature resulting from reduced forest cover	North shore	Hostetler 1991
High mature forest cover	Higher abundance of piscivores, coldwater fish, proportion YOY, silt-intolerant fish, and fish preferring moderate current speeds	North Shore Lake Superior	
Higher watershed storage	Fishes with higher silt tolerance, warmer temperatures, weaker sustained swimming capability		

development of a TMDL assessment and plan for the impaired Poplar River. As part of this study, researchers identified potentially significant impacts on winter low flows due to winter withdrawals for snowmaking at the Lutsen Mountain ski resort, and confirmed that actual withdrawals are higher than the permitted volume and represent a significant percentage of winter baseflow (Nieber et al. 2008). Fish communities in the Poplar River show evidence of impairment below the resort, particularly the coaster brook trout run (Persons, 2007). Brook trout are particularly vulnerable to depleted winter baseflows in Minnesota's Lake Superior streams because of the timing of spawning, egg, and larval fish development over the winter (Huckins et al. 2008; Schreiner et al. 2006, 2008). These streams have very little if any groundwater and are dependent on surface water, which has a greater tendency to freeze completely at low flows, causing scouring and dewatering of eggs and spawning beds.

Table 2.3 Fish metrics significantly related to landscape hydrologic variables (Species, fish assemblage or functional trait)

Indicator species • Brook trout • Common shiner • Longnose dace Abundance/assemblage structure • # of species • # of life stages • # Fish/100m2 • # YOY/100 m2 • # adults/100m2 • Proportion adults • Proportion YOY • Biomass/100m2 • Dominance Physiological traits • Size (Large, Medium, or Small) • Swimming speed • Body shape	Habitat preference • Current preference (fast, moderate, or slow) • Silt tolerance (Low, medium, high) • Thermal preference (cold, cool, or warmwater) • Substrate preference (silt, sand, gravel, cobble) Reproductive strategy / Spawning guild • nest guarders • open-substrate spawners • Multiple spawners • Lithophils • Speleophils Feeding guild • Piscivores • Omnivores

Options for further characterizing ecological response to flow and flow alteration for Minnesota's Lake Superior basin drainages. Data and models developed and products for Minnesota's Lake Superior Basin have been generated via Great Lakes Aquatic GAP project, and could be used to develop flow ecology response curves.[16] Under GLGAP, models of streamflow and temperature were developed and used to develop a fish-based classification for the North Shore. Using environmental flow components derived from the GLGAP flow models and a modified classification, a range of flow ecology response analyses and curves could be generated for Minnesota's Great Lakes Basin as soon as the data products are released later in 2011 or early 2012 (Jim McKenna, USGS, pers. comm.) The pilot flow ecology analysis would evaluate ecological response to flow alteration in terms of expected: observed fish communities in relation to environmental flow component statistics and indicators of hydrologic alteration/condition derived from GL Aquatic GAP flow models.

Stream habitat and flow recommendation studies have been conducted for both the Cloquet and St. Louis Rivers to guide development of flow recommendations as part of the FERC relicensing on the hydropower dams at Jay Cooke State Park (Fond du Lac Dam) and Cloquet (Knife Falls and Scanlon Dams) and the paper mill dam at Cloquet. As with most other hydropower facilities in Minnesota, relicensing agreements have for the most part eliminated hydropower peaking operations that have shown to be consistently detrimental to fish and other aquatic ecosystems. Other reservoirs and water control structures that service mine operations (including mine dewatering) have site-specific

[16] This was added as an objective of this project early in the process and part of the reason we focused on the Great Lakes Basin as a pilot. However, for various reasons, release of the GL GAP data and products has been delayed and so they were unavailable for this phase of the project.

conditional water use permits which require monitoring of downstream flow conditions. These studies provide the potential to model habitat impacts as well as representative fish and mussel species population response across a range of scenarios designed to reflect increasing levels of withdrawals in those basins (MN DNR Stream Habitat Program).

For other options for characterizing ecological response to flow for Minnesota's Lake Superior basin, see the options for the state as a whole (below).

Indicators of Hydrologic and Ecological Condition -- Statewide

In Minnesota, there are two primary programs or initiatives designed explicitly for the purposes of long-term statewide biological and ecological assessment and monitoring of watershed health: (1) the biomonitoring program of the MPCA to support Clean Water Act implementation and (2) the Watershed Assessment Tool of the MN DNR designed for use by resource managers and decisionmakers at multiple scales.

The **biological monitoring database developed by the Minnesota Pollution Control Agency (MPCA**, the agency charged with water quality protection) is the most robust and comprehensive ecological dataset available statewide. The MPCA has invested significantly in monitoring and development of reference criteria to support regional assessment, monitoring, and standard setting under the Clean Water Act. MPCA conducts biological assessment and monitoring for fish and macroinvertebrates on a 10 year rotating assessment cycle covering all 81 of the state's major watersheds, resulting in a dataset representing thousands of data points at hundreds of sites with multiple visits[17]. To support interpretation and development of reference standards, they have been developing a biologically driven stream classification framework to describe unique stream types for the purposes of developing Indices of Biotic Integrity (IBI) that accurately reflect biological condition and potential. The classification was developed by identifying a set of physical/chemical stream features that could best predict the occurrence of similar fish and invertebrate assemblages. The state now has a complete set of fish and invertebrate IBIs tied to the stream classification framework for both warmwater and coldwater streams (Figure 2.7). The fish classification and IBIs are in the process of being published. Agency technical staff have made the data available for many research purposes. For example, MPCA biological monitoring dataset was the basis for the fish models and predictions developed under Great Lakes Aquatic GAP.

The MPCA biological monitoring dataset used to support development of the statewide IBI is also the basis for the state's Tiered Aquatic Life Use (TALU) classification framework for setting CWA goals, which represents a significant revision to the Water Quality Standards of the state's aquatic life use classification[18]. The dataset is also currently being used to develop Tiered Aquatic Life Use (TALU) goals and standards as the basis for revising and updating state water quality standards. The TALU framework builds upon existing water quality standards with a goal of improving how water resources are monitored and managed, while advancing the ability to identify "stressors" (including hydrologic

[17] http://www.pca.state.mn.us/index.php/water/water-monitoring-and-reporting/water-quality-and-pollutants/water-quality-condition-monitoring/watershed-sampling-design-intensive-watershed-monitoring.html
[18] http://www.pca.state.mn.us/index.php/water/water-monitoring-and-reporting/water-quality-and-pollutants/the-tiered-aquatic-life-use-talu-framework.html

alteration) and develop effective mechanisms to improve and maintain the condition of waters in the state of Minnesota. Already, a TMDL study of Little Rock Creek in Central Minnesota was initiated because of a biological impairment in the headwaters, through which groundwater withdrawals (primarily for irrigation) were identified as a key stressor.

Both the IBI and the TALU classification frameworks are based on the concept of the Biological Condition Gradient (BCG; Figure 2.8). Essentially, the flow ecology response curve represents the biological condition gradient in response to a particular stressor, that is, hydrologic alteration. The Biological Condition Gradient has also been cited as the conceptual basis for proposed and adopted streamflow protection standards in Maine, Connecticut, Massachusetts, Michigan, Ohio, Maine, and Pennsylvania. As such, several states (including Maine, Ohio, and Connecticut) have made efforts to integrate water quality and streamflow quantity standard setting frameworks.

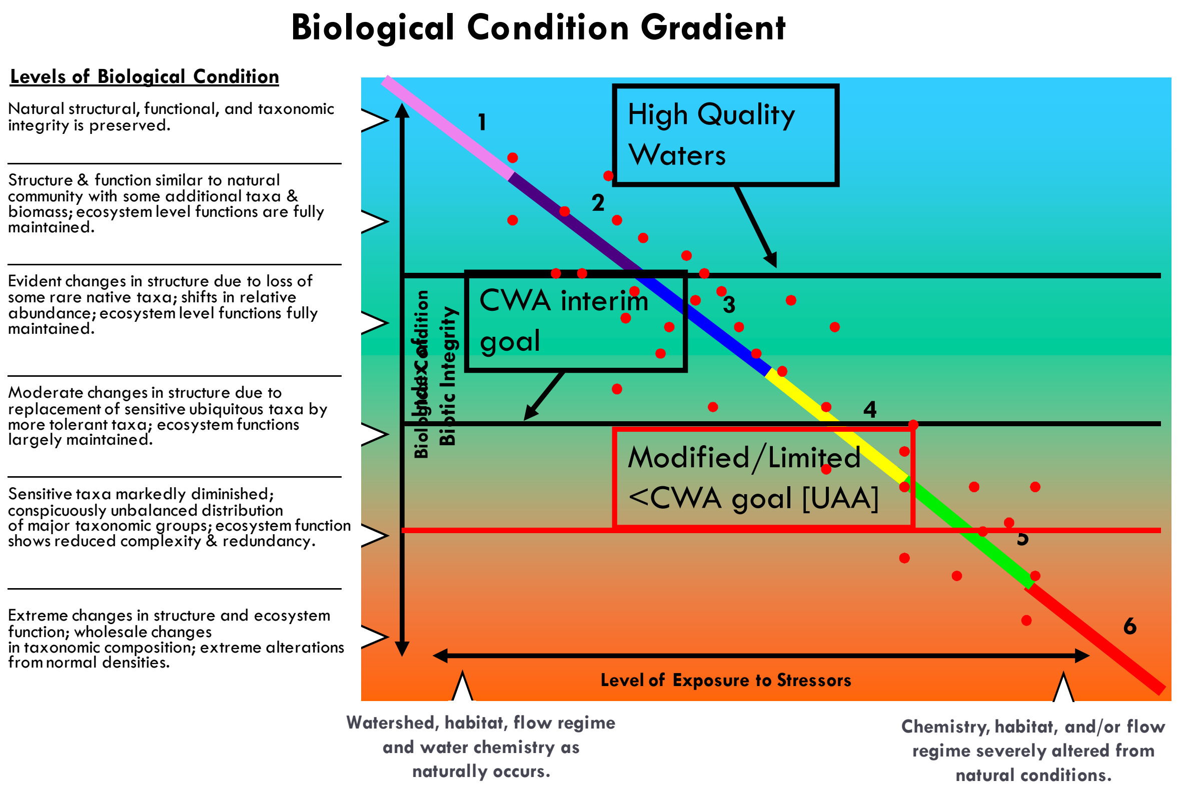


Figure 2.8. The Biological Condition Gradient.

The fish and macroinvertebrate dataset developed to support IBI development includes hundreds of sample sites across the state. “Fuzzy Set” BCG models have been developed and assigned scores for riverine fish and invertebrate communities across the state, and have been used to develop biocriteria (IBI impairment thresholds) as supporting information in the waterbody assessment process (Figure 2.9). The dataset may even be sufficiently robust to generate statistically significant flow response models at 6- or 8-digit HUC scales. For this reason, the MPCA’s biological assessment framework and monitoring datasets currently represent the best opportunity to explore empirical flow ecology relationships in Minnesota.

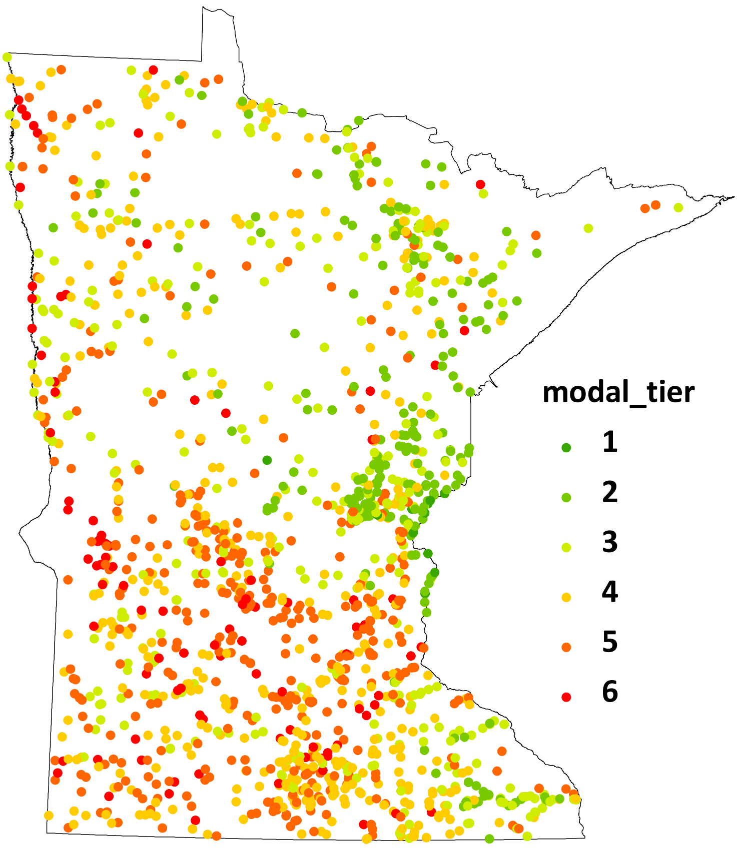


Figure 2.9. Distribution of sample sites in MPCA statewide river and stream biological monitoring dataset, showing current conditions as based on Biological Condition Gradient fuzzy model scores. [Source: John Sandberg, MPCA].

Bouchard (2011) listed the benefits of using the biocriteria approach (in the TALU context) as providing the ability to:

- Separate natural variability from anthropogenic impacts
- Identify and preserve the highest quality resources
- Set realistic and attainable management goals
- Designate beneficial (designated) uses realistically and accurately
- Develop accurate assessments
- Facilitate better and more effective management
- React to incremental changes
- Determine appropriate management actions when conditions decline

All of these benefits are fully applicable in the specific context of environmental flow protection, and have the added value of being designed to interpret current ecological conditions in the context of all potential water quality and habitat stressors.

The **Minnesota DNR Watershed Assessment Tool (WAT)** provides another potential framework for statewide exploration and development of flow ecology response relationships. The Watershed Assessment Tool (WAT) was conceived as a tool to present background information and a comprehensive series of GIS layers, organized and delivered within a 5-component framework of hydrology, geomorphology, biology, connectivity and water quality (Figure 2.10). It is intended by DNR as a tool to facilitate discussion and quantification of healthy watershed function by managers and stakeholders when routine decisions are being made that have the potential to affect current and future resource conditions. The WAT itself has three distinct phases of development:

1. Text incorporated throughout the website that explains important concepts and the connections between the five components of watershed health.
2. An online mapping interface that delivers pre-loaded data within the component framework. The Watershed Assessment Map displays, summarizes and compares GIS natural resource data by major watershed boundary. Spatial distribution and summary tables are used to describe the status of resource features for each component within a selected watershed.
3. The scoring results *(in development)*, organized and presented for each watershed and resource component. Used together, the text, maps and health scores will lead to a better understanding of the components, their connection to each other and our activities on these landscapes and the complexity of interactions to consider prior to making resource management decisions.

The first two phases are complete and products are currently available online: http://www.dnr.state.mn.us/watershed_tool/index.html. The third phase is being prototyped and will soon be available online as well.

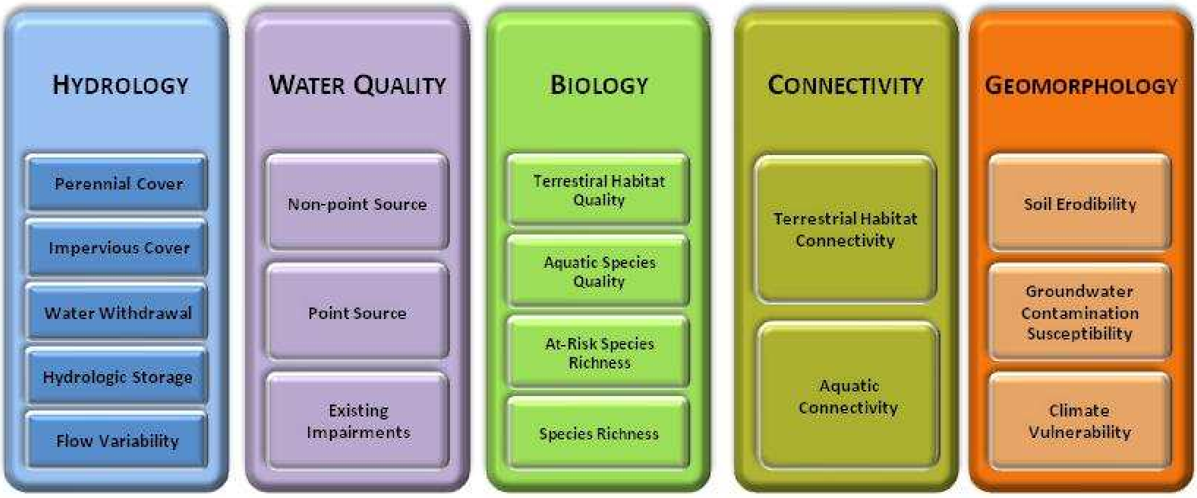


Figure 2.10. The MN DNR Watershed Assessment Tool's five components of watershed health, with component indices.

The WAT develops individual and composite indicator scores, scaled from 0-100, for each of the 5 component frameworks (Figure 2.10). For example, the hydrology component score is a composite ranking consisting of component scores for watershed perennial cover, impervious cover, water withdrawal index, hydrologic storage (a measure of lake and wetland storage), and flow variability (a measure based on the Indicators of Hydrologic Alteration. Each of the subcomponent scores also consist of multiple metrics.

Development, selection, and inclusion of the metrics and scores for the WAT were based on a robust, iterative technical process and thoroughly vetted criteria including data availability, accuracy, non-redundancy, and relevance/usefulness.   The team acknowledges that many of the metrics could be improved and updated. The web site includes discussion and rationale for each metric, descriptions of how each metric was developed and applied, as well as strengths, weaknesses, and potential future improvements. The scores, methods, and data have not yet been formally released, as they are currently being internally pilot- tested within the Minnesota DNR and partner agencies, so these represent preliminary results. The final phase is scheduled to be released to the public via an online interactive web site sometime in 2012; however, much of the background information, tool and indicator descriptions, methods, and functionality of the WAT are already deployed.   The WAT offers a potential framework and platform for expanded development of flow ecology relationships in the future at scales more detailed than the eight-digit HUC, and as improved methods and datasets become available statewide. Potential enhancements and future phases for the WAT include developing health index scores where possible at the minor watershed scale (12-digit HUC) in order to help managers and decision-makers apply a systems perspective to local scale assessment and planning.

Figures 2.11 and 2.12 show the results of preliminary analysis of selected indicator scores developed and calculated for Minnesota's 81 "major" watersheds. The biology component scores in the Figures represent the composite watershed score on the component indices for terrestrial and aquatic habitat quality, at-risk species richness (numbers of species of greatest conservation need), and overall species richness.   Figures 2.13 and 2.14 represent example approaches to the analysis of fish species richness, corrected for regional covariates, in response to flow, based on data underlying the existing WAT. These figures demonstrate how the WAT provides a new and promising tool for exploring "ecological response to flow alteration" in Minnesota, at least at the eight-digit HUC scale. In the future, the WAT also provides a potential platform for building decision support around environmental flow protection, especially if it is developed for planning at smaller scales (e.g., 12-digit HUC).

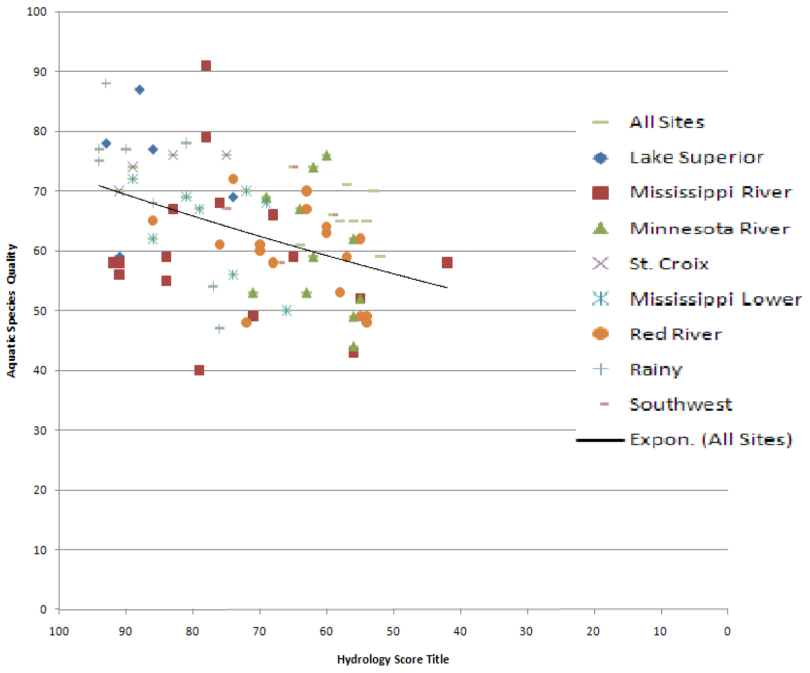


Figure 2.11. Aquatic species quality score plotted against the hydrology component composite score for Minnesota's 81 major watersheds, depicted by region/river basin. The aquatic species quality score is one of 4 subcomponent metrics of the biology component score in the MN DNR WAT. Aquatic species quality score is the mean score of (a) mean observed vs. expected fish species ratio, (b) mean observed:expected aquatic invertebrate species and (c) live/live and dead shell records for mussel species). All metrics are scored from 0-100, where 100 represents the best possible condition.

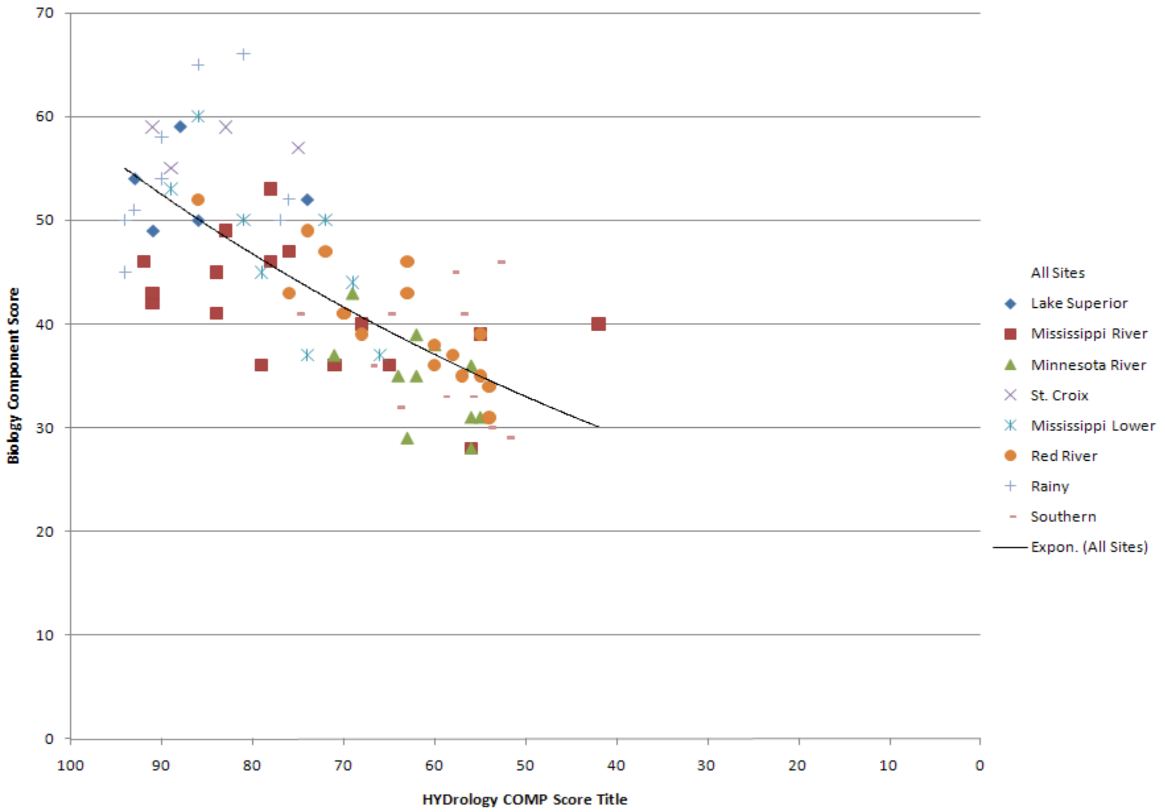


Figure 2.12. Biology component score from the Watershed Assessment Tool plotted against the hydrology component score for the 81 major watersheds, depicted classified by region/major river basins.

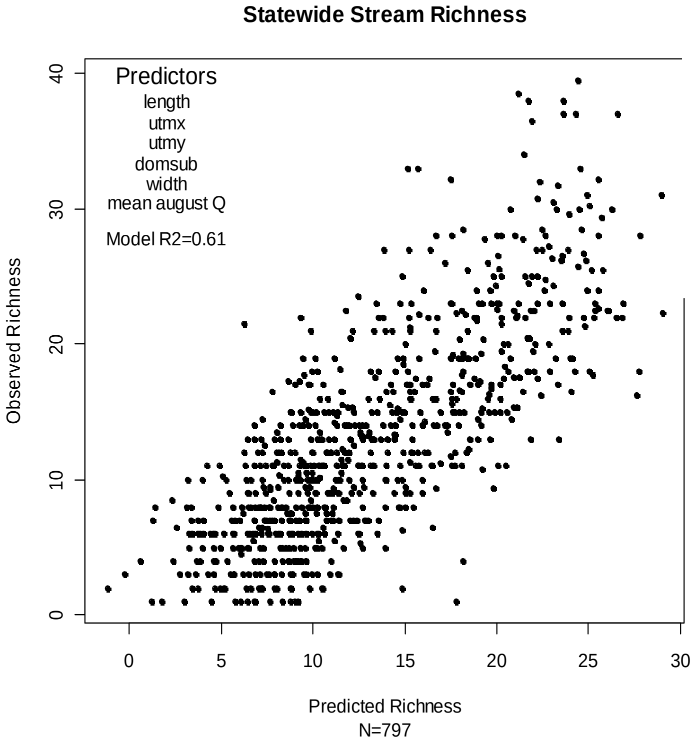


Figure 2.13. Analysis of observed versus species richness statewide based on data in the MN DNR watershed assessment tool [Source: Dan O'Shea, MN DNR Stream Habitat Program]

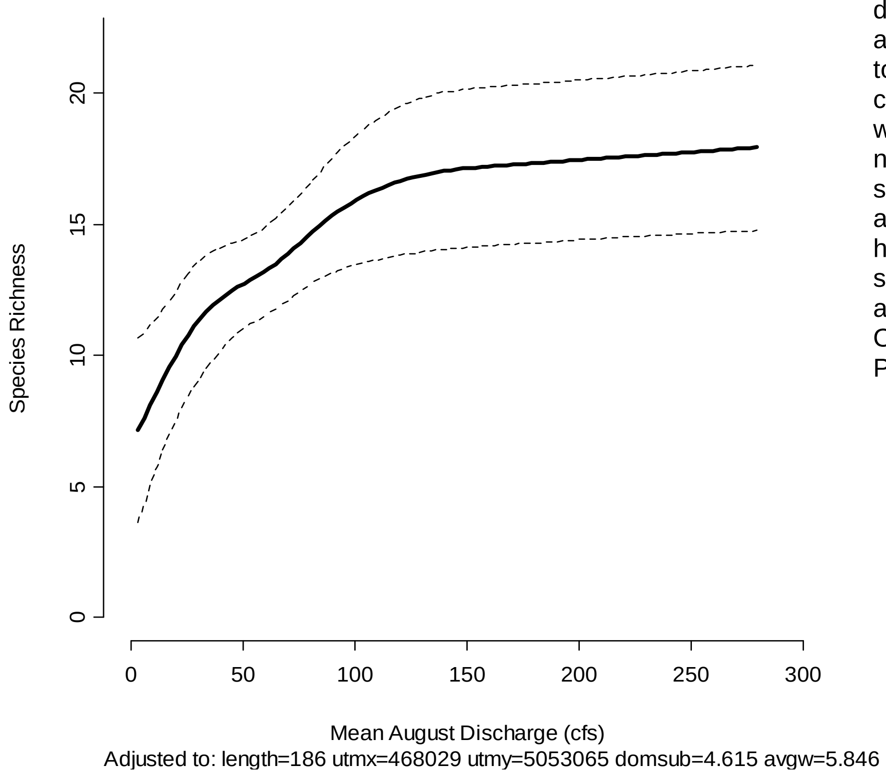


Figure 2.14. Effect of August discharge on richness after accounting for covariates (adjusted to mean of length, UTM x and y coordinates, dominant substrate and width). Note that larger streams do not change as much as smaller streams. Based on IBI biological assessment data in relation to hydrologic statistics developed to support the MN DNR watershed assessment tool [Source: Dan O'Shea, MN DNR Stream Habitat Program]

Several other recent ecological assessments suggest additional data and techniques potentially useful in identifying flow-related ecological thresholds in Minnesota. Boosted Regression Tree is being used by Downstream Strategies, a consulting firm that obtained a 2010 Multi State Conservation Grant to conduct fish habitat assessments on behalf of the 5 Midwest Fish Habitat Partnerships (FHPs) established under the National Fish Habitat Action Plan (NFHAP). Similar to CART, models developed using BRT identify threshold values for each of the predictor variables significant in habitat models predicting species presence/absence (Fritz Boettner, Todd Petty, and Roy Martin, June 2011, Downstream Strategies). Initial results for the Midwest Glacial Lakes Partnership suggest that variables related to watershed and groundwater hydrology were significant predictors of coldwater and intolerant species presence in lakes. Models being developed for the Fishers and Farmers FHP will also predict presence/absence for a range of species of greatest conservation need (SGCN) native to rivers and streams of the Upper Mississippi River Basin.

Baker and King (2010) developed Threshold Indicator Taxa ANalysis (TITAN) for determining changes in taxa distributions along an environmental gradient over space or time. They then assessed synchrony among taxa change points to identify community thresholds to environmental change, including flow alteration. A similar species-based method was presented by Lucinda Johnson for developing Great Lakes Environmental Indicators at the first MN ELOHA workshop in Duluth, Nov 2010. These single species approaches work best where there is a predictable and continuous response across the entire community along a continuum of the predictor variable. For example, Johnson et al. (2010) and Baker and King (2010) both use total phosphorus as a predictor of algal species in their illustrated examples.

2.3.5 Recommendations for Minnesota

Recommended Approach for Defining Flow-Ecology Relationships in Minnesota

Minnesota should commit to a formal process to characterize ecological response to hydrologic alteration across the full range of aquatic system types throughout the state. With an adequate hydrologic foundation, quantitative analysis of ecological response to flow statistics is imminently feasible and should be pursued. The state has a wealth of biological response and assessment data, primarily the biological assessment data developed by MPCA as well as the data underlying the MN DNR Watershed Assessment Tool. (Eventually the MN DNR Fisheries' long-term lake and stream survey datasets will also be available in digital form; however, they are still several years away from completion). Although the state has a wealth of data, knowledge and expertise applicable to site-level and major watershed impact assessment, there is still no set of easily transferable flow-ecology relationships that can be applied to ecological risk screening in local or regional planning or permitting processes to efficiently triage limited staff and technical resources. We recommend a phased approach to the development of flow ecology relationships to support establishment of ecologically-based flow protection criteria. Based on our review, we recommend a combination of quantitative and qualitative methods and approaches carried out in the following steps:

a. <u>Review, refine, and prioritize the draft set of flow alteration – ecological response hypotheses for the major aquatic ecosystem types</u> (lake, wetland, river and stream types across Minnesota) generated in year one of this project, and <u>listed in Appendix 3</u>. This step includes additional work by the existing ad hoc or an expanded formal Flow Ecology technical committee to regionalize the existing river specific streamflow and habitat criteria (i.e., those developed using Minnesota's extensive species-specific flow related habitat suitability models), comparing habitat to flow relationships across stream sizes and regions.

b. Conduct pilot analyses to quantify flow-ecology relations with existing data. A few exploratory analyses for Minnesota could be pursued relatively soon with available datasets (Table 2.4).

Table 2.4. Datasets and programs that could potentially contribute to the analysis of flow-ecology relationships in Minnesota

Ecological Assessment Programs/Datasets	**Source**	**Predictor variables**	**Response variables**	**Spatial scale *(& availability)***
Great Lakes Environmental Indicators	Natural Resources Research Institute	Measured flows *(current conditions)*	Multiple ecological metrics; species assemblage	Minnesota's Great Lakes basin only, primarily wadeable streams. *Available.*
Great Lakes Aquatic GAP	James McKenna and Howard Reeves, USGS	Modeled monthly flow statistics based on AFINCH (Reeves et al) *(current conditions)*	Expected: observed and species richness; fluvial or sensitive spp. richness	Minnesota's Great Lakes basin only, at 12-digit HUC scale. *Ecological data complete; hydrologic models in press.*
MN Watershed Assessment Tool (WAT)	MN DNR WAT - (MPCA & USGS)[Source: Beth Knudsen & Dan O'Shea]	MPCA biological sampling data & HUC8 flow statistics (USGS gage derived flow estimates for 8-digit HUCs) *(current conditions)*	Expected: observed and species richness; fluvial or sensitive spp. richness	Statewide, HUC8 *Basic structure and databases are available now.*
MPCA watershed models (TMDL and CWA compliance)	HSPF TMDL model outputs + biological assessment data [Source: Chuck Regan, MPCA; Scott Niemela, MPCA]	Flow metrics derived from baseline and current condition flow time series from HSPF models	Fluvial or sensitive species metrics ; Species richness	HUC8 *currently available only for the Minnesota and Red River basins* (see Figure 3.1)
MN DNR Stream Habitat Program IFIM studies and HSI curves	Site-based stream habitat assessments	Expert process *(current conditions)*	HSI data	Scalable; statewide

c. Use available biological and ecological datasets to assess indicator responses to flow statistics and evaluate hypotheses developed above. Development of a complete and comprehensive understanding of ecological response to flow alteration in Minnesota systems requires a multivariate statistical approach capable of separating out the portion of independent and shared variance contributed by other stressors. For the purposes of developing a comprehensive and holistic picture of potential ecological flow responses, a range of multivariate and bivariate exploratory analyses should be conducted. We recommend analyzing the datasets compiled to support development of the MN DNR Watershed Assessment Tool (WAT), as well as expanding and applying the statistical approaches developed by the MPCA biomonitoring program, to the assessment of flow ecology relationships, *once hydrologic statistics and indicators of alteration are available (see Section 2.1.5)*. (Note that MPCA biological assessment data are also the basis for the "aquatic species quality" component index in the WAT). Identification and development of flow-sensitive metrics (e.g., fluvial fish species richness, sensitive species' relative abundance) for different stream classes using the IBI dataset offers the greatest potential to evaluate fish and macroinvertebrate response to flow and flow alteration statewide, and would also be valuable in the context of stressor identification.

Development of fish or other indicator response curves using the "thriving" and "characteristic" community concepts–analogous to the "fish curves" used in development of the Michigan Water Withdrawal Assessment Tool to identify adverse resource impact thresholds in response to increasing levels of withdrawals --could also be useful in the context of identifying risk screening thresholds and developing tools for decisionmakers. Such an approach to representing community-level impacts could be potentially be crafted using data and habitat suitability models developed by DNR Stream Habitat Program to support instream flow recommendations (Aadland and Kuitunen 2006).[19] Additional models, studies, and tools will likely be needed to fully evaluate ecological response to and adverse resource impacts from altered hydrology, such as thresholds and patterns governing response of mussel communities, wildlife species of greatest conservation need, shorebirds and waterfowl, or riparian, shoreland, and wetland plant communities.

Challenges and Caveats

There are many challenges to developing flow ecology relationships to support state instream flow protection policies, particularly fully empirical approaches (Martin 2010). Ecosystem response to variable flow regimes is inherently complex (Richter et al. 2006). Rose (2000) listed 6 reasons why quantifying the effects of anthropogenic changes on fish populations has remained elusive and contentious :

(1) detectability—high interannual variation and interaction effects among climatic variables that affect population dynamics make isolating effects of individual stressors difficult;
(2) complex habitat and nonintuitive responses—spatial heterogeneity in habitat can result in population responses that are disproportionate to the changes in EQ;

[19] Unlike Michigan, MN DNR fisheries does not currently have long-term historically collected stream and lake fish survey data in database format; however, such a database has been designed to house future survey results (Rick Nelson, MN DNR Fisheries, pers. comm.).

(3) regional predictions—biological realism is often sacrificed unnecessarily when broad spatial scale predictions are needed;
(4) community interactions—too little attention is paid to how community-level interactions can affect population-based analyses;
(5) sublethal effects—sublethal effects are often ignored but can have large effects on population dynamics; and
(6) cumulative effects—the combined effect of multiple stressors can be much different than expected from the sum of their individual effects. Examples include a variety of freshwater and marine species. Quantifying effects on fish populations can be improved by considering these issues in analyses, and by taking a true multidisciplinary approach that combines individual-based modeling and life history theory
(7) Lag times in detecting surface water impacts

Different approaches to generalizing flow alteration to biological response have different advantages and disadvantages. Of the most commonly used models and methods for setting instream flow requirements, virtually all have been subject to criticism based on oversimplification or reductionist treatment of complex ecosystem processes and interactions (Richter et al. 1997, Martin 2010).

Certainly, there are always tradeoffs between the cost and resources required to develop models with increasing empirical certainty. Increasingly, with constraints on federal and state agency science and monitoring budgets, approaches that link flow alteration to assemblage structure or coarse ecological indicators are generally more feasible for large spatial scale applications than more resource-intensive approaches based on habitat modeling (e.g., river-specific flow recommendations.) The user community may also appreciate the more consistent and predictable approach of a regional approach compared to site and resource-specific limits. In any case, complete empirical certainty is practically unobtainable due to the complexity and variability inherent in living ecological systems. Furthermore, the more extensive and detailed the science characterizing ecological response to altered flow, the more difficult it may be to communicate and fully engage stakeholders in discussions about the appropriate level of protection. Simple representations of flow ecology response abstracted from a large foundation of more detailed scientific studies but which still capture the complexity are often valuable in communicating with non-scientists, but are difficult to develop.

Because of this inherent complexity, many analysts have recommended a precautionary approach to streamflow standard setting. In other words, they suggest it would be preferable to err on the side of preserving more instream flow than is thought to be needed—at least initially, in order to preserve the adaptive management option-- than to risk the high and irreversible costs of preserving too little (Postel and Richter 2003). The potential negative consequences of neglecting instream flow protection, as enumerated in Gupta (2008), include: (1) public health risks associated with more concentrated pollution and reduced availability of drinking water, 2) loss of food security due to less water for agriculture and damage to fisheries; 3) loss of biodiversity, recreation, and tourism; and 4) increasing competition for water. Climate change has complicated the attempt to establish reference flows for the purposes of environmental flow assessments, and will only get worse (Martin 2010). Ecological complexity and lag times also contribute to the fact that in many places, a substantial portion of the public-- particularly those who do not directly engage in subsistence or recreation activities in aquatic ecosystems-- do not recognize or acknowledge these ecosystem services as benefitting them directly in their everyday life (Martin 2010).

2.4 Making Flow-Ecology Relationships Operational: Implementing Environmental Flows at a Regional Scale

Sections 2.1 - 2.3 discussed the development of flow-ecology relationships. Figure 2.2 illustrates the use of these relationships to translate an ecological condition goal (y-axis) into an environmental flow criterion (x-axis). In this section, we discuss ways to establish those ecological condition goals, and then how such goals are being pursued in policy and on the ground.

Environmental flow thresholds or criteria cannot be defined by science alone. Science quantifies the tradeoffs (flow-ecology relationships) that underlie their definition, but the criteria themselves are socio-political decisions about the desired ecological condition of water bodies.

Consider water quality standards as an analogy. Scientific analyses determine the concentration of a pollutant that has a risk of killing one in a million people who ingest it, the concentration with a risk of killing one in a thousand, and so forth. Statutes or rules state the allowable risk associated with ingesting pollutants based on societal tolerance, feasibility of removing the pollutant, and other factors. The water quality standard is the concentration associated with that risk.

Now consider environmental flow criteria. Scientific analyses determine the degrees of flow alteration associated with various levels of ecological degradation. These relationships are expressed as flow-ecology response curves. Status, rules, or perhaps guidelines state the allowable level of ecological degradation based on societal tolerance, existing water uses, and other factors. The environmental flow standard is the degree of flow alteration associated with that level.

Two major policy decisions are needed to put the flow-ecology relationships into practice. First, *ecological condition goals,* or risk levels, are defined in terms of the biological metrics used in the flow-ecology response models. For example, what range of invertebrate richness indicates a high level of risk of ecological degradation? What range represents low risk? This decision should begin with ecologists proposing threshold levels, should include opportunity for public input, and should culminate with formal adoption through an appropriate legal process. The flow-ecology curves translate then ecological condition goals into environmental flow criteria. Hydrologists may use models to help water users understand implications of the proposal on water availability. Plans should be made for monitoring, periodic review, and risk level revision as new information becomes available.

Second, *policy actions associated with each ecological risk level* must be determined. For example, if a proposed water withdrawal has a low risk of harming the ecosystem, can it be approved immediately? If its risk is high, will the proposed withdrawal automatically be denied? Or, if the risk is already high, will that river reach be prioritized for water right transactions?

Sections 2.4.1 and 2.4.2 further explain how these policy decisions are made, and how they are being implemented in various water management contexts.

2.4.1 Establishing Ecological Condition Goals

For practical reasons, not every aquatic system can be managed to maintain outstanding ecological qualities; for some heavily used water bodies, a functioning ecosystem is the best condition attainable. With input from scientists, ELOHA encourages stakeholders to define “acceptable ecological conditions” (Figure 2.2), or ecological condition goals, for every water body. Then, flow-ecology curves may be used to associate an acceptable degree of flow alteration with each condition class. Condition goals and river types need not overlap. For example, Figure 2.1 depicts four different condition goals for single river type. Likewise, a large geographic region should contain excellent-condition rivers of every river type within it.

Some state flow management programs, such as Maine’s, have simply adopted condition classes from existing water quality programs[20]. Others have defined new condition goals that apply explicitly to water quantity, based on existing conditions and stakeholder input. For example, the State of Connecticut proposed a condition goal class for each of the state’s river reaches, mapped the state’s water bodies by goal class, facilitated a formal public comment process, and revised the map accordingly, all through a regulatory rule-making process.

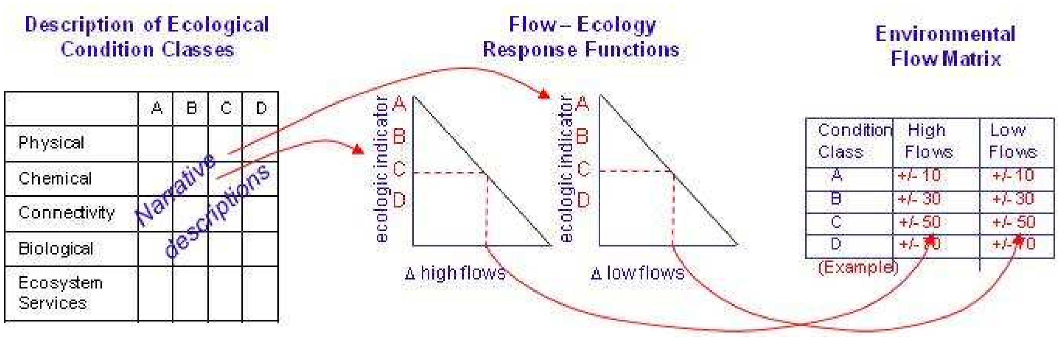


Figure 2.15. Process for translating condition classes (left) into environmental flow criteria expressed as degree of allowable flow alteration from baseline (right) for two flow components (high and low flows) for a hypothetical river type.

[20] http://www.maine.gov/dep/blwq/topic/flow/index.htm

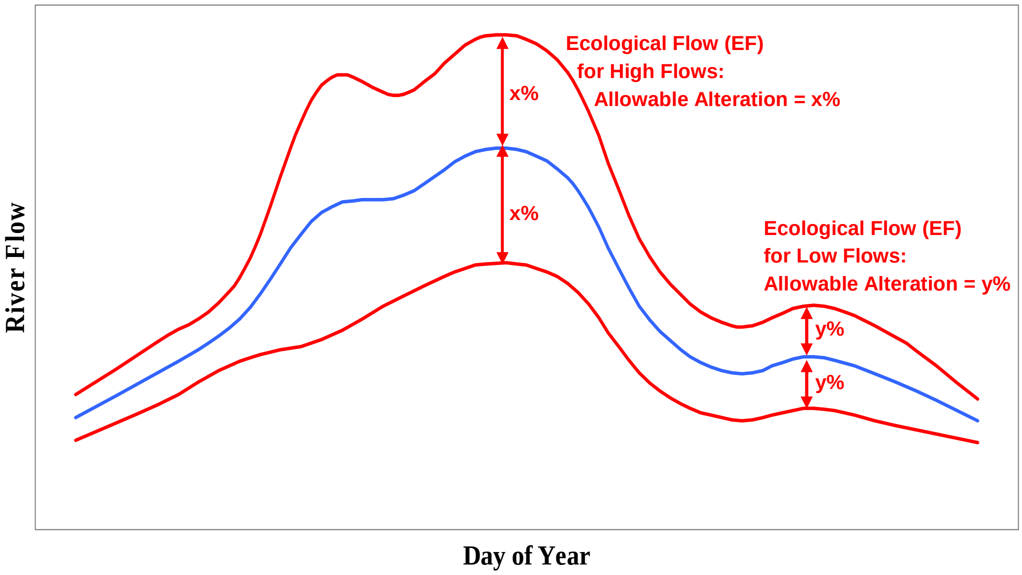


Figure 2.16. Sustainability boundaries (Richter 2009) shown in red, around natural hydrograph (blue) resulting from environmental flow criteria depicted in Figure 2.15.

Thresholds between condition classes should be informed by ecologists, who describe the specific ecosystem outcomes associated with each ecological condition class for each river type. These ecological outcomes may describe key attributes of river ecosystem health, principally: (1) physical habitat, (2) water quality, (3) flow connectivity, (4) biological composition and (5) ecosystem services.

Figures 2.15 and 2.16 illustrate conceptually the translation from river conditions classes to environmental flow criteria for one River Type. Ecologists describe the ecological outcomes associated with each River Condition Class (A-D) in terms of physical habitat, water quality, flow connectivity, biological composition, and ecosystem services. From these descriptions, they identify hydrologic and ecological indicators that are important to each River Type. Then, scientists develop flow alteration-ecological response functions that relate these indicators to each other, again by River Type. Next, they assign each River Condition Class to a range of ecological indicator values along the y-axis. They obtain the Ecological Flow ranges for each River Condition Class from the x-axis of the flow alteration-ecological response functions. In this example, environmental flows are expressed as a percent alteration from baseline condition, and these percents happen to be the same for high and low flows. Figure 2.15 shows the environmental flow ranges in hydrograph form for a particular River Type and Condition Class. The blue line represents the baseline hydrograph. For the example shown, the Ecological Flow matrix indicates that both x and y = 50% for Condition Class C.

That is the science that informs the policies associated with each river condition. In Michigan (see case study), a broad range of stakeholders participated in the process of defining ecological condition goals. Ultimately, the legislature codified the condition goals, as well as the policy actions associated with each, into law.

It is worth noting that, depending on political circumstances, **quantitative flow-ecology analyses may not be necessary to get to environmental flow criteria**. In the Susquehanna River basin, experts based quantitative flow recommendations primarily on conceptual models. In the Connecticut River basin, flow recommendations are based on a sustainability boundary approach (Richter 2009, Richter et al. 2011). In both cases, however, the flow metrics themselves (as opposed to their values) were rigorously identified as those that best represent flow variability and ecosystem dependence for their respective river types.

2.4.2 Practical Applications

The ability to determine environmental flow needs for every water body in a large region unlocks a broad range of opportunities for implementation. Previously, biological streamflow criteria had to be developed for one river reach at a time – a process far too slow and costly to meet policy needs. Now, with scientifically rigorous, socially acceptable environmental flow criteria in hand, our case studies are integrating ecosystem health into water withdrawal permitting, multi-reservoir re-operation, and water supply planning at the policy level. Elsewhere, ELOHA is being used to define environmental flows for integrated water resource management across large river basins.

A decision-support system (DSS) is almost essential for regionalizing environmental flow management. Water managers and stakeholders need simple tools that make the decision variables and results accessible and hide the complex models, equations, and databases behind them. The following subsections describe some DSSs in the context of our case studies.

Setting water withdrawal standards

Michigan used flow-ecology relationships to inform two major policy decisions regarding water withdrawals. First, the state legislature defined the threshold for “adverse resource impact,” culminating a science-driven stakeholder process. Second, condition classes were reframed in terms of ecological risk levels, and water withdrawal permitting policies were designed to address each risk level. These policies were then incorporated into an online screening tool for prospective water users to determine which policy would apply to their proposed withdrawal. The Water Withdrawal Assessment process, as it is called, has won three national awards for streamlining government programs, and is very well documented (see Michigan case study for a complete list of references). In Ohio, scientists proposed, and the legislature debated, the threshold below which water withdrawal permits would be required.

Decision support systems for managing water withdrawals can readily incorporate environmental flow thresholds. For any site, the Massachusetts SYE and Michigan WWAT can calculate the streamflow depletion that would result from a proposed new withdrawal, combined with the cumulative impacts of all upstream withdrawals and return flows, and compare it to environmental flow targets to determine the availability of water for additional withdrawals. This type of DSS also can support integrated water resource planning, as described below.

Managing reservoir releases

Dams are designed, built, and operated to achieve specific objectives, including water supply, hydropower, recreation, and flood control. Only very recently has dam design begun to consider downstream ecological health. Therefore, it is critical to work with dam owners and operators from the onset to find opportunities and understand constraints on re-operating existing dams to provide environmental benefits. This rings as true for regional-scale dam management as it does for individual dam re-operations. In both cases described below, dam owners were consulted throughout the process, and decision support tools were designed to answer their specific questions. These tools helped everyone understand and communicate the impacts of different reservoir release rules on achieving dam objectives.

Establishing statewide reservoir operation rules

Through an expert consultative process, an approach has been set up that should define environmental condition goals for all rivers in the State of Connecticut. Extensive negotiations with dam owners and other stakeholders have translated these goals into a set of general dam operating rules that apply to every dam in the state. Setting aside some exemptions and special cases, the rules require:

- Run-of-river operation for dams on rivers with Class 1 (highest) condition goals.
- Release 75% of inflow from dams on rivers with Class 2 condition goals.

Bioperiod-specific release requirements for rivers with Class 3 condition goals. All of these releases are based on estimated natural flow statistics and summer releases are also conditioned on the previous two week streamflow conditions.

With input from dam owners, numerous analyses tested these and earlier renditions of these rules as they evolved over several years. New computer models were designed specifically to evaluate relations between reservoir storage, safe yield, and instream flow (Vogel et al. 2007). These models informed prolonged negotiations over the form and substance of the final reservoir release rules[21], which will result in improved environmental flow releases to 156 river reaches.

Optimizing multi-reservoir operation

The interstate Connecticut River basin has more than 70 large dams, each of which has always been operated independently. The case study describes how federal and state agencies have come together to improve system-wide efficiency and add environmental flow objectives by changing the dams' operating rules. One of the most challenging aspects of the effort has been to constructively involve individual dam owners. Through a series of workshops and one-on-one meetings, the dam owners themselves helped build a decision support system to optimize basin-scale efficiency and provide environmental flows. With the owner of 14 of the largest dams playing a central role in the project, the likelihood of implementing the optimized scenario is high.

It is often the case that high-flow releases prescribed for environmental benefits conflict with downstream land uses. Land acquisitions or flood easements on floodplains may be needed before these environmental flow components can be implemented. In the Connecticut River basin, The Nature Conservancy's floodplain and dam management strategies work in concert to restore the basin's aquatic ecosystems.

[21] http://www.ct.gov/dep/cwp/view.asp?A=2719&Q=434018

Regional water resource planning and integrated water resource management

Traditionally, water resource planning accounts for water supply and demand, hydropower, flood control, and perhaps other economically-driven factors. Only recently have environmental flows begun to be considered. ELOHA gives planners the information they need to integrate environmental flows with other water demands. Doing so at the basin scale creates opportunities for efficiency; for example, the same water that is used for environmental flow upstream can be used for irrigation downstream.

In Colorado (see case study), stakeholders are being asked to determine all future water needs for their basins, to feed into a statewide water resources planning effort. Using ELOHA, scientists created a decision support tool that calculates cumulative streamflow depletion and associates it with ecological risk levels for any location. Color-coded basin maps indicate the degree of ecological risk to which each river segment would be subject under various scenarios, thus helping basin stakeholders understand tradeoffs between water management options.

In this case, the majority of river reaches are already under some degree of stress due to flow alteration, so environmental objectives are geared toward flow restoration. Under Colorado water law, re-allocation of water to the environment is possible, but each re-allocation requires extensive research, relationship-building, and often a lot of money. The decision support system helps target flow restoration to river reaches that would most benefit the basin overall.

In the interstate Middle Potomac River, water managers are using ELOHA to understand how the combined anthropogenic influences of land use change, water withdrawal, and impoundments affect low flows and stream health in small streams and rivers. A basin-scale decision support system is being considered for development to inform each state's future land and water use management to benefit the entire basin. The DSS could factor in future water use, land use, and climate change projections. The environmental flows analysis also may feed into a comprehensive basin-wide water resources plan in the future.

In Colombia's Magdalena River basin, a large, biodiverse basin with enormous development potential, the Ministry of Environment is using an ELOHA approach to determine environmental flow needs. Water Evaluation and Planning (WEAP[22]) software is incorporating the hydrologic foundation and environmental flows into a water management decision support system. This is being integrated with plans for biodiversity conservation and for basin-scale hydropower siting and design. The Nature Conservancy is helping to coordinate this application of integrated water resource management (IWRM).

[22] http://www.weap21.org/index.asp?doc=05&all=1

2.4.3 Recommendations for Minnesota

Development of decision support tools to support integrated land and water use planning and management

In Minnesota, land use, agricultural drainage, agricultural and forestry practices, and urbanization have all factored significantly in altered watershed hydrology and surface water flow regimes, with consequences for aquatic ecosystems. Increasingly, as demand for water resources grows, water appropriations and use also have the potential to impact streamflows and water levels, particularly at low flows. Although the state has a robust policy framework for environmental flow protection, water managers currently lack many of the tools needed to quantify ecosystem flow needs and impacts.

Consistent with ELOHA efforts in other states, we recommend further development of models and decision tools to improve qualitative and quantitative understanding of ecological response to flow and water level alteration. Such models and tools will facilitate the identification of acceptable criteria for assessing flow alteration, as well as the implementation of sustainable water management that protects freshwater ecosystems. Identification and quantification of ecological thresholds and criteria based on flow-ecology response could also support an integrated and proactive approach to watershed protection. The state acknowledges a need for integrated land and water planning tools, as well as a need to design water quality and streamflow standards proactively in an effort to effectively prevent high quality or outstanding resource waters from being degraded in the first place. Based on the high cost of impaired waters and effective TMDL implementation, "keeping healthy waters healthy" by implementing upfront regulatory protections that prevent degradation in the first place offers the most promise of being cost-effective and sustainable in the long run.

We recommend development of a formal work group or steering committee to oversee phased development of ecological criteria to support determination of "unacceptable adverse resource impact" in policy and decisionmaking contexts. **In Phase 1, this work group would oversee technical staff and ensure funding to implement risk-based screening and cumulative water accounting tools in conjunction with online permitting**, building on tools and techniques described in this report and additional consultation with developers of similar tools. Existing mapped areas of concern, as well as a variety of groundwater data, studies and models within the agencies could be incorporated—in conjunction with screening level ecological response thresholds and criteria—into an initial screening tool for water withdrawal applications, using tiered thresholds based on increasing risk to ecological resources and other protected uses. Such an application would not supersede existing site-level ecological assessments where warranted, but rather help to triage permit requests so that staff time could be more efficiently allocated to the highest priority assessments. The current state legislature has expressed significant interest in streamlining permitting processes, and the governor has signed an executive order to that effect. MN DNR has recently received funding from the Clean Water Fund to implement online water appropriations permitting. Until recently, details of the user interface and screens had not been thoroughly discussed, nor how the online permitting application would interface with standard permit review or online risk screening. Based on this report and recent discussions among the established work group, there is recognition that the timeline and amount of funding is currently insufficient to develop a comprehensive risk screening interface.

In Phase 2, building on the hydrologic and flow-ecology foundation developed in Phase I, the state should pursue **improved understanding flow ecology relationships, including expanded understanding of impacts of altered hydrology due to land use and drainage modifications, to support implementation of environmental flow protections in integrated land and water resource management and policy contexts**.

For example, ELOHA-based decision support systems could potentially include alternative land use scenarios in addition to water use information. If the DSS is built from a process-model-based hydrologic foundation, then options can be added to explore sensitivity of water quality, quantity, and timing/availability in response to different land cover scenarios.

Decision tools that can simultaneously assess both water quantity and water quality impacts have the potential to facilitate implementation of more comprehensive local and regional land and water use plans, as well as enable integrated assessment of watershed scale ecosystem services. We are optimistic about the potential to integrate ELOHA efforts with these efforts as a way to make simultaneous progress on multiple water sustainability challenges.

3.0 Summary of Recommended Next Steps for Minnesota

The recommendations below reflect an emerging synthesis of lessons learned and methods gleaned from literature review, case studies, as well as 16 months of meetings, discussions, and workshops focused on developing ecological criteria to support instream flow protection in Minnesota. Workshop and process participants in The Nature Conservancy's Ecological Limits of Hydrologic Alteration (ELOHA) project are listed in Appendix 2. Although these recommendations do not represent a full consensus, they are intended to spark continued discussion and forward movement on development and implementation of expanded tools for sustainable water management and environmental flow protection in Minnesota.

Consistent with ELOHA efforts in other states, we recommend further development of models and decision tools to improve understanding of ecological response to flow and water level alteration and to support flow protection standards. Such models and tools will facilitate the identification of acceptable criteria for assessing flow alteration, as well as the implementation of management and policy that protects freshwater ecosystems. Identification and quantification of ecological thresholds and criteria based on flow-ecology response could also support an integrated and proactive approach to healthy watershed protection. The state acknowledges a need for integrated land and water planning tools, as well as a need to design water quality and streamflow standards proactively in an effort to effectively prevent high quality or outstanding resource waters from being degraded in the first place. Based on the high cost of impaired waters and effective TMDL implementation, "keeping healthy waters healthy" by implementing upfront regulatory protections that prevent degradation in the first place offers the most promise of being cost-effective and sustainable in the long run.

We recommend development of a formal work group or steering committee to oversee phased development of ecological criteria to support land and water management. In the first phase, we recommend Minnesota create **a risk-based screening tool[23] to evaluate water appropriations permit requests based on tiered classes of risk to ecological resources and other protected uses.** A risk-based screening tool is needed to interface with the water appropriations permitting process to streamline and simplify the current process. A risk-based screening tool calculates the degree of risk that any proposed new water withdrawal poses to ecological resources, based on ecological risk zones and thresholds developed via a science-policy process designed by the work group. The tool would expedite issuance of permits where they represent little or no risk to protected uses and long-term water sustainability, freeing up agency technical staff and resources to focus on the most pressing needs. The work group should oversee the process of establishing the appropriate risk thresholds, permit review procedures, and policy response associated with each increasing level of risk. Such an application would not supersede existing site-level ecological assessments where warranted, but rather help to triage permit requests so that staff time could be more efficiently allocated to the highest priority assessments.

Key steps and tasks are outlined below.

[23] also recommended in the 2011 Minnesota Water Sustainability Framework report, p. 33

(1) Develop a hydrologic foundation for assessing hydrologic alteration and ecological response. Quantify "baseline" and "reference" (or "unaltered") flow and hydrologic conditions for the state's full range of aquatic system types as the basis for assessing hydrologic alteration. Use the best available water use data, and work to improve these data – and the hydrologic foundation – over time. Methods and options are described in Section 2.1.5.
    a. Immediately begin working with existing process models where they exist.
    b. Over the next 1-2 years, develop a regression-based model for the rest of the state.

(2) Develop empirical models of ecological response to altered flows in Minnesota. Flow-ecology curves are designed to illustrate how ecological health or condition varies with corresponding measures of flow alteration. They provide tools for representing thresholds and zones of ecological risk, and are useful to the process of establishing and communicating about protective limits. Because Minnesota has such extensive biological datasets, this goal is imminently feasible wherever measures of hydrologic alteration can be estimated or derived, and should be pursued. Initial hypotheses are listed in Appendix 3. Models should also build on the Stream Habitat Program's existing instream flow protection data and methods. Regions where this work could be piloted include the Lake Superior Basin as well as watersheds of the Minnesota, Red, and Mississippi where focused TMDL studies are underway.

(3) Develop a statewide water use and availability accounting model that can track existing and proposed withdrawals in a cumulative framework, i.e. a model that can estimate incremental additional streamflow or wetland water level effects of groundwater and surface water withdrawals, accounting for cumulative existing permitted uses. This model would ideally be developed to interface in real-time with online permitting and ecological risk screening. Some local and regional groundwater flow models and databases have been developed for specific applications. Furthermore, as part of the groundwater management area planning process, DNR Division of Waters has developed methods for estimating gradient changes in aquifers that have the potential to cause interaquifer and groundwater/surface water impacts. We recommend the technical work group or steering committee oversee the development of such a model, beginning with options described in Section 2.4.2, building on these existing models and methods.

(4) Quantify thresholds of ecological risk. The work group should propose a process for defining ecological risk levels associated with key biological metrics developed in the flow-ecology response models. For example, what percent change in fish community structure is considered acceptable? This process should involve both expert scientific opinion/best professional judgment as well as public / stakeholder input. Plans should be made for monitoring, periodic review, and risk level revision as new information becomes available. **To support implementation of online water appropriations permitting as well as future applications, we recommend a phased approach to the identification and quantification of ecological criteria and adverse impact thresholds**.

In summary, we recommend a comprehensive ELOHA effort for Minnesota, addressing both science and policy elements. We see value in a formal interagency commitment to a comprehensive ELOHA process, charged with implementing recommendations, including each of the following components:

- A screening tool that tracks cumulative water withdrawals and associates different zones of risk for increasing levels of scrutiny/oversight to interface with online water appropriations permitting
- Streamflow estimates for ungaged streams to support the analysis and development of flow-ecology relationships (development of distributed hydrographs)
- Flow-ecology curves representing all aquatic ecosystem types in Minnesota to support both statewide risk screening as well as determination of site-based adverse impact thresholds
- Regional estimates of total seasonal ground and surface water availability as measured by increasing risk to aquifer levels, protected water resources, instream flows, and water basin elevations, as well as implications for waste load allocation, projected future uses, and other anticipated needs

Ultimately, development of the hydrologic and flow ecology data and models described above could support development of decision tools designed to explore the impacts of both water AND land use and management on water resources, as well as potential implications of climate change. Such tools would facilitate integration of land and water planning that could fully account for changes in ecosystem services, as recommended in the 2011 Water Sustainability Framework. We are optimistic about the potential to integrate ELOHA efforts with related efforts as a way to make simultaneous progress on Minnesota's water sustainability challenges.

4.0 Case Studies

The case studies described here span a broad range of regional-scale approaches to environmental flows among completed or nearly completed projects. In each case, ELOHA was adapted to meet the needs and practical constraints of the particular situation. The intent of these descriptions is to convey the social and science *processes* that each project undertook, and to provide references for readers to pursue more detailed accounts of scientific methods and models.

Table 4.1 summarizes how each project built a hydrologic foundation, classified river types, related flow alteration to ecological response, and applied (or is applying) the science outcomes to water management policy.

Although we are aware of other applications of the ELOHA framework, the case studies profiled here were selected because of their successful positioning at the intersection between science and policy. In each case, scientists, stakeholders, and decision makers worked together to ensure that the scientific work supported a specific policy need. Consequently, these case studies trace selected ELOHA applications from their initiation to their implementation of environmental flows across large geographic areas.

Table 4.1. Summary of case studies of four states and three interstate river basins that adapted ELOHA to meet their regional environmental flow policy needs.

Case Study	Hydrologic Foundation	River Type Classification	Flow-Ecology Relationships	Application
Michigan	Median August flow, based on multiple linear regression; streamflow depletion model (STRMDPL) estimates groundwater pumping delay.	11 by water temperature, catchment area	Fish community-flow models based on large fish database	Online tool for permitting water withdrawals
Ohio	Mean September flow based on regression	5 by Aquatic Life Use	Fish community-flow curves using quantile regression based on large fish and habitat databases	Determine thresholds for permitting water withdrawals
Massa-chusetts	Daily flow based on duration-curve regression model and water accounting (Sustainable Yield Estimator, SYE)	Not used	Fish community response to August median flow alteration using quantile regression and generalized linear models based on large fish database	Establish instream flow standard for permitting water withdrawals
Colorado	Daily water accounting (Colorado StateMod)	3 by ecoregion	Fish, invertebrates, vegetation, recreation response to various flow metrics using various approaches based on data found in literature	Risk-mapping tool for water use planning
Middle Potomac River basin	Daily flow based on process model (HSPF), channel morphology, flow routing, water accounting, and non-linear ground-water recession in a Watershed Online Object Oriented Meta-Model (WOOOMM)	Preliminary classification by watershed characteristics, followed by selective de-classification and grouping based on flow and bio-metric behaviors in each class.	Benthic invertebrate response to 18 flow metrics using quantile regression based on large invertebrates database	Interstate water use planning; potential water withdrawal permitting in individual states
Susque-hanna River basin	Daily flow from minimally-altered index gages; daily streamflow estimator tool based on duration-curve regression model and water accounting (i.e., SYE) in progress)	5 by watershed size, hydrology, and temperature	Nineteen hypotheses relating various taxa and ecological processes to flow components, based on literature review and expert workshops	Water withdrawal standards and dam operations
Connec-ticut River basin	Daily flow based on duration-curve regression model and dam operations model (SYE)	Not used	Conceptual models of full range of taxa and flow components, based on literature review and expert workshops	Collaborative decision support tool to optimize operations of >60 dams

4.1 Michigan's Water Withdrawal Assessment Process

The Michigan Water Withdrawal Assessment process demonstrates an effective science-policy process with user-friendly decision tools developed to support it. Hamilton and Seelbach (2011), Ruswick et al. (2010) and Steinman et al. (2011) provide detailed overviews of the entire scientific and policy processes.

A series of interstate compacts and Michigan water management laws initially spawned the process. Annex 2001 to the Great Lakes Charter, ratified in 2008 in the Great Lakes Compact, stipulates that signatory states may cause no significant *adverse individual or cumulative impacts* on the quantity and quality of the Waters and Water-Dependent Natural Resources of the Great Lakes Basin. Signatory states further commit to:

- establish programs to manage and regulate new or increased withdrawals;
- implement effective mechanisms for decision making and dispute resolution;
- develop mechanisms by which individual and cumulative impacts of water withdrawals can be assessed; and
- improve the sources and applications of scientific information regarding Waters of the Great Lakes Basin and the impacts of withdrawals from various locations and water sources on the ecosystems.

Michigan's 2006 state water law defined "Adverse Resource Impact" as one that functionally impairs the ability of a stream to support characteristic fish populations. As the top of the food chain, these fish are seen as biological indicators of the overall health of Michigan's rivers and streams. The law also committed the state to create an integrated assessment model to determine the potential for any proposed water withdrawal to adversely impact the state's waters and water-dependent resources.

An Advisory Council composed of industry, advocacy, NGO, agency, and academic stakeholders was convened and given a 1-year timeline, and strong bi-partisan support, to recommend a process to the Michigan legislature to carry out this mandate. The Council developed and operated under Guiding Principles (see box), to which its success is largely attributed. These Principles focused Council members on their common interests, regardless of their other differences. The process recommended by the Council(Michigan Groundwater Conservation Advisory Council 2007) ultimately was adopted into state law (2008 Public Act 189) and carried out as follows. The Michigan Department of Environmental Quality was the primary implementing agency.

Michigan's 30,000 NHD+ (National Hydrography Database Plus) river reaches were grouped into about 6,800 segments believed to have characteristic and relatively homogeneous hydrology, geomorphology, hydraulics, water quality, water temperature, and biological attributes with segment boundaries that distinguish between different fish assemblages neighboring segments (Brenden et al. 2008). Reviews by field scientists further aggregated the number of stream segments to about 5,400 for subsequent analysis.

Michigan Guiding Principles
March 20, 2007

1. Michigan has an abundance of water resources. There is no overall shortage of water in the State. Currently, water withdrawals in Michigan do not present a crisis.
2. Not all water withdrawals are alike, and have differing levels and types of impacts. Certain water sources can support a large amount of withdrawal without harm to other users or to the ecosystem. Other water sources are more vulnerable to large withdrawals.
3. Some areas of the state have been identified as sensitive to groundwater withdrawals. Current and future withdrawals in these areas require a higher degree of monitoring, scientific research, and understanding.
4. Water is a valuable asset, and if used efficiently, can provide the basis of a strong economy and high quality of life in Michigan.
5. Ground and surface water are strongly interrelated and cannot be viewed as separate and distinct.
6. In order to protect basic ecological function, adequate stream base flow must be maintained.
7. Water use by type of user or by purpose of use is not prioritized.
8. The amount of water withdrawn from a hydrologic system must be sustainable. Water resource sustainability involves the use of scientific analysis to balance the economic, social and environmental demands placed on the resource to ensure that the needs of current and future generations are not compromised by current usage.
9. Indicators of sustainability are important to assessing Michigan's water use.
10. The accuracy and effectiveness of water management is an evolutionary, long-term process that must be continually enhanced with scientific information. Additional monitoring of stream flows, water levels, aquatic ecosystems, and related mapping and analysis is essential to protecting water resources.
11. Any water management process must be consistent with applicable statutory and common law in Michigan, neither abrogating nor expanding the law absent specific legislative action.
12. Consistency of regulation and predictability between state and local units of government are essential to managing the resource.
13. Education is critical for all water users, private and public, to understand their responsibilities for water conservation and efficient use.
14. Local, voluntary problem-solving approaches for resolving water use disputes and withdrawal impacts are the desirable starting point for conflict resolution. Michigan has a role in disputes involving impacts on environmentally sensitive areas. Legal action by any party should be seen as the last option.
15. Withdrawals presenting the greatest risk of causing an adverse impact to natural resources should be the primary focus of a water management process.
16. Information gathered and provided for the purpose of preliminary evaluation of water withdrawal projects must be simple and understandable in the most accurate and represented manner possible.
17. Mitigation of adverse resource impacts is a reasonable alternative for new and expanding water withdrawals where deemed appropriate.
18. Conservation of water resources includes the efficient use and protection of quality.
19. Preliminary evaluation of potential adverse resource impacts on fish populations and other existing water users caused by new water withdrawal must have value to new and existing water users, is important prior to significant economic investment and is critical to determining the need for further analysis.
20. The goals of a water use assessment tool are to provide a better understanding of withdrawal impacts, to minimize water use conflicts, to facilitate water planning among stakeholders, and to assess long-term

Michigan's hydrologic foundation is a database of the median daily flow for the month of lowest summer flow (typically August) for each stream segment. This can be thought of as the typical low flow during the relatively dry summer months. This "Index Flow" was chosen because it represents the most ecologically stressful period of the year. The amount of water that can be withdrawn is expressed as a percent of Index Flow, as suggested by Richter (2009), rather than as a minimum flow. Multiple linear regression using landscape and climate characteristics (aquifer transmissivity, forest cover, average annual precipitation, and soil permeability) was used to estimate the Index Flow for all ungaged stream segments (Hamilton et al. 2008). A safety factor was added to ensure that estimated flow exceeds actual flow only 10% of the time, acknowledging model uncertainty and further protecting rivers from Adverse Resource Impacts due to excessive withdrawals.

During the summer low flow period, groundwater discharge into Michigan's rivers provides most of their flow, and regulates their temperature and dissolved oxygen levels. Therefore, in Michigan, groundwater discharge plays a significant role in determining fish species assemblage. Groundwater withdrawals by pumping wells reduce natural groundwater discharge to rivers. To account for groundwater withdrawals, a computer model estimates streamflow depletion from the nearest stream segments for any proposed withdrawal based on well location, depth, aquifer and riverbed characteristics, and the timing and quantity of withdrawal (Reeves 2008, Reeves et al. 2009).

Michigan's stream segments were classified according to catchment size (streams, small rivers, large rivers) and thermal regime (cold, cold transitional, warm transitional and warm), the dominant variables previously shown to influence fish assemblages in Michigan (Lyons et al. 2009, Wehrly et al. 2003, Zorn et al. 2009). This classification yielded 11 river types[24] (Brenden et al. 2008, Seelbach et al. 2006), which were mapped onto the Michigan NHD+ stream segment data layer.

For each of the 11 river types, Zorn et al. (2009) developed fish response curves that relate population and density changes in characteristic and thriving fish communities to percentage reductions in Index Flow (figure 1). The curves are modeled, based on a representative subset of samples collected from about 1,700 locations over 30 years (about one sample per year per site from about 20 sites per river type) and housed in three databases. Curves for thriving species (those expected to be especially abundant) can be considered "early warning flags" of Adverse Resource Impact, which the legislature

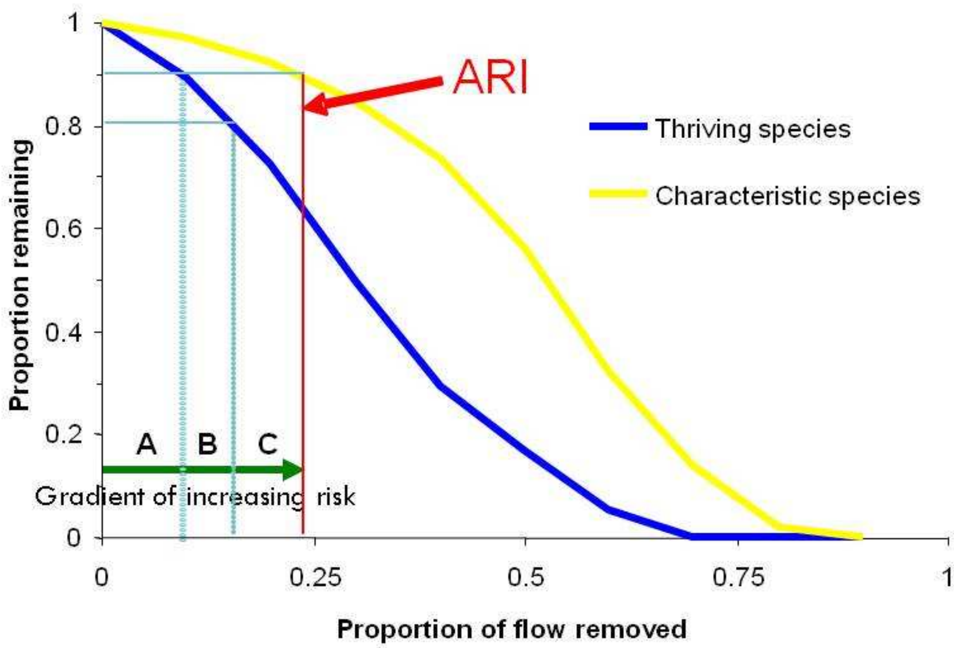


Figure 1. Typical fish-response curves. ARI indicates Adverse Resource Impact, defined in this figure as a 90% of characteristic fish species remaining. Light lines indicate thresholds between water management zones associated with different degrees of ecological change. A = issue permit, B = notify local water users, C = form a water user committee.

[24] The final Michigan classification also resembles the Index of Biotic Integrity (IBI) classification currently under development by the Minnesota Pollution Control Agency for use in state biological assessment and monitoring.

defined in terms of characteristic species (expected to be more abundant than the state mean abundance). Michigan's ecological response curves are unique because they essentially summarize in a single model the response of the entire fish community to flow alteration in a given river type.

To account for uncertainties in the models, the 2008 Michigan state law created "management zones" representing increasing levels of risk to the environment (figure 1), and prescribed a suite of water management actions for each level. Because the curve for each river type is different, the flow removal associated with a given change in fish assemblage -- and therefore the boundaries between management zones -- differ by river type (figure 2).

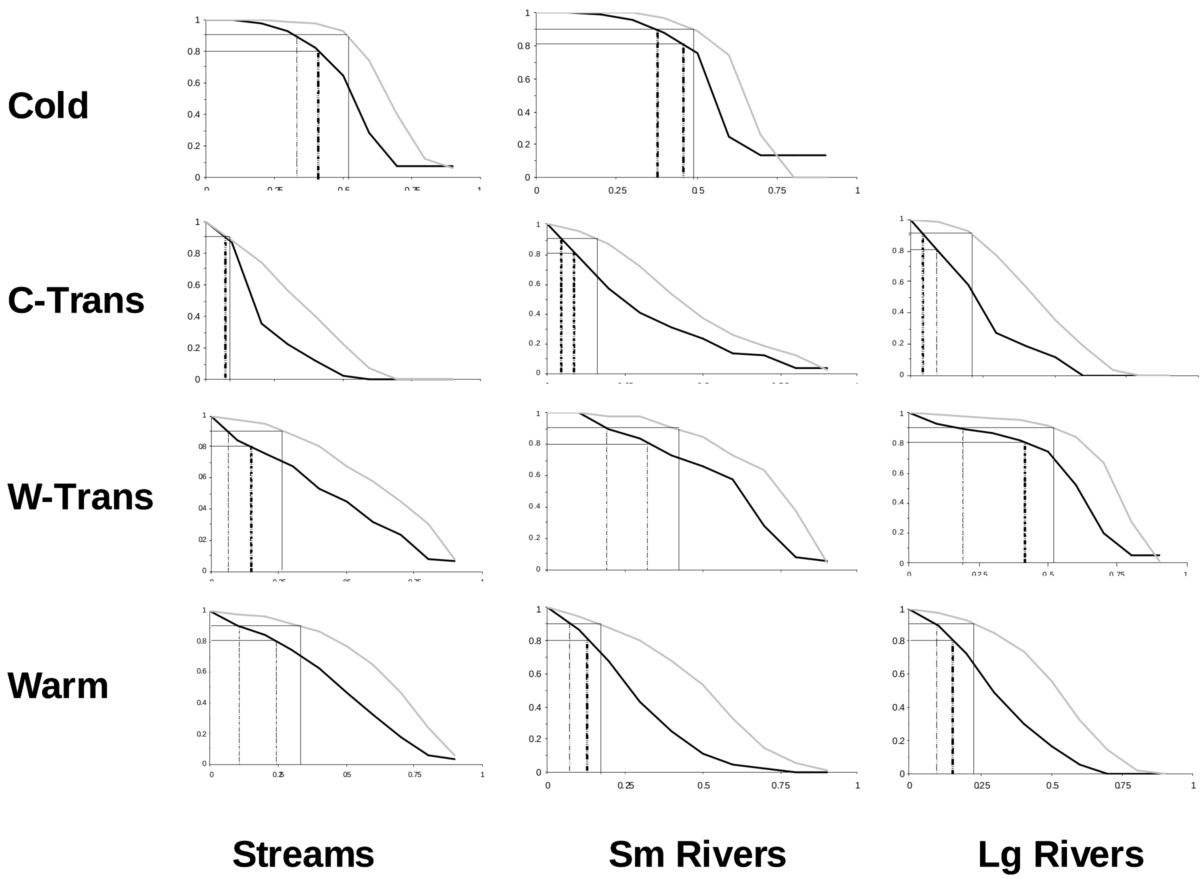


Figure 2. Michigan's fish response curves, showing how each type of river has different curves, and therefore different water withdrawals associated with each management zone. From Zorn et al. (2009).

Prospective water users employ on an online Water Withdrawal Assessment Tool (Michigan Department of Environmental Quality 2009) to determine the level of risk associated with their proposed withdrawals. Users enter the location, timing, quantity, and if relevant, the screen depth of their proposed groundwater or surface water withdrawals. Using the hydrologic foundation, stream types, fish response curves, and groundwater model, the WWAT calculates flow depletion of the nearest stream segment during summer low flow due to the proposed withdrawal, added to the cumulative withdrawals from upstream segments. Using the fish curves, the WWAT associates that depletion with its risk level for that type of river. If the risk level is low, then the withdrawal permit is approved online with no further analysis. If the risk level is high, meaning the withdrawal would likely cause an Adverse Resource Impact, then site-specific review by Department of Environmental Quality staff is required, using local flow and fish data and expert opinion instead of the less-accurate statewide model. After site review, the permit may be issued, issued with modifications, or rejected.

Outcomes of the process are:

- Permitting is expedited when environmental risk is low.
- Government staff time focuses on withdrawals that pose the most risk, and those that are most highly valued by society (because anyone can request a site review).
- Future water withdrawals will likely be taken from least-sensitive rivers.

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4.2 Ohio thresholds for ecological flow protection

This case study demonstrates (1) the integration of flow-ecology relationships -- and, ultimately, streamflow protection standards -- with existing water quality standards using a tiered Aquatic Life Use (ALU) approach and (2) the development of flow-ecology response curves relating fish species assemblage to flow reduction in late summer based on statistical analysis of an extensive biological database.

Ohio's development of ecological flow protection standards stems from its commitment to comply with the Great Lakes Compact (see Michigan case study). It is a work in progress. The process outlined below was carried out independently by a non-profit research institute (Midwest Biodiversity Institute) with funding and guidance from The Nature Conservancy. A coalition of environmental groups is using the results to secure ecologically-based low flow protection in the ongoing Ohio Great Lakes Compact Implementation process. Additionally, the Ohio Department of Natural Resources has expressed interest in using the flow-ecology response curves developed during this process to evaluate proposed water withdrawals once a regulatory program is in place.

Several factors shaped the process. The allotted time of one year constrained the initial focus to *low flows,* which represent the most ecologically stressful period of the year. Given the time limit, water users' resistance to new regulatory programs, and the highly altered condition of Ohio's streams, the approach was designed to mesh with the Ohio Environmental Protection Agency's *existing* ecological monitoring and tiered ALU framework. Because the Compact drove the process, initially it was developed only for the Ohio streams that are tributary to the Great Lakes.

The hydrologic foundation is a database of mean daily flow for the month of lowest flow (historically September) over a 20-year period, housed in the U.S. Geological Survey StreamStats system (Koltun et al. 2006). Flow regression modeling (Koltun and Whitehead 2002) was used to estimate this flow statistic for ungaged sites. A total of 3,070 unregulated sites for which ecological data exist were then paired with mean September flows. Because pre-development flows are not determined, the hydrologic foundation implicitly sets the current condition as the baseline. However, the number and distribution of data points represent large gradients of hydrologic alteration such that pre-development conditions could be inferred from flow-ecology relationships (figure 1). Groundwater-surface water interactions were not considered during this initial phase.

To classify river types, researchers considered base flow index, upstream catchment size, biotic assemblage, water quality, temperature, and other ecoregional characteristics. They found that none of these could better explain ecological response than does the existing ALU classification (table 1). Furthermore, adopting an existing classification avoids creating a new regulatory framework. The Ohio ALU classification stratifies on the basis of ecological condition, existing flow alteration, and thermal regime (coldwater or warmwater habitat).

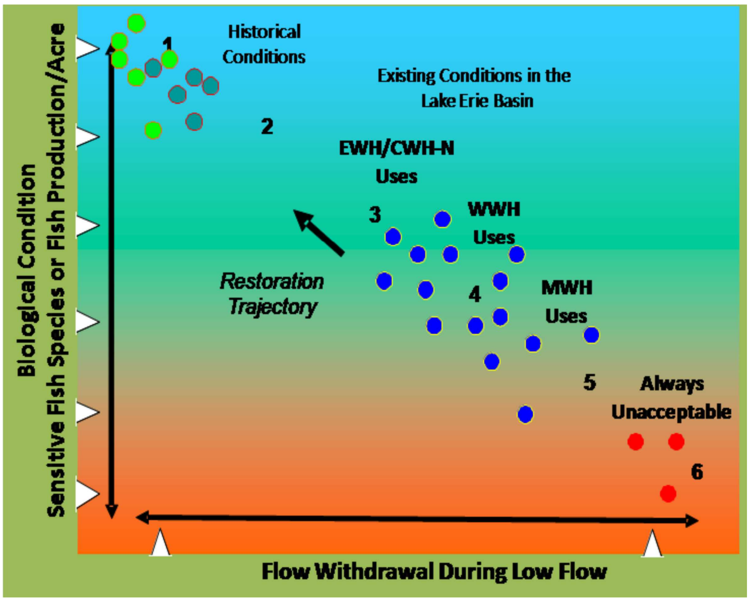

Figure 1. Conceptual flow-ecology graph showing the inference of historical, pre-development conditions from current-condition data by plotting data for all river types on one graph. See text for river type abbreviations (EWH, CWH-N, WWH, MWH).

Table 1. Ohio's Aquatic Life Use Classes (Ohio EPA 2004).

A	Description	% of Waters
Warmwater Habitat (WWH)	Principal restoration target for most of Ohio's rivers and streams in Ohio, with "typical" warmwater species assemblages.	77.4
Exceptional Warmwater Habitat (EWH)	Protection goal for Ohio's best water resources, which support "unusual and exceptional" assemblages of aquatic organisms, with a high diversity of species, particularly those which are highly intolerant and/or rare, threatened, endangered, or special status (i.e., declining species).	10.2
Modified Warmwater Habitat (MWH)	Streams and rivers that have been subjected to extensive, maintained, and essentially permanent hydromodifications such that the biocriteria for the WWH use are not attainable, with species that tolerate low dissolved oxygen, siltation, nutrient enrichment, and poor quality habitat.	3.8
Limited Resource Water (LRW)	Small streams (usually less than 3 mi^2 drainage area) and other water courses that have been irretrievably altered to the extent that no appreciable assemblage of aquatic life can be supported; includes small streams in extensively urbanized areas, those that lie in watersheds with extensive drainage modifications, those that completely lack water on a recurring annual basis (i.e., true ephemeral streams), and other irretrievably altered waterways.	6.2
Coldwater Habitat (CWH-N and CWH-F)	Waters that support assemblages of native cold water organisms (CWH-N) and/or those that are stocked with salmonids with the intent of providing a put-and-take fishery on a year-round basis (CWH-F).	2.4

Ohio's flow-ecology curves (figure 2) relate number of sensitive fish species or species richness (depending on catchment size) to mean daily flow in September for each river type. These relationships are derived from fish-habitat and habitat-flow relationships, and are based on the premise that water withdrawals reduce available habitat, which reduces the number of sensitive fish species that a stream can support.

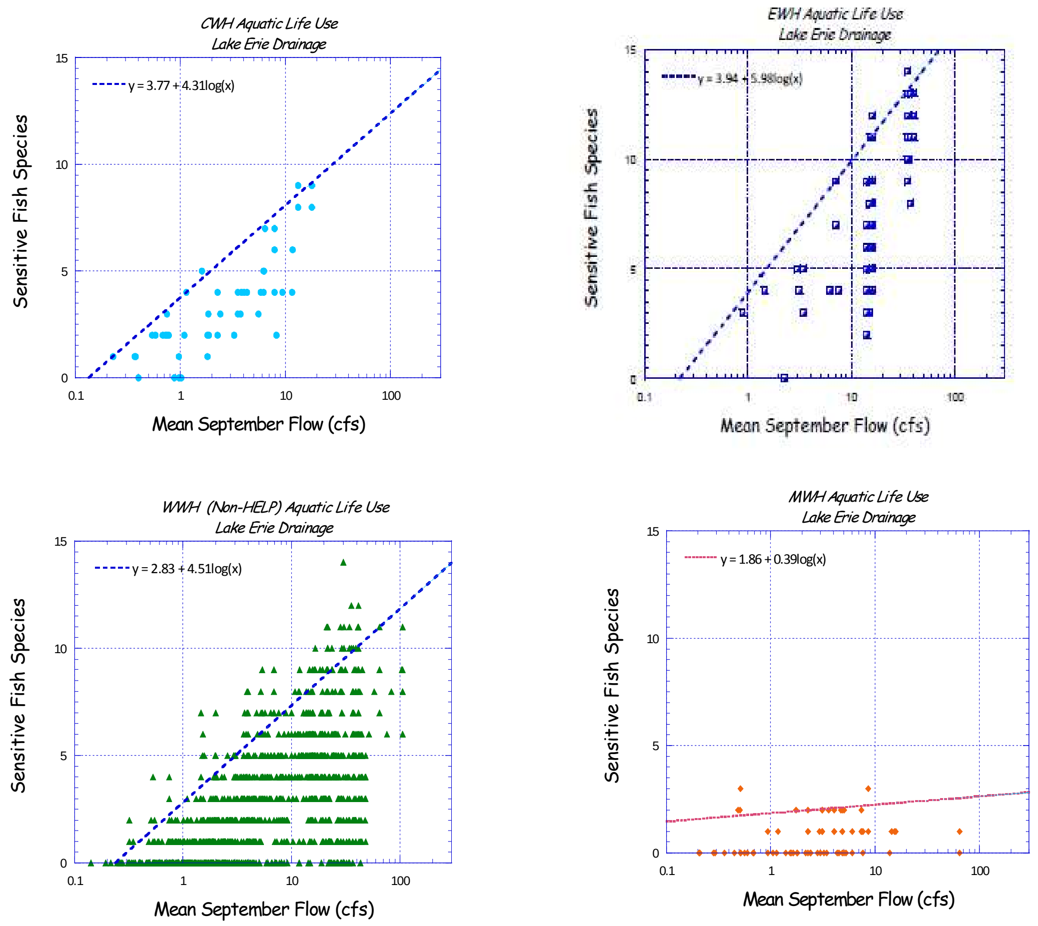

Figure 2. Flow-ecology relationships for Ohio's four river types. See text for river type abbreviations (EWH, CWH-N, WWH, MWH).

Existing fish and habitat databases support this hypothesis and were used to develop flow-sensitive species curves. Ohio's fish database contains information on pollution-sensitive fish which, according to expert opinion and literature review, are also sensitive to flow alteration. Ohio's Quantitative Habitat Evaluation Index (QHEI) is a measure of habitat availability at biological sampling locations where sensitive species data are collected. Quantile regression (Cade and Noon 2003, Konrad et al. 2008) at the 95th percentile quantified the flow-ecology relationships, using USGS Blossom software.

Currently, the Ohio Department of Natural Resources registers but does not otherwise regulate large consumptive withdrawals. To comply with the Great Lakes Compact, withdrawals will need to be managed actively to prevent “adverse resource impact.” Midwest Biodiversity Institute and subsequently a coalition of environmental groups proposed defining adverse impact in terms of percent loss of sensitive fish species or species richness, depending on catchment size and stream segment classes (table 2). These figures initially were received well by representatives of regulated industries and the Ohio Chamber of Commerce during a stakeholder small workgroup process. The flow-ecology curves relate these percentages to the cumulative amount of flow depletion that would trigger agency review before registering a new water use.

Table 2. Proposed thresholds for “adverse resource impact” in Ohio, expressed as percent loss of sensitive fish species (for catchments <300 mi^2) and species richness (for catchments >300 mi^2). River types are defined in Table 1. Water withdrawals that cause a stream to exceed this threshold would be subject to agency review.

River Type	Threshold for agency review, in percent loss of sensitive fish species and species richness	
	Catchment area < 300 $miles^2$	Catchment area > 300 $miles^2$
Warmwater Habitat (WWH)	10	5
Exceptional Warmwater Habitat (EWH)	2	2
Modified Warmwater Habitat (MWH)	50	10
Coldwater Habitat (CWH-N and CWH-F)	2	2

To calculate cumulative flow depletion, the Ohio Department of Natural Resources, Midwest Biodiversity and The Nature Conservancy recommend modifying the existing Ohio Stream Withdrawal Evaluation Tool (OSWET). Currently, OSWET calculates streamflow depletion due to an individual withdrawal. In the future, OSWET could also calculate cumulative depletion during September due to all local and upstream withdrawals.

Overall, the proposed Ohio thresholds are not highly protective. Because the process developed for Ohio uses existing river condition to classify river types and uses current conditions as the baseline, it “grandfathers in” existing water uses and sets no restoration goals. Moreover, future withdrawals that cause thresholds to be exceeded still could be approved after agency review. Even so, regulated interests rejected the proposal and sought legislation to exempt almost all withdrawals from regulation. Although the legislature passed the industry-backed bill in spring 2011, Ohio’s Governor vetoed it due to technical and legal shortcomings. At present, it is not clear exactly how the Ohio Department of Natural Resources will use results of this project to comply with the Great Lakes Compact.

Acknowledgment

The authors thank John Stark of The Nature Conservancy for describing this project to us and reviewing this case study.

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4.3 Massachusetts Sustainable Water Management Initiative

The Massachusetts Sustainable Water Management Initiative demonstrates the use of (1) a duration-curve regression approach to build a hydrologic foundation, (2) bioperiods as a temporal basis for setting flow criteria, (3) quantitative flow-ecology response curves to inform decision-making, and (4) a management framework that associates implementation actions with different condition goals. It is a work in progress.

Responding to water quality and quantity concerns, the 1987 Massachusetts Water Management Act (WMA) established a water withdrawal permitting system. Twenty years later, implementation of the Act was falling short of its objectives, as evidenced by persistent impacts from stream depletion. Consequently, environmental groups appealed permit decisions for not adequately protecting rivers and streams from excessive water withdrawals, and filed legislation requiring the development of environmental flow protection standards. In 2009, responding to continuing controversy, the State[25] launched the Massachusetts Sustainable Water Management Initiative (SWMI). Both the social and scientific processes of SWMI closely follow the ELOHA framework.

An Advisory Committee representing water suppliers, conservationists, agriculture, state agencies, and other stakeholders was established to develop a comprehensive approach to water management, including water withdrawals. A Technical Committee representing the same stakeholders and state and federal agencies was formed to help inform and scientifically ground this effort. To date, these committees have met formally more than 100 times over the course of 2 years to design and carry out the criteria development process.

The hydrologic foundation is the Massachusetts Sustainable-Yield Estimator (SYE), a statewide, interactive decision-support tool developed by the U.S. Geological Survey (USGS) (Archfield et al. 2010). SYE first estimates the 1960-2004 series of unregulated (baseline), daily streamflow at ungaged sites using a duration-curve regression approach (figure 1). Quantile regression is used to estimate the flow-duration curve for the ungaged site, based on climate and physical parameters. A systematically selected reference gage is then used to transform the flow-duration curve into a daily time series of flows. Earlier, Armstrong et al. (2004) had analyzed streamflow and fish populations at the reference sites to confirm that they were minimally altered.

Current-condition flows are calculated by adding and subtracting water withdrawal and return flow data provided by the Massachusetts Department of Environmental Protection (DEP) for the period 2000-2004. Water use data that are reported monthly are divided evenly by the number of days in the month; however, the user has the option of overriding this with more detailed information. Stream depletion due to groundwater withdrawals is assumed to occur instantaneously with the withdrawal. Alternately, STRMDEPL (Barlow 2000) may be used to distribute the depletion over time, given well locations and basic aquifer characteristics. Additional, detailed dam operation data are needed to

[25] Massachusetts Department of Conservation and Recreation (MDCR), Massachusetts Department of Environmental Protection (MDEP), and the Massachusetts Department of Fish and Game (MDFG)

simulate reservoir storage (Archfield et al. 2010). Weiskel et al. (2010) added several enhancements to SYE, including distributed flow models to simulate groundwater discharge into rivers in certain parts of the state.

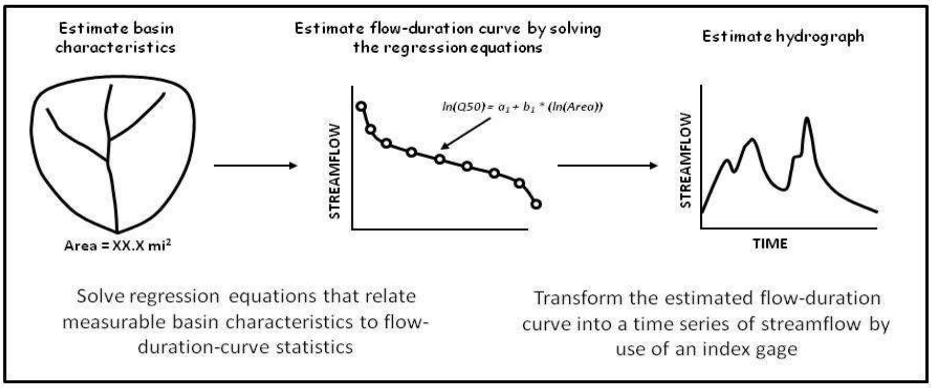

Figure 1. Duration-curve regression approach used to estimate baseline daily flow series in the Massachusetts Sustainable Yield Estimator (SYE).

The Technical Committee of stakeholders, guided by state resource agencies, identified four seasonal *bioperiods* necessary to support life histories and biological needs of resident fish communities and fluvial-dependent diadromous species: overwintering and salmonid egg development, spring flooding, rearing and growth, and fall salmonid spawning. The Technical Committee confirmed that January, April, August, and October adequately represent the four bioperiods.

Weiskel et al. (2010) delineated 1,395 nested, topographically defined sub-basins draining to National Hydrography Database (NHD) stream reaches. For each sub-basin, they calculated the baseline and current-condition median flow during January, April, August, and October, using daily flow data generated by the SYE. They then calculated flow alteration by comparing baseline to current-condition data. Armstrong et al. (2008) had previously confirmed the non-redundancy of the median monthly flow metrics, based on principle-components analysis. In addition, they calculated impervious surface for each subbasin and performed the subsequent modeling and regressions to identify the relative contribution of impervious surfaces and flow alteration to changes in fluvial fish communities.

Flow-ecology relations were evaluated by Armstrong et al. (2010) using data from 756 fish-sampling sites in the Massachusetts Division of Fisheries and Wildlife fish-community database. Literature review guided the selection of a set of flow-sensitive fish metrics, including two fish-community metrics (fluvial-fish relative abundance and fluvial-fish species richness) and five indicator species metrics (relative abundance of brook trout, blacknose dace, fallfish, white sucker, and redfin pickerel). Using quantile regression (Cade and Richards 2005) and generalized linear models, they quantified fish response to August median flow alteration (figure 2), water-use intensity, and withdrawal and return-flow fractions. Median daily August flows were estimated using weighted-least-squares regression with basin characteristics (Ries and Friesz 2000). Although other hydrologic statistics were tested, August median was used because it had the strongest association with fish response.

Adopting the biological condition gradient concept (Davies and Jackson 2006), the Massachusetts Department of Fish and Game (DFG) assigned ranges of fish-metric values to five condition classes, or Biological Categories. These condition classes reflect the combined effects of withdrawals, reservoir operations, and impervious surfaces. The flow-ecology curves associated each Biological Category with a range of median August flow alteration (Table 1, left). The DFG then proposed seasonal streamflow criteria for each bioperiod, represented by the four months (Table 1, right), and asked for Technical Committee review and concurrence. Maps of existing flow alteration (Weiskel et al. 2010) informed the review, which led to some modifications.

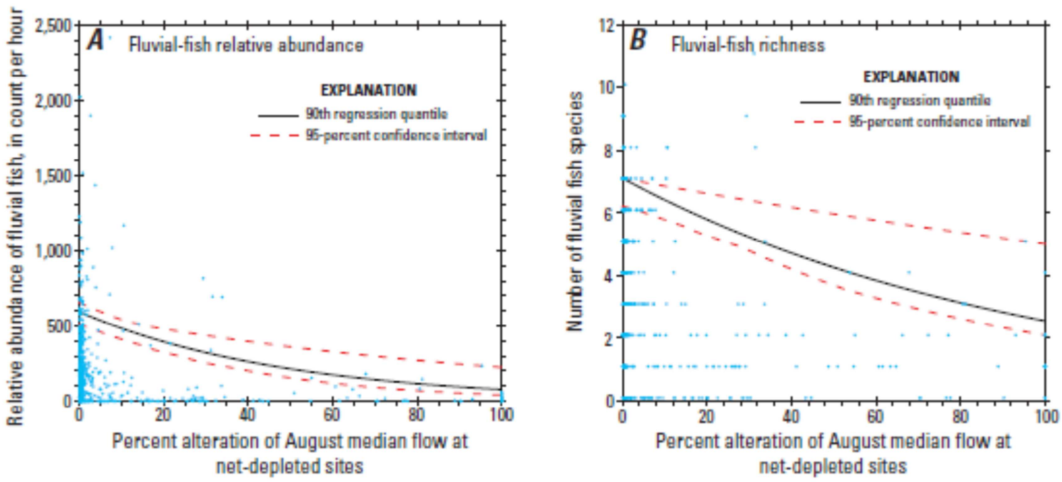

Figure 2. Examples of flow-ecology curves for Massachusetts showing relationships between fish-community metrics and August flow depletion. From Armstrong et al. (2010).

Currently, focus groups are negotiating an implementation process, so the framework remains under development. The process will require different action levels to minimize or mitigate impacts, based on the amount of water requested and the condition class of the water source. For withdrawals from streams that are highly impacted by flow depletions, applicants will need to minimize existing impacts. For high-quality streams, defined as either those with documented cold water fisheries or those in Biological Categories 1, 2 or 3, additional review and minimization of impacts will be required. The framework also is designed to prevent stream degradation from an existing to a lower Biological Category.

ACKNOWLEDGMENTS

The authors thank Alison Bowden, Colin Apse, and Mark P. Smith of The Nature Conservancy for describing this project to us and reviewing this case study. Thanks also to the participants in the Massachusetts Sustainable Water Management Initiative process, including Massachusetts resource state agencies, and the U.S. Geological Survey.

Table 1. Draft streamflow criteria by bioperiod (month) and ecological condition goal (Biological Category). Flow-ecology curves relating fluvial fish communities to percent flow alteration in August informed the development of these proposed criteria.

Fluvial Fish Relative Abundance	
Biological Category (BC)	August Percent Alteration
1	< 5%
2	< 15%
3	< 35%
4	< 65%
5	> 65%

	% allowable alteration of estimated unimpacted median flow*			
Flow Level (FL)	AUG	OCT	JAN	APR
1	< 5%	< 5%	< 5%	< 5%
2	< 15%	< 5%	< 5%	< 5%
3	< 35%	< 15%	< 15%	< 15%
4	Feasible mitigation and improvement			
5				

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4.4 Colorado Watershed Flow Evaluation Tool

The Colorado ELOHA project demonstrates (1) using flexible approaches to develop flow-ecology curves based on studies reported in the literature and (2) using flow-ecology curves to inform basin-scale water-resource planning. Sanderson et al (2011) provide a useful overview of the entire project.

In 2005, the Colorado Legislature passed the Colorado Water for the 21st Century Act, launching a statewide water planning effort. The Act mandated that representatives of cities, farms, and other water users join conservation and recreation interests at “basin roundtables” to assess future water supply needs for their watersheds. The results of these assessments are framing discussions about future water allocations. The assessments must address both consumptive and nonconsumptive (recreation and environmental flows) water needs.

The Colorado Water Conservation Board funded this 1-year, approximately $200,000 project to help two pilot basin roundtables -- the Roaring Fork watershed in western Colorado and the Fountain Creek watershed in eastern Colorado -- understand tradeoffs between consumptive and nonconsumptive water uses. In 2008, the consulting firm Camp Dresser McKee (CDM) managed scientists from Colorado State University and The Nature Conservancy, engineers from CDM, staff from the Colorado Water Conservation Board, and representatives of the Colorado Basin Roundtable to apply ELOHA to estimate flow-related ecological risk at the basin scale. The Watershed Flow Evaluation Tool (WFET) displays the results under various water management scenarios.

A hydrologic foundation existed for the Roaring Fork watershed before this project began. The State of Colorado’s water supply model, StateMod (CDWR and CWCB 2009), is a monthly water accounting program that begins with gaged streamflow data under current conditions. Reservoir storage changes, water diversions, and return flows are added or subtracted to obtain baseline flows. Simple water accounting, weighted by drainage area and precipitation, is then used to calculate baseline flows at ungaged sites. Monthly flows are disaggregated into daily flows using one of several techniques, most commonly through the use of pattern gages. Baseline flows at ungaged sites are calculated by apportioning flows across watersheds according to their drainage areas and mean annual precipitation rates. Current-condition flows at ungaged sites are calculated by adding or subtracting reservoir storage change, water diversions, and return flows to the baseline flows. Groundwater withdrawals and return flows are similarly added and subtracted from streamflow, allowing for an aquifer-dependent time delay. Several options are available for distributing monthly water use data to daily time steps. StateMod has not yet been calibrated for the Fountain Creek watershed.

Indicators of Hydrologic Alteration (IHA) software (The Nature Conservancy 2009) used output from StateMod to calculate changes in five ecologically relevant flow statistics: mean annual flow, mean August flow, mean September flow, mean January flow, and mean annual peak daily flow. Because StateMod was developed for purposes other than ecological assessments, engineers analyzed its assumptions and output to determine that these particular IHA metrics could be calculated with sufficient accuracy.

River type classification was simple. As an informal framework for organizing information about flow and ecology, rivers were designated as Interior West, Rocky Mountains, or Great Plains, according to the Level-1 ecoregion (CEC 1997) in which they are located. Geomorphologic subclassification limited the application of resulting flow-ecology relationships to appropriate river reaches. A Colorado State University Ph.D. student developed relationships between streamflow and warmwater and coldwater fish, riparian vegetation, invertebrates, and white-water rafting and kayaking, based on his review of 108 studies in the literature. Quantitative approaches varied, depending on the form and abundance of relevant information, and ranged from statistical analysis using quantile regression (Cade and Noon 2003) to categorical relationships and expert consultation (Camp Dressser & McKee Inc. et al. 2009). Figure 1 shows some examples.

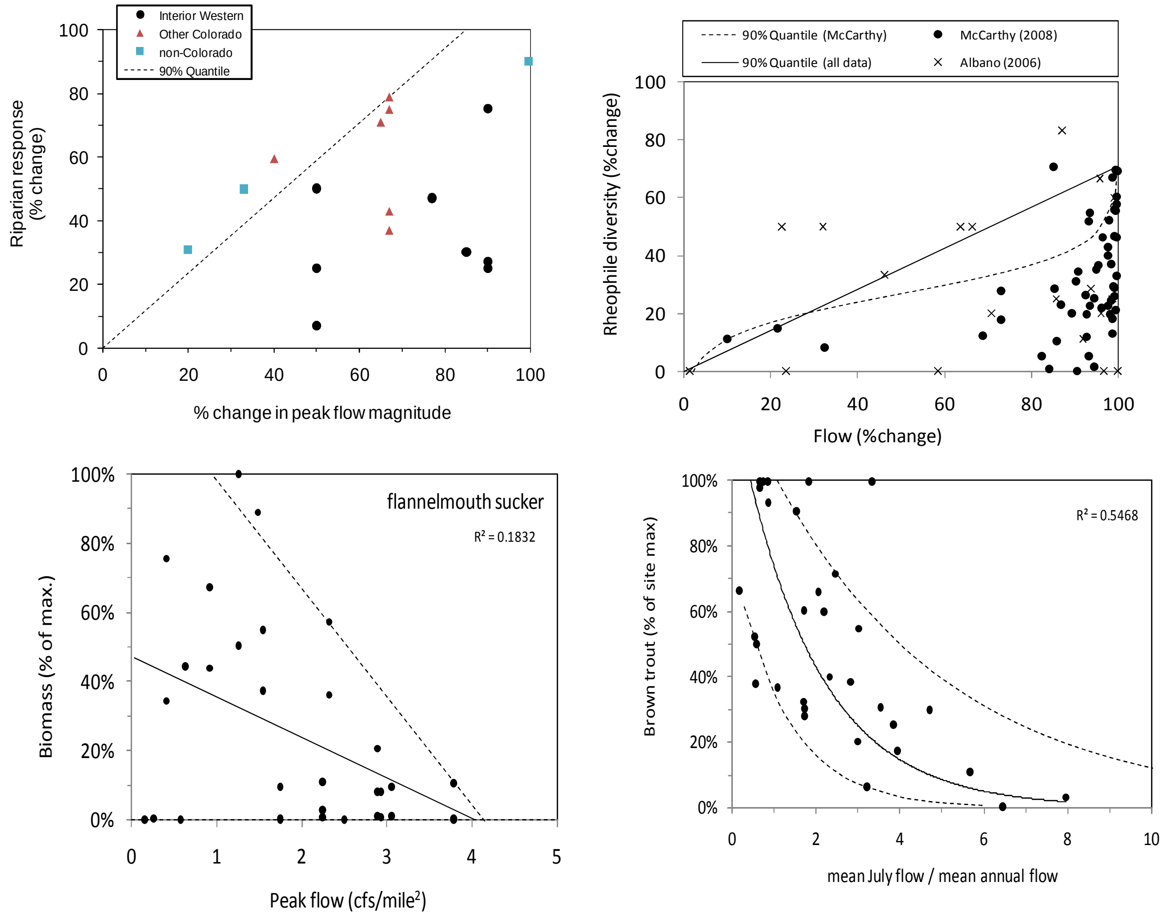

Figure 1. Selected flow-ecology relationships for Colorado (Camp Dressser & McKee Inc. et al. 2009). Upper left: Response of riparian plant communities to peak flow alteration. Upper right: Response of Rocky Mountain invertebrate species diversity to flow depletion on the day of sampling, using data from two studies. Lower left: Response of flannelmouth sucker, a warmwater fish, to peak flow. Flow data were divided by watershed area to compare different sized rivers. Lower right: Response of brown trout recruitment success to mean July flow. Regression lines indicate percentiles advised by expert committee.

The technical team then identified 3-5 risk classes for each ecological attribute, based on expert opinion if the flow-ecology relationships were not already categorical. Using the flow-ecology relationships, they determined the range of flow values associated with each ecological risk class. Then, using the StateMod and IHA output, they associated each river segment with its level of ecologic risk. The resulting map (figure 2) indicates the risk that flow alteration has compromised ecological values for every river reach within a basin. The WFET allows basin roundtables to similarly analyze the spatial distribution of ecological risk associated with different potential *future* water use scenarios.

Figure 2. Watershed Flow Evaluation Tool output detail, showing level of flow-related ecological risk for each river reach. Risk levels: red = high, orange = moderate, yellow = minimal, green = low. Blue = not modelled (no flow data).

As mentioned earlier, unlike the Roaring Fork watershed, the Fountain Creek watershed lacks streamflow data for ungaged sites where biological data have been collected. The researchers found that without a hydrologic foundation, they were unable to formulate flow-ecology relationships with sufficient certainty to warrant the development of a WFET for that watershed.

Following the successful deployment of the Roaring Fork WFET, the Basin Roundtable chose to expand the WFET to the entire mainstem of the Colorado River within Colorado and its tributaries. Stakeholders are now using the results of the WFET to assess where flow restoration may be feasible, to estimate the quantities of flow that may be needed for restoration, to identify areas where additional study is needed, and to identify areas with little flow-related ecological risk where river protection actions are well suited. The WFET is emerging as a valuable tool in the development of a basinwide plan for the protection and restoration of river health.

ACKNOWLEDGMENT

The authors thank John Sanderson of The Nature Conservancy for describing this project to us and reviewing this case study.

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4.5 Middle Potomac River basin environmentally sustainable flows

The Middle Potomac River basin project demonstrates (1) the determination of environmental flow needs for rivers and streams that are generally more impaired by land use change than by withdrawals or impoundments; (2) pro-active engagement of multiple water resource agencies and other stakeholders across jurisdictional boundaries; and (3) a structured, iterative approach for selecting flow and ecology metrics and refining river types to strengthen flow-ecology relationships.

The project began in May 2009 and is slated for completion in spring 2012. Its approximately $1 million ELOHA project budget is funded mainly by the U.S. Army Corps of Engineers (75% Federal cost-share through the Corps' Section 729 Watershed Assessment program) and The Nature Conservancy (25% non-Federal cost-share), with additional support from the National Park Service, the Interstate Commission on the Potomac River Basin (ICPRB), and other basin jurisdiction agencies. Boundaries of the 11,500-mi^2 Middle Potomac project area were determined by Congressional authorization for the Corps' study authority, but the project analyses extended upstream to allow for system connectivity. The project area includes parts of Pennsylvania, Maryland, Virginia, West Virginia, and all of Washington, DC.

ICPRB is the project's technical lead. The Commission was created by interstate compact in 1940, primarily to provide technical support and expertise to the watershed jurisdictions. ICPRB lacks authority to regulate streamflow. Therefore, the project was designed to support efforts of the five watershed jurisdictions to protect and restore environmental flows.

The project team has made special efforts to inform and involve the watershed jurisdictions throughout the project development and analytical process. A seven-part webinar series, technical advisory group meetings, a technical workshop, agency consultative meetings, and a project website (potomacriver.org/sustainableflows) have maintained watershed states' involvement throughout the project, from inception to completion. Through these interactions, stakeholders have reviewed the technical approach, discussed potential policy applications, and considered how to use the flow-ecology relationships to inform water and land use management decisions.

Because the Potomac River basin project area has few large dams and flow is relatively unimpaired by major impoundments, this assessment was not oriented towards changing dam operations. In fact, the analysis is finding that land use change is having a greater impact on the river's hydrologic regime than dams or impoundments. The project goals are to:

- Estimate current and future water withdrawals, given population, land use, and climate change projections;
- Determine impacts of water withdrawals, discharges, impoundments, land use, and climate change on flow;
- Characterize flows needed to support healthy biotic communities in smaller streams and rivers;
- Provide data, information, and analyses to support water and land use planning and decision making at the state level.

A modified version of the site-specific "Savannah" process (Richter et al. 2006) was used to determine flow needs for selected segments of the Potomac River mainstem and selected large tributaries (Cummins et al. 2011), while the regional-scale ELOHA framework was used for smaller tributary streams and wadable rivers. Here we describe only the ELOHA process (Cite final report here).

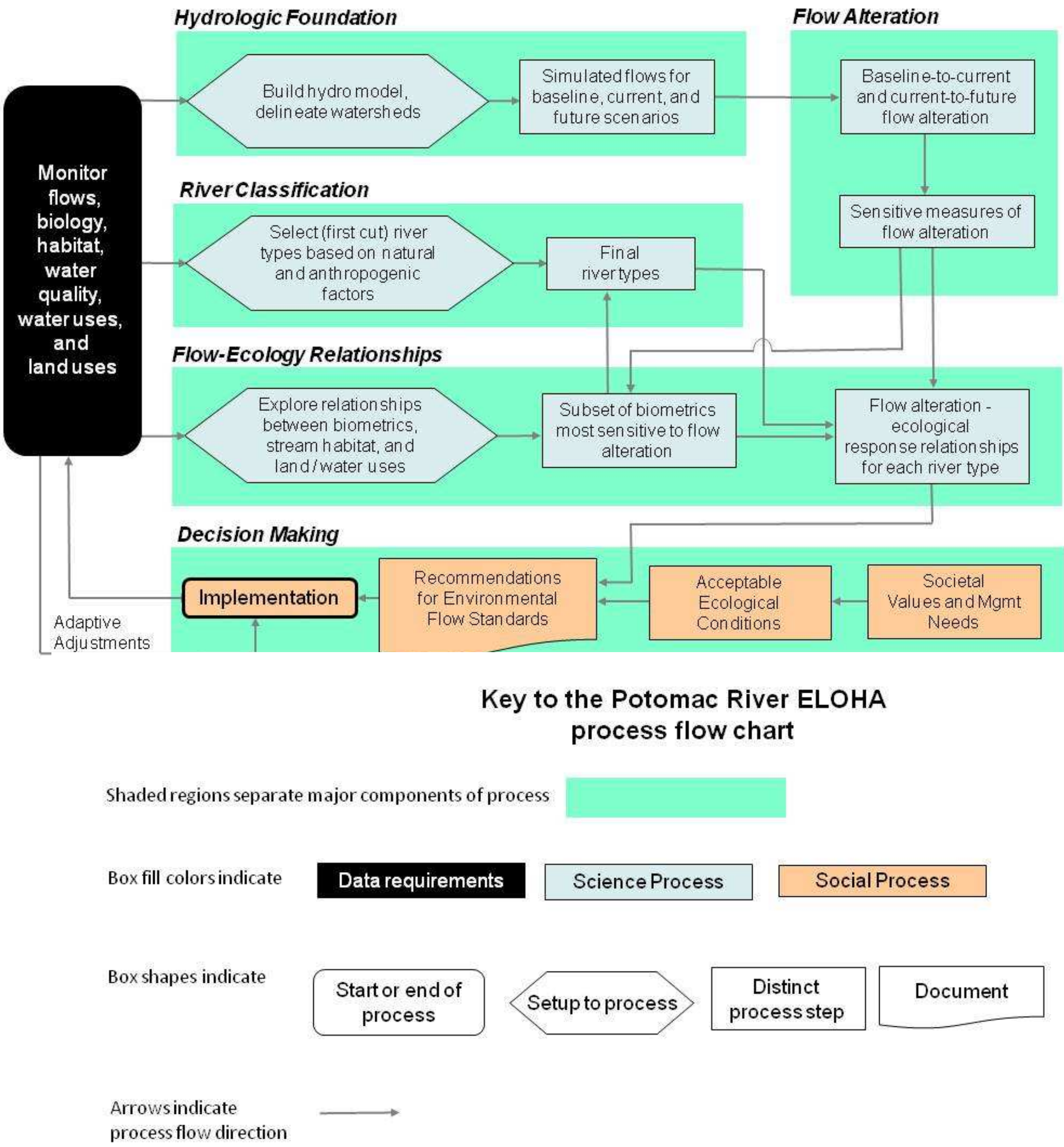

Figure 1 Modified ELOHA framework for the Middle Potomac River basin sustainable flows study.

Figure 1 shows how the project team modified the original ELOHA framework. Of special note is the iterative process of refining river types, flow metrics, and biometrics to strengthen flow-ecology relationships. The project website (potomacriver.org/sustainableflows) documents the process in detail, particularly through the archived webinar series, which describes the project's analytical process.

The hydrologic foundation consists of 21 years of daily flow data at biological monitoring points under seven scenarios -- baseline (or relatively unaltered), current, and five future alternative flow scenarios --

simulated by the Virginia Department of Environmental Quality's decision support system, WOOOMM (Watershed Online Object Oriented Meta-Model).[26] Input to WOOOMM includes edge-of-stream flows generated by the Chesapeake Bay Program's Phase 5.2 HSPF (physical process) model (enhanced to include non-linear groundwater recession and re-segmentation at major impoundments), a U.S. Geological Survey (USGS) channel morphology model, and a channel routing routine. The model was calibrated to measured flow at 56 USGS gages. The 747 subwatersheds in the final model capture 869 biological monitoring sites and representative distributions of bioregions, land cover and catchment areas. Both baseline and current-condition flow series use 1984-2005 climate data.

To identify baseline flow conditions, modelers used a Category and Regression Tree (CART) analysis of 105 gaged watersheds in the Potomac and adjacent Susquehanna River basins. The CART analysis determined thresholds when flows were significantly impacted by anthropogenic land use, withdrawals, discharges, and impoundments. For each anthropogenic factor, thresholds were defined above or below which flows are considered altered. The analysis found that watersheds with greater than or equal to 78% forest cover and less than or equal to 0.35% impervious cover and no impoundments, withdrawals, or discharges have the least altered flows. Therefore, in the modeled baseline scenario, land use in every watershed was adjusted to have at least 78% forest, less than or equal to 0.35% impervious cover, and no withdrawals, impoundments, or discharges.

Current conditions were represented in the models using land use data for 2000, withdrawal and discharge data for 2005, and significant impoundments. Surface-water withdrawal data were obtained from the individual states. Groundwater withdrawals were not modeled due to incomplete data, insufficient understanding of complex groundwater flow systems, and limitations of the hydrologic foundation models. Permitted point-source discharge data were obtained from the Chesapeake Bay Program's discharge database. The Chesapeake Bay model includes four large impoundments in the study area. Twelve smaller impoundments were added to the Middle Potomac project model because they are located near biological monitoring sites and contain significant storage or are used for hydropower production.

Eighteen flow metrics were selected for flow-ecology analysis from 256 metrics initially calculated by Indicators of Hydrologic Alteration (The Nature Conservancy 2009) and Hydrologic Integrity Tool (Henriksen et al. 2006) software (figure2). Analysis of flow alteration reduced the initial set to those that have changed the most from baseline to current conditions and are expected to change the most from current to future conditions. Metrics that correlate strongly with other metrics were then removed. The selected subset of hydrologic metrics represents all parts of the hydrograph (table 1).

Table 1. Subset of flow metrics selected for the Middle Potomac Sustainable Flows Project after screening. Italics indicate metrics exhibiting strong relationship to benthic index of biotic integrity (Chessie BIBI).

Flow Range	**Magnitude**	**Duration**	**Frequency**	**Other**
High	*Mean high flow volume*	*High flow duration*	*High pulse count, High flow frequency, Flood frequency*	Skewness in annual maximum flows
Medium	Median annual flow	*Flood-free season*		*Fall rate,*

[26] http://sifn.bse.vt.edu/sifnwiki/index.php/WOOOMM_Modeling

	volume			*Flashiness*
Low	4-day harmonic mean low, Seasonal Q85, 7Q10	*Low pulse duration, Extreme low flow duration, Coefficient of variation in low flow pulse duration*	*Low pulse count, Extreme low flow frequency*	

River type classification initially was based on watershed size and percent karst geology. This first-cut classification was later abandoned in favor of an iterative statistical approach aimed at increasing sample sizes and strengthening flow-ecology relationships. Ultimately, hydrologic and biological metrics were selected and normalized to account for natural variability, thus obviating the need to classify rivers.

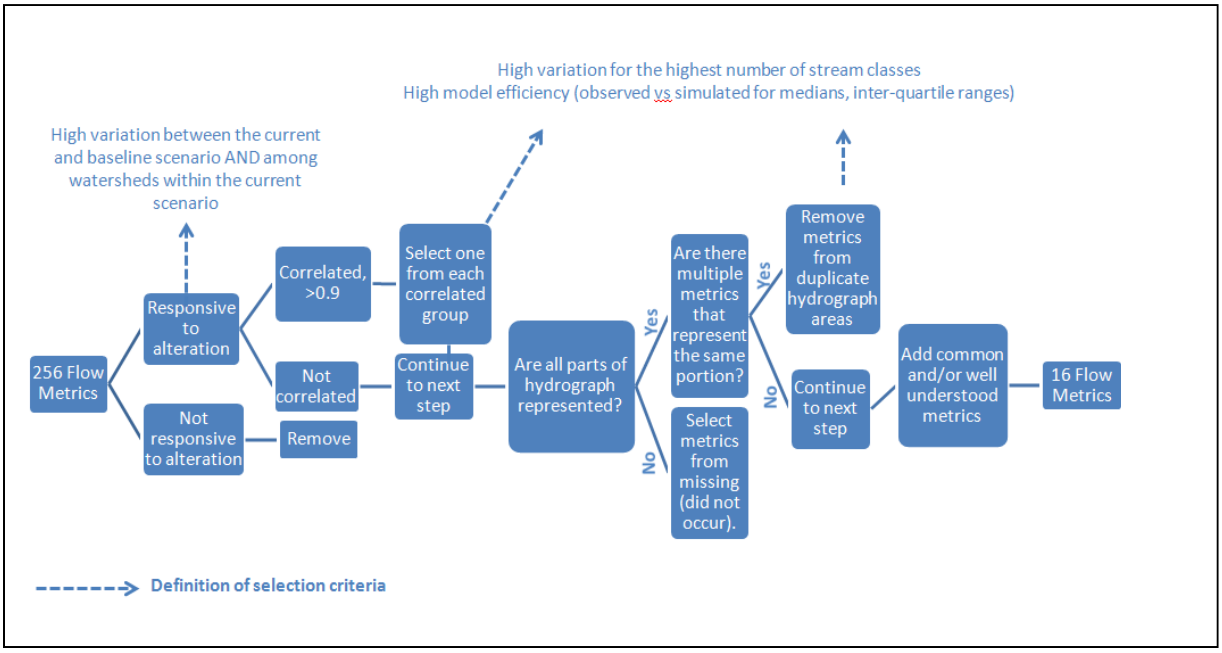

Figure 2. Process for selecting flow metrics for flow-ecology analysis.

Biometric selection began with multiple exploratory data analyses to identify those that are most responsive to anthropogenic stress and habitat degradation. Correlations between those biometrics and candidate flow metrics then were tested. The Chesapeake Bay benthic index of biotic integrity database ("Chessie BIBI") combines marcoinvertebrate, habitat, and water quality data from 23 federal, state, local, and ICPRB monitoring programs in a uniform database structure. Starting with 50 family-level benthic invertebrate metrics, scientists selected the overall index metric (Buchanan et al. 2011) and 19 metrics that indicate community status, are not correlated, and are expected to respond to flow alteration. These metrics represent taxonomic composition, pollution tolerance, functional habitat group, and functional feeding groups. Biological data for 2000-2008 were used.

Two types of flow-ecology relationships were developed. Plots of biological metric scores enable direct comparison between plots of different metrics. Quantile-regression plots of the actual data help quantify uncertainty. The biology samples represent status at a single point in time, but are being used to represent status over a longer time period. To account for uncertainty in the true biological status around the value calculated from a single point, flow-ecology curves were defined as the 90th percentile regression rather than the maximum values of biological metrics reported. The regression curves (calculated with the Blossom program (Cade and Richards 2005)) represent the best possible biological score (with 10% allowance for uncertainty) for a given degree of flow alteration. At a November 2011 workshop, local and regional experts evaluated the biological relevance of the statistical relationships.

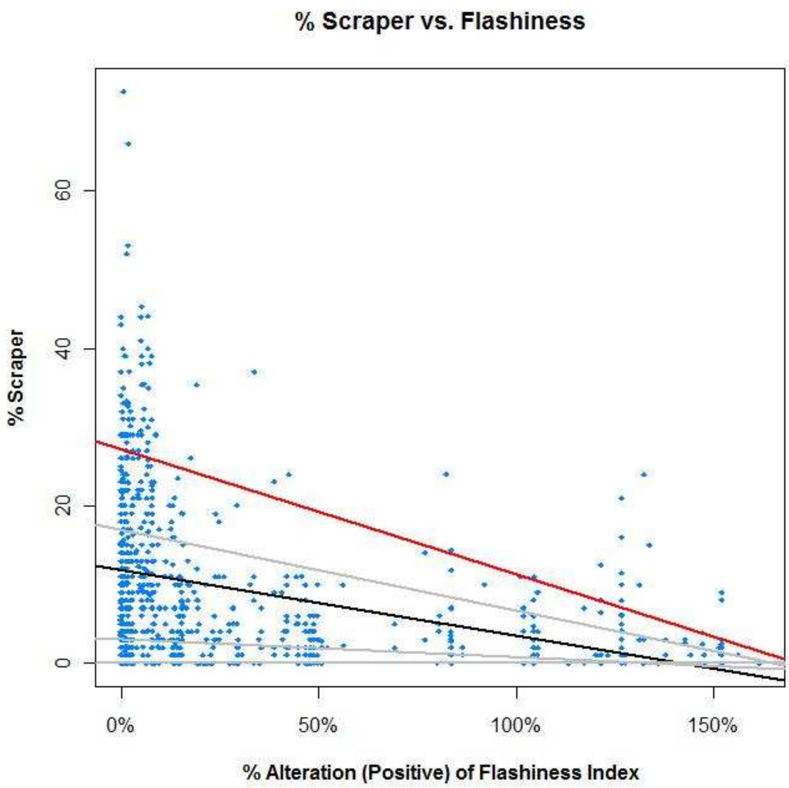

Figure 3. Example flow ecology response curve depicting response of % scraper taxa to altered flashiness index.

The Potomac project was designed as a holistic, interstate environmental flow needs assessment for the entire watershed, using a shared hydrologic foundation and biological dataset. However, no basin-wide authority regulates water withdrawals in the Potomac watershed, and land use decisions that affect flows are often made at the county or local level. For this reason, flow recommendations emerging from this regional analysis will need to be implemented at the individual state or local level. The Potomac project team is sharing flow alteration-ecological response relationships with state-level resource managers and teams to support their technical ental flows and stream health

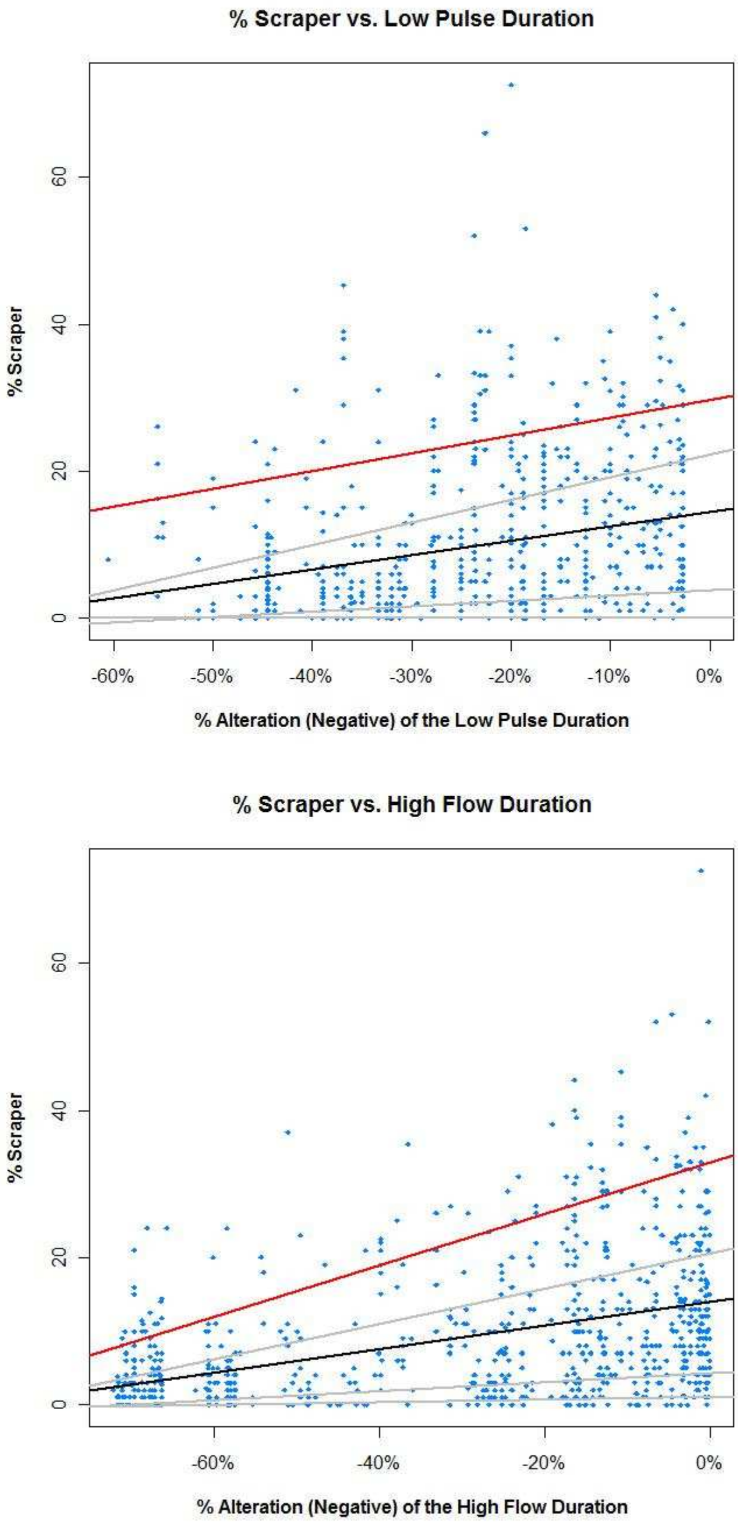

Figure 4. Example flow ecology response curves depicting response of % scraper taxa to alteration of (a) low pulse duration and (b) high pulse duration.

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4.6 Susquehanna River basin ecosystem flow recommendations

The Susquehanna River basin project demonstrates (1) the systematic organization of relevant information sources, including published and gray literature and existing data, to facilitate expert input and (2) a novel expression of environmental flows needed to maintain long-term hydrologic variability.

The 1972 Susquehanna River Basin Compact between New York, Pennsylvania, Maryland, and the Federal government established the Susquehanna River Basin Commission (SRBC). SRBC's mission is to manage the basin's water resources under comprehensive watershed management and planning principles, and it has authority to regulate water withdrawals within the three basin states. SRBC facilitated this science-based process to determine environmental flow needs throughout the basin. Because the SRBC has interstate regulatory authority, the resulting recommendations are expected to be used to revise water policy, inform basin planning, and improve water releases from reservoirs within the basin.

This project was completed under Section 729 authority of the Water Resource Development Act, which authorizes the U.S. Army Corps of Engineers (Corps) to assess water resource needs of river basins, including needs related to ecosystem protection and restoration and water supply. SRBC provided the non-federal cost share and contracted with The Nature Conservancy (TNC), who was the technical lead. The project began in early 2009 and was completed in 18 months.

The project's success hinged on the ability to synthesize diverse sources of information, present it in formats that facilitate group discussion and to convene and use expert knowledge effectively. Box 1 outlines the project schedule, organized around three pivotal meetings.

Through consultations with experts, the technical team assembled a broad list of ecological indicators, including flow-sensitive taxa groups, vegetation community types, and physical processes. The technical team then surveyed scientific literature to find dependencies between these indicators and specific flow components and, where possible, to extract relationships between flow alteration and ecological response. Using species distribution data and expert consultations, they associated species groups with major habitat types and described common traits and habitat preferences for each species group.

A basic habitat classification based on watershed size, temperature, and flow stability was developed for organizing and synthesizing information. Three existing classification systems were tapped to assign river reaches to five major habitat types. The Northeast Aquatic Habitat Classification (Olivero and Anderson 2008) defined "major tributaries" and "mainstems" as reaches with drainage areas exceeding 200 mi^2. Hydrologic classification using the USGS Hydrologic Integrity Process (HIP) software (Henriksen et al. 2006) defined "high-baseflow streams." Water-quality designations from state regulatory programs defined "cool and coldwater streams" and "warmwater streams."

Long-term data for 45 minimally-altered (baseline) streamflow gages indicate that the flow volume on any day of the year varies considerably from year to year. To capture this variability, the technical team defined monthly high, seasonal, and low flow components for each major habitat type.

Box 1. Susquehanna River Basin Ecosystem Flows Study Outline

Orientation meeting (9 March 2009)

Meeting outcomes

Engaged stakeholders
Nominated ecological indicators
Suggested information sources
Identified potential data gaps

Technical team work (Mar 2009-Oct 2009)

Reviewed and synthesized literature
Identified functional species groups
Delineated preliminary river types

First expert workshop (14-15 Oct 2009)

Materials provided to participants before the meeting

Hydrographs showing 1960-2008 inter- and intra-annual flow variability and the timing of life-history stages for each species group
Table of detailed information associated with each species and life stage

Meeting outcomes

Drafted flow-ecology hypotheses by river type
Prioritized additional information for summary report
Suggested analyses to help develop flow recommendations

Technical team work (Oct 2009-Apr 2010)

Reviewed literature and consulted experts to support hypotheses
Drafted flow recommendations
Drafted summary report

Second expert workshop (7-8 Apr 2010)

Materials provided to participants before the meeting

Draft flow-needs diagrams for each major habitat type (figure 1)
Draft flow recommendations (figure 2)
List of published literature cited

Meeting outcomes

Peer-reviewed major products

Technical team work (Apr 2010-Sept 2010)

Analyzed effects of flow recommendations on streamflow under different water withdrawal scenarios; obtained further expert consultation
Finalized recommendations

Final report (Sept 2010)

DePhilip and Moberg (2010)

Representative hydrographs juxtaposing these flow components to life-history stages of native species prepared participants for the first expert workshop. Workshop participants used this information to identify the most sensitive periods and life stages for each habitat type, and to formulate flow-ecology hypotheses. Following the first workshop, the technical team further compiled and synthesized diverse information, using the flow-ecology hypotheses to focus their research.

Ecosystem flow needs were then summarized graphically by season in relation to high, seasonal, and low flows for each major habitat type (figure 1). These graphs and supporting narratives describe the role of inter-annual as well as seasonal hydrologic variability in forming channels and floodplains; maintaining water quality; and supporting life stages of fish, aquatic insects, mussels, reptiles, amphibians, birds, and mammals.

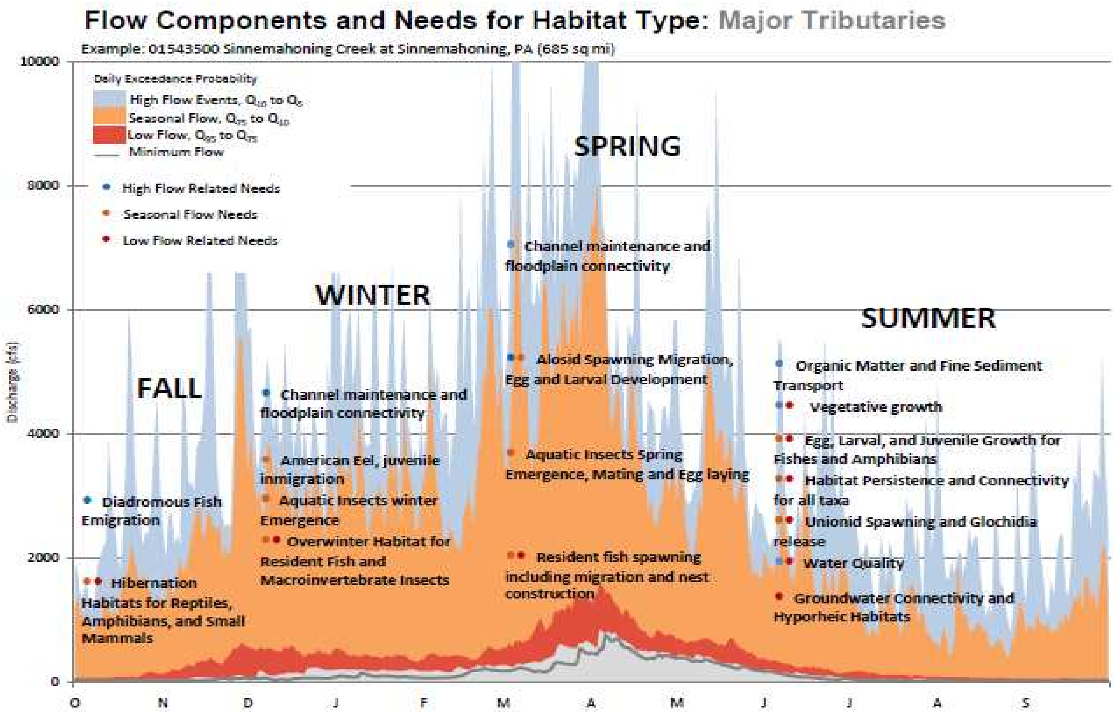

Figure 1. Graph showing ecological functions that depend on typical low, seasonal, and high flows during fall, winter, spring, and summer for one habitat type (Major Tributaries) in the Susquehanna River basin. A similar graph for each habitat type greatly facilitated development of flow recommendations in an expert workshop setting.

The vast array of ecosystem flow needs convinced the project team that it needed to develop environmental flow recommendations for many different taxa -- even those that lack large databases. Rather than assume that a single species or group of species can represent all ecosystem needs, the team took a novel approach. The resulting flow recommendations are based on (a) existing literature and studies that described and/or quantified relationships between flow alteration and ecological response, (b) expert input, (c) the analysis of long-term flow variability at minimally-altered gages, and (d) results of water withdrawal scenarios that tested the sensitivity of various flow statistics.

Ten types of flow statistics were selected to represent the frequency, duration, and magnitude of ecosystem-dependent flow components. These were based on monthly exceedance values and magnitude and frequency of high flow and events. In addition, monthly range and monthly low-flow range statistics were used to quantify changes in flow-duration curve shape, building on the ecodeficit concept (Vogel et al. 2007). DePhilip and Moberg (2010) explain how to process output from Indicators of Hydrologic Alteration software (The Nature Conservancy 2009) to calculate flow alteration as differences between flow duration curves. Flow recommendations are expressed in terms of acceptable ranges of these flow statistics.

The team systematically documented the flow needs that each recommendation supports, and the literature and studies on which the recommendation is based (figure 2). Structuring the flow recommendations in this way facilitated the review process and provides a framework for adding or refining flow needs, substituting flow statistics, revising flow recommendations, and documenting additional supporting information. This structure also focuses future research on relationships between specific types of flow alteration and specific ecological responses. To further facilitate the review process, the technical team analyzed the sensitivity of each flow component to a suite of future water withdrawal scenarios.

Flow Need	Flow Component and Statistic	Recommended Range	Supporting Literature and Studies
SUMMER			
Egg and Larval Development and Juvenile and Adult Growth for all Fishes, Reptiles, and Amphibians- Summer and fall baseflows needed to maintain a range of persistent habitat types, including high velocity riffles, low velocity pools, and backwaters and stream margins. Flows should be high enough to maintain habitat types and connectivity between them. *All habitat types*	May-Oct Seasonal Flow • Monthly Mean • Monthly Range (Q75 to Q10)	May-Oct • ≤ 20% change to monthly mean • ≥65% of daily flows within seasonal range	In a large river, availability and persistence of shallow-slow water habitats were directly correlated with fish abundance, particularly percids, catostomids and cyprinids (Bowen et al 1998).
	May-Oct Low Flow • Monthly Q95 • Monthly Low Flow Range (Q95 to Q75	May-Oct • No change to monthly Q95 • ≤ 20% of daily flows within low flow range	On headwater and small streams, a simulated removal of 8% of Aug median (p50), predict 10% shift in fish assemblage; On large rivers removal of 10% in of the Aug median (p50) predict 10% shift in fish assemblage (Zorn et al 2008). Baseflows in a large river were augmented by an estimated 100% under regulated conditions resulting in an estimated 40% reduction of shallow slow water habitat patch size during normal baseflow periods (summer-fall-early winter) (Bowen et al 2003). Young-of-year abundance most correlated with shallow-slow habitat size and persistence. Suitable conditions predicted by statistics including seasonal median daily flow, high pulse magnitude, duration and rate of change (Freeman et al 2001). A comparison of large warmwater streams along a withdrawal index gradient finds a shift in fish assemblages from fluvial specialists to habitat generalists as withdrawals increase above 50% of 7Q10 (Freeman and Marcinek 2006).

Figure 2. Format of Susquehanna River basin flow recommendations, associating ecological function with ranges of associated flow statistics, and information that supports the recommendation. Colors indicate flow components (low, seasonal, or high (not shown)).

TNC currently is extending the work described in this case study to the Ohio and Delaware River basins in Pennsylvania and adjoining states. At the same time, USGS is developing a Virtual Gage Tool similar to Massachusetts' Sustainable Yield Estimator (Archfield et al. 2010) to estimate minimally-altered (baseline) daily time series for ungaged sites in Pennsylvania. Adding water-use data to these time series will enable comparison between flows under baseline and current conditions. Pennsylvania Department of Environmental Protection (PA DEP) and SRBC plan to use this tool to help review proposed water withdrawals and to ensure that future water use maintains the environmental flows recommended in this and future studies.

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4.7 Connecticut River basin ecosystem flow restoration

The Connecticut River basin project demonstrates (1) coordinating diverse stakeholders to re-operate more than 70 dams within an interstate basin and (2) pursuing basin-wide environmental flow and water use objectives through collaborative optimization modeling.

This case study describes a major component of The Nature Conservancy's Connecticut River Program to restore important river processes, thereby improving the health of declining native species and diverse habitats along the river and its tributaries. With 44 major tributaries, approximately 70 large dams, more than 2,600 smaller dams and 44, 000 road-stream crossings spanning four States within the 11,000-mi^2 watershed, coordinated basin-scale planning and management clearly was needed. Currently, operation of the 70 dams – including 14 owned and operated by the US Army Corps of Engineers (Corps is not fully integrated as a system.

The objective of the ecosystem flow restoration component is to modify management of dams and water supply systems to provide environmental benefits while continuing to supply water, reduce flood risk, and generate hydropower (Zimmerman et al. 2008). It is collaboratively managed and funded by the Corps New England District Office through a Congressionally authorized (in Water Resource Development Act, or WRDA) study budgeted at $3 million. The Nature Conservancy is an authorized cost-share partner and has raised its $1.5 million share through a private donation.

Preliminary technical studies by The Nature Conservancy established the spatial extent, distribution, and scope of flow alteration. Zimmerman (2006a) documented how streamflow patterns influence physical processes and the native species and communities of the Connecticut River basin, based primarily on literature review. Zimmerman (2006b) rigorously analyzed hydrologic alteration downstream from flood-control dams on two tributary rivers. Zimmerman and Lester (2006) mapped the potential degree and extent of such alteration across the basin. Zimmerman et al. (2009) modelled sub-daily flows and analyzed hourly flow variability downstream of multiple dams across the basin. Additionally, Gannon (2007) inventoried permitted withdrawals and discharges to gain insight into each state's water resource management policies and their relative contributions to hydrologic alteration within the watershed. These studies laid a sound technical foundation and helped focus and engage stakeholders.

Local, State, and Federal stakeholders were convened on numerous occasions and in a variety of formats, beginning with a 2008 kick-off meeting. In 2009, the non-profit Consensus Building Institute interviewed all key stakeholders across the four states. One constituency that was crucial to the project's success was the dam owners. A 2009 workshop and one-on-one onsite visits with dam owners over 1.5 years proved crucial for understanding their operational constraints and for gaining their involvement in the process. A 2010 workshop introduced stakeholders to the modeling that was underway.

The modeling team is building a hydrologic model and decision–support tool (figure 1) for integrated water resource management. Water managers and stakeholders will be able to use the tool to evaluate environmental and economic outcomes of various water management and climate change scenarios. The tool also will be useful for upcoming Federal Energy Regulatory Commission FERC relicensing actions, for setting individual dam operations in their regional context. Model construction began in 2009 and is nearing completion.

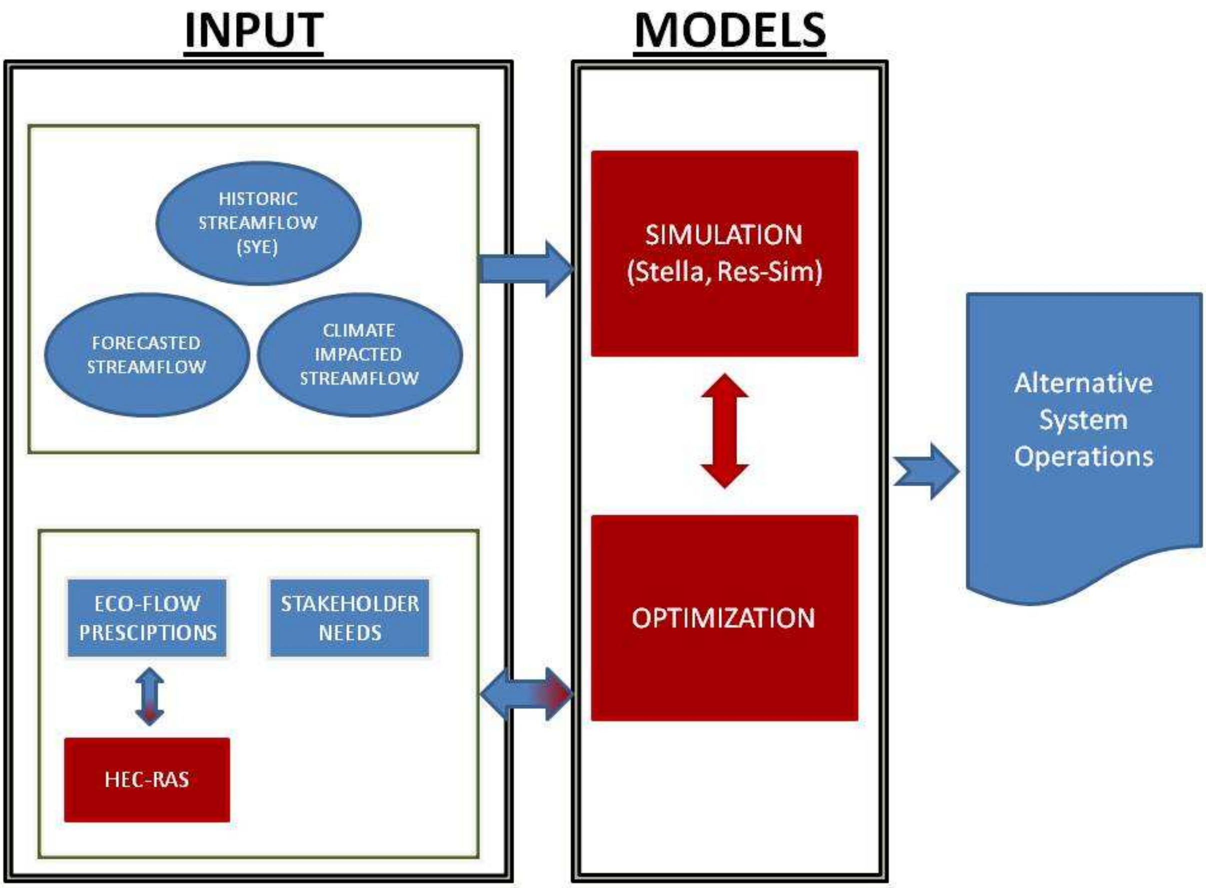

Figure 1. Basic structure of multi-agency water management decision support system for the Connecticut River basin, which includes an optimization routine with environmental flow targets.

The DSS includes two simulation models, one built by University of Massachusetts Amherst (UMass) modelers, and the other by the US Army Corps of Engineers (Corps). The UMass model uses STELLA system-dynamics software to directly represent current reservoir operations and economic outcomes in sub-basins. This model readily solicits and synthesizes feedback from stakeholders. The Corps model generates essentially identical output to the UMass model, but in the Res-Sim format with which Corps dam engineers -- who will implement the recommendations that result from the project -- are most comfortable. Both models input a hydrologic foundation of unimpaired (baseline) daily streamflow hydrographs developed by the U.S. Geological Survey, using duration-curve regression modelling (see Massachusetts case study) for the middle 90 percent of flows, and a modified basin-area technique for extreme high and low flows.

The simulation models are linked to a multi-objective optimization model built by UMass modelers using Lingo programming language. The optimization challenge was to find daily releases from 70 reservoirs that meet flood control, hydropower, water supply, recreation and ecosystem requirements over a time periods ranging from one season to many years. The Connecticut River Wiki Page tracks model development progress.

The inclusion of environmental flows is novel to water resource optimization modeling. In 2010, environmental flow scientists convened a workshop with UMass modelers to better understand modeling constraints. Together, they devised a way to tailor an expert workshop in 2011 to express flow needs in "model" language: environmental flows are modeled as optimization targets with penalty functions that describe their flexibility. A steep penalty function indicates that the target must be met; a shallow penalty function implies less urgency in meeting that target.
At the 2011 expert workshop, The Nature Conservancy provided participants with a list of preliminary flow recommendations organized by species and biological communities, based on extensive literature review. Each flow recommendation was expressed in terms of season, environmental flow component, flow metric, and the underlying flow-ecology hypothesis. In breakout sessions, participants grouped according to their scientific disciplines to review and refine the preliminary flow recommendations. Then, all participants reconvened to eliminate any inconsistencies between the discipline-specific flow recommendations.

Although the workshop participants were comfortable setting flow targets, they felt unprepared to define penalty functions needed for optimization modeling. Left with that model input unresolved, the modelers proposed environmental flow penalty functions based on the "presumptive standard" proposed by Richter et al. (2011), who suggested that <10% flow alteration provides a high level of protection and 11-20% alteration provides a moderate level of protection.

The workshop attendees have agreed to reconvene to learn how the optimization and operations models represent the environmental flow recommendations, examine how their flow recommendations perform in terms of maintaining key aspects of unregulated hydrographs and flow duration curves, and show how often these recommendations can be achieved under various water management scenarios. HEC-RAS, a hydraulic model that calculates stage-discharge relations, will facilitate this conversation. Participants will be asked to refine their initial recommendations based on these results.

In 2012, project efforts will focus on implementation. The Nature Conservancy will actively involve stakeholders in exploring opportunities for dam re-operation to provide environmental flows Monitoring will document ecological conditions before and after flow implementation and strengthen flow-ecology relationships. Already, baseline mapping of vegetation at 91 floodplain sites and geomorphology in 2 tributaries has been completed.

ACKNOWLEDGMENT

The authors thank Kim Lutz of The Nature Conservancy for describing this project to us and reviewing this case study.

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Appendices

Appendix 1: Table of flow-related factors, predictor variables, and response variables used in flow-ecology studies

Appendix 2: Meeting Summaries and Participants

Appendix 3: Conceptual Flow Ecology Hypotheses

Appendix 4: Technical Options for Developing Ecological Flow Criteria and Protections in Minnesota based on ELOHA framework