



STATE OF MICHIGAN DEPARTMENT OF NATURAL RESOURCES

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Michigan's Water Withdrawal Assessment Process and Internet Screening Tool

**David A. Hamilton
and
Paul W. Seelbach**



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MICHIGAN DEPARTMENT OF NATURAL RESOURCES FISHERIES DIVISION

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Table of Contents

Introduction	2
Assessment Process Overview.....	3
Measuring Environmental Impact from Water Withdrawal	4
<i>A metric to measure environmental impact using streamflow.....</i>	4
Determining How Much Water can be Responsibly Removed.....	4
<i>A method to determine allowable withdrawal amounts using fish response curves.....</i>	4
Adequately Representing the Diversity of Streams and Aquatic Ecosystems	5
<i>Water budgets are set for unique stream segments.....</i>	5
Accounting for Varied Sensitivity to Changes in Flow and Risk of Adverse Impacts	5
<i>Accounting for sensitivity through risk-based management zones.....</i>	5
Easily Recognizing and Authorizing Withdrawals that will not have Adverse Impacts.....	6
<i>Relating water withdrawal to streamflow depletion.....</i>	6
<i>Determining how much water withdrawal is too much – legislation.....</i>	6
Identifying Potential Problems	6
<i>Authorizing a water withdrawal if it is not likely to cause an ARI.....</i>	6
Process Implementation.....	7
Site-specific Review	7
Internet-based Screening Tool.....	7
Description of Each Major Component of the Assessment Process.....	8
Delineation of Water Management Areas Based on Ecological Stream Classification.....	8
Determining Index Flow for all Water Management Areas	10
<i>Building a statewide streamflow model.....</i>	10
<i>Regression equation for the Index Flow.....</i>	11
Fish Assemblage Types.....	12
Fish Population Response Curves	14
Determining Acceptable Ecological and Streamflow Withdrawal Thresholds	15
Screening Tool.....	22
Groundwater Withdrawal Model—Run Dynamically in the Screening Tool	22
Relationship Between Bedrock Aquifers and Streams.....	24
Miscellaneous Assumptions Used in the Screening Tool.....	24
Miscellaneous Assumptions Used in the Screening Tool.....	25
<i>Shoreline watersheds.....</i>	25
<i>Simulation period in Groundwater Withdrawal Model.....</i>	25
<i>Streamflow depletion in neighboring WMAs.....</i>	25
<i>Possible ARIs in Cold Transitional streams downstream of Cold stream withdrawals.....</i>	25
<i>Withdrawal from a shallow pond.....</i>	25
Example of the Screening Tool Calculation of Streamflow Depletion	25
Water Accounting Database	27
Operation of the Internet-based Screening Tool.....	28
Screening Tool Evaluation	30
Whether the Tool Works Appropriately as a “Screen”—Testing Existing Wells	30
Comparing Screening Tool Response with Site-level Review.....	32
Results from the First Year of Operation	32
Discussion.....	33
Acknowledgments.....	34
References.....	35

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Michigan's Water Withdrawal Assessment Process and Internet Screening Tool

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Abstract.—Michigan's Water Withdrawal Assessment Process is used to regulate new or increased large quantity withdrawals (more than 100,000 gallons of water per day) from any source. The purpose of the regulation is to prevent Adverse Resource Impacts on streams. The Water Withdrawal Assessment Process is ecologically based, built around a stream classification system and expected fish communities for those classifications. Every stream in the state is classified as one of eleven habitat types. Fish community responses were modeled as an outcome of changes in streamflow for each stream type. Through a legislative process, the resulting fish response models were used to determine and define in statute the maximum withdrawals allowed for each stream type as a percentage of an Index Flow. To facilitate decision making, an Internet-based Screening Tool was developed to estimate the impact of withdrawing water on the nearby stream ecosystems. The Screening Tool processes data about factors such as stream flows, pumping frequency, well depth, watershed areas, soil types, and the flow needs of the characteristic fish community. The Screening Tool uses these data to estimate how much water will be depleted from the nearby streams and determine if the withdrawal is likely to cause an adverse impact on the stream ecosystem. If the Screening Tool determines the withdrawal is not likely to cause an adverse impact, the user may register their withdrawal through the Screening Tool and proceed with the withdrawal without any additional contact with the Department of Environmental Quality (DEQ). If the proposed withdrawal is in a sensitive stream, or the Screening Tool evaluation indicates there is an increased likelihood of an adverse impact, the user is referred to the DEQ for a site-specific review. DEQ staff will further use any information available to refine the understanding of the local hydrology, hydrogeology, and stream classification. The DEQ will consider the refined information in combination with the legislatively determined maximum withdrawals to determine the likelihood of an Adverse Resource Impact occurring. Use of the Screening Tool avoids the cost of having every withdrawal individually evaluated by professional staff as would happen in a conventional permitting program. Locations with abundant water supply relative to the proposed withdrawal, and where the withdrawal might adversely affect the environment are identified through use of the Screening Tool. The goal of this report is to document the Water Withdrawal Assessment Process, including an explanation of how the Screening Tool operates.

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Introduction

Michigan has a new assessment process to identify, and efficiently authorize, surface or groundwater withdrawals that are not likely to cause an Adverse Resource Impact (ARI) to local stream ecosystems. The process links ecological and hydrologic principles and applies them to water management decisions. It is part of a Great Lakes regional effort to protect overall water resources and prevent large scale diversions from the basin.

Aquatic ecosystems are an integral part of the Great Lakes environment. Hydrology determines what kind of aquatic ecosystem exists at any location. While the detriments of physical habitat disruption such as dredging and filling are readily apparent, changes in stream flow characteristics can also alter an entire aquatic ecosystem. Key to protecting aquatic ecosystems is to protect instream flows and the natural seasonal variation in flows. Much of the summer low flow depends on groundwater contributions to the channel. An effective water management process should explicitly recognize and account for the interconnection between surface and groundwater. Surface water withdrawals directly reduce streamflow, while groundwater withdrawals may indirectly deplete streamflow by intercepting groundwater that otherwise would replenish the stream. Additionally, understanding cumulative impacts of multiple withdrawals within a watershed is paramount to a sustainable approach for both the aquatic ecosystem and the human users of the resource.

In 2001, the governors and premiers of all Great Lakes states and provinces, respectively, committed to developing a progressive water management system to protect the waters of the Great Lakes basin. This resulted in the Great Lakes—St. Lawrence River Basin Water Resources Compact (Compact) that was adopted by each of the states and provinces, and Congress, and signed by the President in October 2008 (ratified Michigan version; 2008 Public Act 190; Michigan Legislature 2008a). The Great Lakes region now has a unified regulatory framework, which is enforceable against the interstate movement of Great Lakes water because it was ratified by the federal government. The Compact allows flexibility in each state's approach to implementation. A common, resource-based conservation standard applies to new or increased large-quantity (over 100,000 gpd) water withdrawal proposals from waters of the Great Lakes basin. The standard is based on the principle that there should be 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. The states and provinces further committed to: 1) establish programs to manage and regulate new or increased withdrawals; 2) implement effective mechanisms for decision making and dispute resolution; 3) develop a mechanism by which individual and cumulative impacts of water withdrawals can be assessed; and 4) improve the sources and applications of scientific information regarding the waters of the Great Lakes basin and the impacts of the withdrawals from various locations and water sources on the ecosystems.

In 2006, Michigan legislation (2006 Public Act 34; Michigan Legislature 2006), charged the Groundwater Conservation Advisory Council (GWCAC; an appointed body representing major water use interests) to design a process to assess all proposed large-quantity water withdrawals. The GWCAC formed a technical work group to design and develop the process. This group included hydrologists, fisheries ecologists, and environmental scientists from a variety of state, federal, university, and private entities. As part of the process development, the GWCAC convened a panel of nationally recognized technical experts on groundwater hydrology, hydro-ecology, complex systems modeling, and state instream flow standards to review the scientific validity and wisdom of the working group's proposed approach. This panel affirmed the approach and added some constructive suggestions. (See details of the council membership, activities, and documents at its website: www.michigan.gov/WRCAC).

In their report to the state legislature the GWCAC provided the vision for a comprehensive state Water Withdrawal Assessment Process (WWAP) (Groundwater Conservation Advisory Council 2007). This process combined a foundation of hydrologic and ecological mathematical models, with a set of management actions driven by the estimated risk of causing an ARI. The goals of the process are: 1) prevent ARIs; 2) provide a better understanding of withdrawal impacts, 3) minimize conflicts

over water use, and 4) facilitate planning for sustainable water use and conservation among stakeholders.

Development of the WWAP coincided with growing interest in the development of environmentally-based river flow standards (i.e., “environmental flows”) across North America and other areas of the world. The WWAP is consistent with the syntheses and recommendations provided by numerous scientific sources, including the Instream Flow Council (Annear et al. 2004), The Nature Conservancy (Apse et al. 2008), and the Ecological Limits of Hydrologic Alteration (ELOHA) working group (Poff et al. 2010). These groups observed that every stream has a characteristic natural flow regime and associated fishes. Furthermore, streams are the lowest point in the watershed landscape and thus integrate the results of actions occurring within the watershed. With their focus on streams, these groups identified significant issues to be considered when developing flow standards:

- Incorporate protection of natural intra- and inter-annual flow variability.
- Identify flow metrics that relate to critical biological periods.
- Protect entire ecosystems rather than single species.
- Incorporate a safety margin to cover variability and uncertainties.
- Adapt, update, and revise the system through time as new and more accurate information becomes available.

The ELOHA working group developed a particularly useful outline of steps for developing environmental flow standards. Steps taken to develop the Michigan WWAP paralleled these recommendations.

Michigan’s new WWAP contains elements representing both objective science and subjective societal values—the two necessary elements for sound policy development. Science elements were agreeable to all parties; societal values elements required in-depth discussion and ultimately a legislative decision. The science-based components offered an objective template to guide and constrain participants during the social-values negotiations. Legislators and stakeholder workgroups reached agreement on the new state water policy and 2008 Public Act 189 was passed (Michigan Legislature 2008b).

The resulting WWAP identifies and efficiently authorizes, surface or groundwater withdrawals that are not likely to cause an ARI to local stream ecosystems. The threshold for an ARI is defined in terms of the maximum amount of streamflow that can be withdrawn. In the development of the ARI, characteristic stream fish populations were used as a surrogate to measure environmental or natural resource impact. Withdrawals that have a higher risk of causing an ARI are flagged for more detailed, individual review. The WWAP was created to ensure thoughtful management of Michigan’s valuable water resources by focusing attention and expertise on water use proposals with the highest environmental risk, while avoiding a permit process that requires staff review of every proposal.

The objectives of this report are to:

- 1) Describe the overall WWAP, in terms of major components and how they are linked;
- 2) Clarify the role of the Internet-based Screening Tool and how it functions;
- 3) Summarize how each of the major components was developed (each has a technical report that documents its full details);
- 4) Document the assumptions and procedures used to create a functioning Screening Tool; and
- 5) Discuss initial experiences related to testing and implementing the assessment process.

Assessment Process Overview

The fundamental question for the assessment process is: “When is an unacceptable impact on the aquatic ecosystem of a stream caused by cumulative large quantity water withdrawals?” In designing a process to answer this question, the technical work group faced many challenging issues, including:

- 1) Measuring environmental impact from water withdrawal
- 2) Determining how much water can be responsibly removed
- 3) Adequately representing the diversity of streams and aquatic ecosystems
- 4) Accounting for varied sensitivity to changes in flow and risk of adverse impacts
- 5) Easily recognizing and authorizing withdrawals that will not have adverse impacts
- 6) Identifying potential problems

To the extent possible, objective metrics were developed to represent the physical environment. Scientifically based fish-response curves were developed to inform the policy determination of how much water can be responsibly withdrawn. The assessment process only applies to large quantity withdrawals, defined as 70 gpm (100,000 gpd) or greater. Responses to these six questions in this section provide a general understanding of how the assessment process works. Subsequent sections provide details and background information for the final implementation of the assessment process and Internet-based Screening Tool.

Measuring Environmental Impact from Water Withdrawal

A metric to measure environmental impact using streamflow.—The hydrology of a watershed interacts with local valley topography, geology, and vegetation to shape the stream channel and its internal habitat characteristics. The summer low flow period is one of the most important, and best understood, biologically stressful periods in the annual streamflow cycle (Zorn et al. 2002; Wehrly et al. 2003; Lyons et al. 2009). In the approach developed for Michigan, the environmental impact of any proposed withdrawals is assessed during this low flow period. An Index Flow was chosen to represent this period. The Index Flow is defined as the lowest summer monthly median flow; for most of the state this is the median flow for August. This is then the reference flow from which each new water withdrawal is subtracted and assessment made of the environmental impacts caused by that withdrawal. The maximum amount of water that can be withdrawn from each stream is calculated as a percentage of the Index Flow. The risk of approaching an ARI is also referenced as a percentage of the Index Flow. This approach is consistent with recent emphasis on keeping stream flows within “sustainable boundaries”, or a range around the environmental index flow (Richter 2009).

The Index Flow is the median value of all the daily flows for the month of lowest summer flow in the period of record measured at a continuous recording stream gage. Since stream gages are only located at a relatively small number of locations, statistical regression using landscape and climate characteristics is used to estimate the Index Flow for all ungaged locations. Some withdrawals may require site-specific analysis before authorization, and streamflow at these sites may be estimated through other hydrologic techniques including additional flow measurements.

Determining How Much Water can be Responsibly Removed

A method to determine allowable withdrawal amounts using fish response curves.—The expected response to water withdrawals of the entire fish population in a stream segment is used as an indicator of acceptable threshold change in overall aquatic ecosystem functions. This is consistent with the definition of ARI found in Michigan 2006 Public Act 34 (Michigan Legislature 2006), that a withdrawal cannot functionally impair the ability of a stream to support characteristic fish populations. This is an example of a biologically based definition, related to stream habitat, and using fish as the environmental indicator. Fish are at the top of the food chain, and as biological integrators, reflect the overall health of the aquatic environment (Karr et al. 1986). Fish response curves were developed that represent population and density changes in representative fish communities as a response to percentage reductions in Index Flow (Zorn et al. 2008).

Adequately Representing the Diversity of Streams and Aquatic Ecosystems

Water budgets are set for unique stream segments.—The new law is designed to prevent ARIs to the state's water dependant natural resources. Streams are an obvious feature to measure the environmental impact of water withdrawals. Streams receive both surface runoff and groundwater from the surrounding watershed, thus an expected water budget can be established for each stream segment. The amount and character of streamflow depends on climate, the physical characteristics of the watershed soils and geology, as well as the land use. Both surface and groundwater withdrawals can reduce streamflow. The reduction of streamflow has an important impact on stream temperature. Surface water withdrawals reduce the volume of water in the stream, and correspondingly reduce the thermal mass of the stream. This means for a given thermal input, the water temperature will rise more readily. In addition to this effect, groundwater withdrawals also reduce the groundwater contribution and its cooling effect on streamflow (Wehrly et al. 2006).

To begin to quantify the impact of withdrawals it was important to classify Michigan's streams into groupings that respond in a similar manner. All streams of the state were classified by size and water temperature, as these have been shown to be the dominant variables shaping Michigan stream fish populations (Zorn et al. 2002). Using Geographic Information Systems (GIS) technologies and statistical models, the ecological diversity of Michigan's stream systems was mapped as a statewide stream classification. A tentative map derived from statistical models was reviewed by staff from every Michigan Department of Natural Resources (DNR), Fisheries Management Unit office for verification and enhancement based on their local knowledge of stream characteristics (Zorn et al. 2008).

Where in the stream network are the most appropriate locations to determine the Index Flow and to make these measurements and environmental assessments? In this assessment process, ecologically similar, neighboring streams are grouped together into a single segment, and streams that represent unique local environments are kept as separate. Each of Michigan's ecological stream segments drains a specific land surface area; these boundaries are identified and comprise 5,400 Water Management Areas (WMAs) that cover the state. The WMAs overlap, as one moves downstream the smaller WMAs are incorporated into larger ones that represent the total watershed at break points in stream segments. Index Flows are all determined at the downstream end of the WMAs.

This assessment process focuses on stream ecology, which of course directly benefits the target stream segment. It also provides some measure of protection to other aquatic ecosystems (i.e., headwater streams, lakes, and wetlands) within the local watershed or water management area, by setting a maximum amount of streamflow depletion allowed from this area. Through the classification system and associated water budgets, this process helps sustain the exceptional diversity of natural hydrologic regimes and the resulting aquatic ecosystem types distributed across the Michigan landscape (i.e., all waters of the state).

Each stream type has different characteristic fish populations that respond differently to the loss of water. For each stream type, a maximum proportion of streamflow can be withdrawn before causing an ARI. For each stream type an ecological response curve was developed using data for fish populations across the state.

Accounting for Varied Sensitivity to Changes in Flow and Risk of Adverse Impacts

Accounting for sensitivity through risk-based management zones.—The final policy decisions (legislation) regarding acceptable impacts were informed by the stream classification system and fish response curves. The state law prohibits an "Adverse Resource Impact." The ARI is defined as a percent reduction in that stream segment's Index Flow. It is an absolute threshold. The flow-fish functional response curves instead illustrate a continuum of increasing risks of resource impact. We cannot say that on one side of a sharp threshold of flow reductions there is no impact, while on the

other side there is an ARI. So the legislation created “management zones” representing increasing levels of risk to the environment, and prescribed a suite of appropriate levels of water management efforts accordingly.

Each stream type has different characteristic fish populations that respond differently to the loss of water. For each type, the legislation determined a maximum amount of water that can be withdrawn before causing an ARI. The risk of approaching an ARI is marked by Zones A through D. Each of these thresholds is likewise defined as a percent reduction in that stream segment’s Index Flow. Zone A has little risk of causing an ARI, while Zone D means an ARI would occur in the stream. Zones B and C lie between these extremes, indicating increasing risk.

Easily Recognizing and Authorizing Withdrawals that will not have Adverse Impacts

Relating water withdrawal to streamflow depletion.—A mechanism is needed to predict how much water will be depleted from any given stream segment by a proposed withdrawal. A surface water withdrawal is taken directly from a stream; the streamflow is instantly reduced by the same amount that is withdrawn. Groundwater withdrawal impacts are lessened and delayed depending on of the local relationship between groundwater and streamflow. The relationship between the withdrawal and actual streamflow depletion is complex. The factors that must be considered are: location of a well in relation to nearby streams; the connection between the aquifer used by the well and the stream; the aquifer material; and the distance and depth of the well screen from the stream. Computer models are used to incorporate these factors into the calculation of the streamflow depletion (Reeves et al. 2009).

Determining how much water withdrawal is too much – legislation.—Science cannot answer the question, “How much resource impact is too much?” This is a social question, decided through the state legislative process. The legislation created the WWAP, and made the key policy decisions. Science did provide the following elements, which together formed a powerful template for guiding the policy discussions. The Index Flow is defined, and used as the metric to measure withdrawals against. The value of the Index Flow will vary from place to place across the state, but the fact that it represents the lowest summer monthly median flow at that location is fixed. The stream classification system is defined, and fish response curves are adopted for each stream type. Based on the curves for each stream type, unique risk based management zones are set, along with the definition of an ARI. Values for these zones and the ARI are determined as a percentage of the Index Flow. The process is built to apply all of these policy decisions to any large quantity withdrawal at any location in the state.

Identifying Potential Problems

Authorizing a water withdrawal if it is not likely to cause an ARI.—Linking the fish response curves, stream classification map, Index Flow estimates, and estimated depletion provides an answer to the fundamental question for each proposed large quantity withdrawal. Every location in the state falls within a WMA; every WMA is classified by its dominant stream type; and for every stream type, the risk management zones are set based on a percentage of the Index Flow. What remains is to determine the Index Flow and the withdrawal’s depletion from the streamflow. These can be done two ways – a site-specific review using data developed from the site, or a generalized statewide screening model. The proposed water withdrawal is compared with the amount of water available in the WMA, and the risk management zone is determined. Based on the zone, certain management options must be followed. If it results in the Zone D (likely to cause an ARI) then the withdrawal will not be allowed. The applicant could propose a preventative measure that would alter the amount of water and/or the water temperature such that the proposed withdrawal would no longer cause an ARI. If the proposal results in Zones B or C, then notifications of other water users and interested parties occur, user groups may be formed, and there may be requirements for water conservation measures.

Zone A determinations allow water users to proceed with the withdrawal. An Internet-based Screening Tool allows Zone A determinations to proceed through an automated registration process.

Process Implementation

Site-specific Review

When the WWAP is implemented at the site level, DEQ staff use the most accurate procedures and data available to consider geographic variations in Michigan's streamflows and groundwater hydrology. Staff determine: 1) the location of the proposed withdrawal; 2) the source and neighbor WMAs; 3) distances to the nearest stream reach in each WMA and their ecological types; 4) available water for withdrawal from each WMA; and 5) the estimated depletion from each WMA.

Once the proposed depletions from each nearby stream segment are determined, steps 6 and 7 are straightforward results from flow-fish relationships and social values regarding water allocations that are fixed by law within the process. In Step 6 the depletion amount is compared with the available water amount, which determines the management zone for the proposal. And in Step 7, based on the zone, the determination is made whether the proposed withdrawal can proceed, and which water management measures are required. There may be discussion with the applicant to modify the proposal to reduce the potential impact.

Site-specific reviews are required by law to proceed efficiently and quickly; indeed a determination must be made within ten business days of an application. To facilitate this, site-specific reviews rely on standard analytical procedures and datasets, and knowledge field staff has of the area. The applicant may also contribute data and analyses.

Internet-based Screening Tool

In order to focus state agency resources on the most sensitive areas and also to efficiently approve withdrawals in areas where water is readily available, a statewide Internet-based Screening Tool was developed. This tool's legal name is the Water Withdrawal Assessment Tool (2008 PA189; Michigan Legislature 2008b), but to clarify its function, it is called the Screening Tool in this report. The Screening Tool provides an initial, screening-level assessment of the impact of a potential water withdrawal on local stream ecosystems. It operates within a Geographic Information System running on the Internet and can be used to examine potential withdrawal sites anywhere in the state. It is designed with enough safeguards so that, when a proposed withdrawal clearly poses little or no risk to nearby stream ecosystems, the Screening Tool can approve, and facilitate, immediate on-line state registration of the withdrawal. But when a proposed withdrawal triggers concerns of risk to the ecosystems, the Screening Tool instructs the person to request a more detailed review by DEQ staff.

The Screening Tool considers the geographic variations in Michigan's streamflows and fish community types. Mathematical models of streamflow, groundwater dynamics, and fish habitat suitability were created. The stream flow model uses information on soils, geology, land use, and precipitation to predict how much summer flow is available in each stream. The estimates provide a very good representation of geographic patterns in hydrology seen across Michigan, but they can be somewhat inaccurate in local cases. The groundwater model uses information about geology, well depth, pumping rate, and distance from nearby streams to estimate how much a well will reduce the flow in nearby streams. And the habitat suitability model determines how a reduction in stream flow is likely to impact the types and abundance of fish species that live there.

The Screening Tool determines the management zone resulting from each proposed withdrawal, and provides instruction on what to do (water management requirements are identical for both Site-

Specific Review and the Screening Tool). The results page also presents options the user may try for revising their proposal to avoid a problem. Revision options include: reduce the pumping frequency; reduce the pump capacity; increase the well depth; and relocate the well farther from nearby streams. These measures all tend to reduce a well's impact on a stream and may allow a revised proposal to receive an authorization to proceed.

The Screening Tool results page contains an important disclaimer informing the applicant that the Screening Tool is only designed to estimate the likely impact of a proposed water withdrawal on nearby streams. It is not an indication of how much groundwater may be available for use. The quantity and quality of groundwater varies greatly with depth and location. The user must consult with a local well driller or other water resource professional regarding groundwater availability at that location.

Description of Each Major Component of the Assessment Process

Delineation of Water Management Areas Based on Ecological Stream Classification

A GIS-based ecological stream classification that describes the state's geography of stream segment types was used as the fundamental framework for delineating Water Management Areas for the WWAP. Through interpretation of a series of landscape maps at both regional watershed and management area scales, the classification identifies both the boundaries and the ecological character of unique stream segments. Landscape maps provided information on: stream network structure, drainage areas, predicted July water temperature, and predicted summer flow; and watershed surficial geology, land slope, and land cover (Brenden et al. 2006). Segments are defined as intermediate-scale units believed to best express a stream's ecological structure and to be practical stream management areas. Each segment is believed to have characteristic and relatively homogeneous hydrology, geomorphology, hydraulics, water quality, water temperature, and biological attributes; and segment boundaries are definitive enough that different fish assemblages are expected between neighbors (Seelbach et al. 2006).

The riverine classification system was developed through several steps. The base digital hydrography was the 1:100,000 USGS NHD-Plus (Bondelid et al. 2006), which is the national standard stream base map, and is comprised of about 30,000 stream reaches (unique GIS lines or arcs) as the basic spatial units for Michigan stream systems. The reach watershed boundaries conform to an approved, most accurate set of watershed boundaries developed earlier by DEQ and USGS. These are based on 1:24,000 topography and field verification. Ecologically similar, contiguous reaches were first aggregated to form ecological stream segments and types according to statistical modeling (Brenden et al. 2008a; Brenden et al. 2008b), with subsequent modifications per expert review by DNR fisheries management biologists (Zorn et al. 2008). Headwater reach networks or mainstem reach series were typically aggregated to form one segment. The aggregation processes reduced Michigan's ~30,000 stream reach units to ~6,800 stream segment units; this formed the DNR "Fisheries Segments" database, meant for broad use in fisheries and water resource management.

For the WWAP framework the Fisheries Segments were further modified. First order stream reaches that flow directly into larger river mainstems (or the Great Lakes) were aggregated into that larger receiving segment, if they were of a similar thermal type. This was a practical action to minimize the number of tiny management units present. Finally, the 2008 Michigan law specifies minimum drainage areas for water management areas of Warm and Cool stream segments (2008 PA189; Michigan Legislature 2008b). The minima are: 3 mi² for direct surface water withdrawals; 6 mi² for groundwater withdrawals; and 20 mi² for segments with Index Flow < 1 cfs. Two base maps were constructed: one that fit the requirements for surface withdrawals; and one that fit the requirements for groundwater withdrawals. These further aggregation processes reduced the ~6,800 "Fisheries" stream segments to ~4800 "Water Management" areas, with the large reduction coming from aggregation within warm and cool stream types. All elements of the WWAP are structured

according to this ~4,800 unit spatial framework (Figure 1). The total up-gradient drainage boundary was delineated for each of the ~4,800 WMAs. Watershed boundaries were aggregated from the reach watershed boundaries provided in the NHD Plus database. In addition, there are approximately 600 more “shoreline” WMAs that are included in the Screening Tool. These drain to small tributaries located immediately adjacent to the Great Lakes. In the Screening Tool it is assumed that any water withdrawal within a shoreline WMA will tap into the very large supply of a nearby Great Lake, and thus is automatically approved.

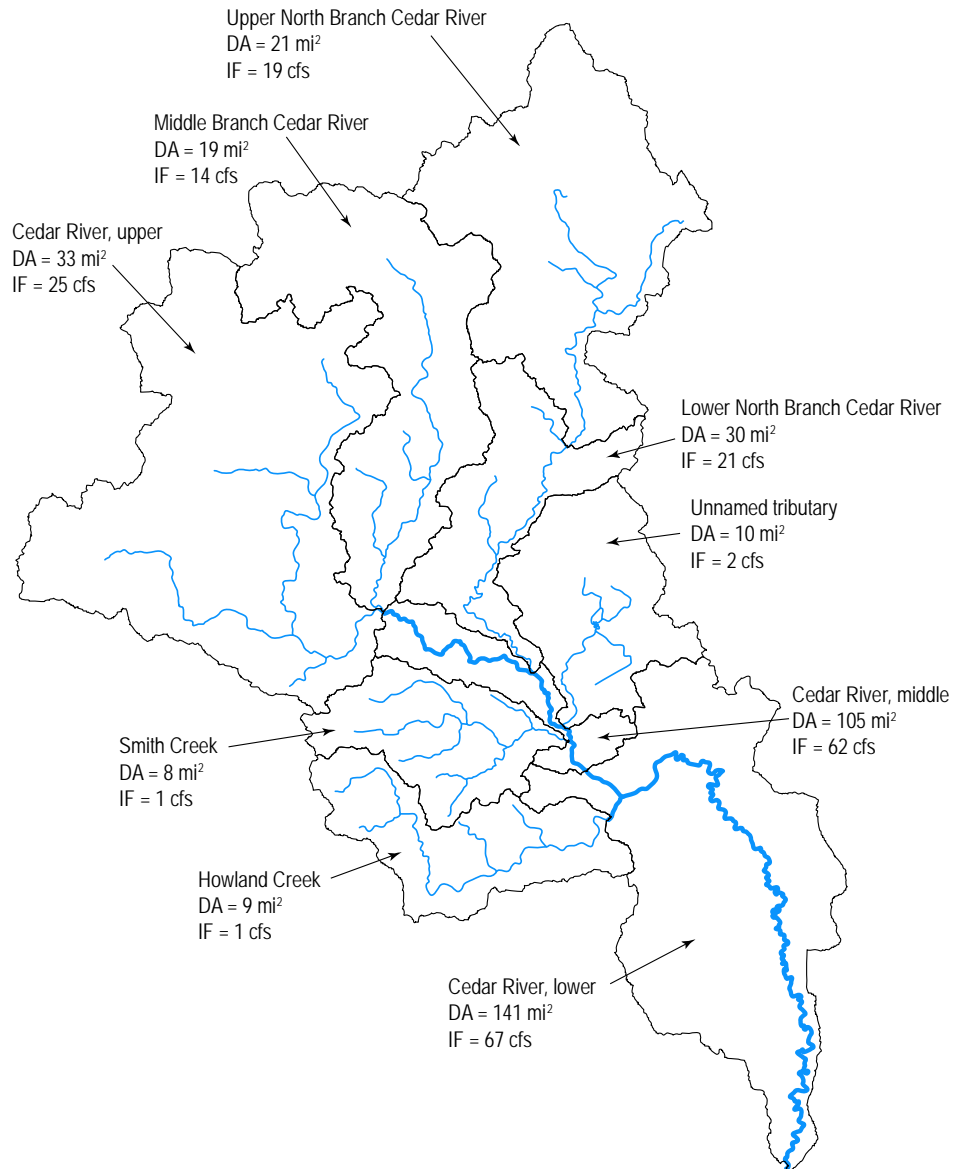


Figure 1.—Example of Water Management Areas delineated for the Cedar River, tributary to the Tittabawassee River and subsequently the Saginaw River. Stream reaches were aggregated into ecological stream segments according to both ecological character and also to meet the minimum drainage area for Warm and Cool (also called Warm Transitional) stream types as specified in state law. Each Water Management Area has a unique drainage area (DA) and Index Flow (IF; based on statewide regression modeling).

Determining Index Flow for all Water Management Areas

The flow regime is the foundation of a stream ecosystem. Flow discharge, velocity, and seasonal variation; and how a stream responds to rainfall and runoff events are all major factors in shaping which plants and animals will thrive in the riverine environment. The ecosystem in each stream segment is adapted to its "natural flow regime" (Poff et al. 1997). Sediment transport and deposition are directly related to flow. The benthic zone can be smothered with sediment, if flow is not adequate to transport fine sediment. The quality of the benthic habitat directly impacts the food web and the reproductive success of many fish species. Fish and invertebrate species show distinct adaptations to, and preferences for, specific channel hydraulic attributes related to water depth and velocity.

Temperature is also a critical ecological factor that is largely controlled by sources of flow; temperature affects the oxygen carrying capacity of water, and which organisms will survive and grow in it. It also constrains animal physiology, directly impacting which stream locations are optimal for specific species. For example, colder summer temperatures are characteristic of streams with high base flow yields (fed by strong supplies of groundwater), while warmer summer waters are found in streams with low base flow yields fed by little groundwater (Wehrly et al. 2006).

The impact of withdrawing water from a particular WMA must be measured against a standard, or "Index flow." By state statute (2008 PA189; Michigan Legislature 2008b), this is defined as the 50% exceedance flow (median flow) for the lowest summer flow month of the flow regime. This is usually either the August or September median flow. The Index Flow, then, can be thought of as a typical low flow during the relatively dry summer months. Under natural conditions, water in streams during low flow periods is primarily groundwater in-flow. Aquatic ecologists consider this a critical time period for streams because certain stream characteristics that limit fish abundance can approach marginal ranges. These characteristics include discharge, amount of dissolved oxygen in the water, and stream water temperature. In the WWAP, allowable withdrawals are determined as a percent of this critical and limiting, Index Flow, with the goal of keeping the flow of each segment within natural "sustainable boundaries" (Richter 2009).

Building a statewide streamflow model.—The Screening Tool requires that an Index Flow be estimated for all WMAs statewide, whether or not streamflow measurements are available for each. So we used a statistical model based on landscape attributes to extrapolate from gaged to ungaged sites. To develop the streamflow model, measured Index Flows at streamflow gages were compared to mapped watershed characteristics (e.g., land cover, precipitation, or other factors) upstream of the gages. This relationship was established statistically using the multiple linear regression method, and then used to estimate Index Flows for all ungaged river segments across Michigan (Figure 1; Hamilton et al. 2008).

A set of 147 USGS continuous streamflow-gaging stations were selected from among stations operated in Michigan for 10 or more years, that were representative of the natural response of streamflow to precipitation. Gaging station records were reviewed to ensure they were unaffected by seasonal or other types of artificial regulation that would produce a biased flow record. In particular, stations where median low flows were thought to have been appreciably affected by regulation, augmentations, or diversions were excluded from the regression analysis. Of the 147 selected stations, minimum monthly median flows occurred in July at 5 stations, in August at 92 stations, and in September at 50 stations. These median flows, referred to in the WWAP as Index Flows, ranged among stations from 0 cfs to 1,850 cfs.

The drainage area of each gage explains a great deal of the observed variation in flow between the gages. To increase the sensitivity of the regression to other characteristics, median flows were rescaled by dividing them by their corresponding drainage areas to produce flow yields as the dependent variable of the regression analysis. Gaged Index Flow yields ranged from 0 cfs/mi² to

1.309 cfs/mi². A square-root transformation was applied to the Index Flow yields to meet the modeling assumption of normally distributed data (Hamilton et al. 2008).

A multiple linear regression equation was developed to predict the square root of the Index Flow yield at ungaged sites using selected watershed and climatic characteristics as explanatory, or independent, variables. The independent variable most highly correlated with the observed median flows was entered first into the regression equation. Independent variables with the next highest correlations were subsequently added until this process did not significantly increase the predictive capability of the regression equation. Selected landscape variables included: percentages of land area underlain by low and high aquifer transmissivity, percentage of forest cover, average annual precipitation, and percentages of land cover associated with hydrologic soil groups A and D (highly and poorly permeable soils, respectively). Several statistical parameters were used to evaluate the accuracy and validity of the resulting regression equation. No spatial bias in the regression estimates was detected among seven hydrologic sub-regions spanning Michigan. Therefore, the single regression equation is appropriate for statewide application.

The statute requires that the Index Flow be calculated as of October 1, 2008. The most recent final data set available on that date was from water year 2007 (ending September 30, 2007.) The regression model developed for this process (Hamilton et al. 2008) used data through September 30, 2005. The analysis was rerun using gage data through September 30, 2007. The average difference between the predicted Index Flows at the 147 gaging stations in the 2008 report and the final version used in the Screening Tool is 0.8%, and the maximum difference is 2.8%. The final regression equation is described below.

Regression equation for the Index Flow.–

$$IF = DA(-0.55077 + (-0.0014132 LT) + (0.0019883 HT) + (0.0039675 F) + (0.02408 P) + (0.0023171 A) + (0.001534 D))^2$$

where,

- IF = Index Flow (cfs)
- DA = drainage area (mi²)
- LT = percent of drainage area with low transmissivity surficial geology (%)
- HT = percent of drainage area with high transmissivity surficial geology (%)
- F = percent of drainage area with forest (%)
- P = annual precipitation (in)
- A = percent of drainage area with A soil type (%)
- D = percent of drainage area with D soil type (%)

Following is an example computation to illustrate the procedure for estimating the Index Flow. The variables for a watershed are: DA = 273 mi², LT = 27.0 percent, HT = 23.9 percent, F = 89.0 percent, P = 32.2 in., A = 14.0 percent, and D = 47.0 percent.

Substituting these variables, the regression equation can be written:

$$IF = 273(-0.55077 + (-0.0014132 \cdot 27.0) + (0.0019883 \cdot 23.9) + (0.0039675 \cdot 89.0) + (0.02408 \cdot 32.2) + (0.0023171 \cdot 14.0) + (0.001534 \cdot 47.0))^2$$

The estimate of Index Flow for this watershed, based on the regression equation, is 131 cfs.

A unique Index Flow is estimated for each Water Management Area, by applying its watershed characteristics to the regression equation. Index Flows are determined by squaring the regression prediction of square root yield and multiplying that result by the corresponding drainage area. The regression equation explains about 94 % of the variability in Index Flows indicated by streamflow gaging station records.

To account for possible under-predictions of Index Flow, a “safety factor” of 0.5 is built into the Screening Tool, and the predicted Index Flows are multiplied by this factor. Using this safety factor, the estimated flow used in the assessment process will be more than the actual flow in the stream only 10% of the time. This provides a level of reasonable conservatism to assure that the Screening Tool will rarely authorize withdrawals for water that are likely to cause an ARI.

Fish Assemblage Types

To the WMA river segments we applied a fish assemblage classification system, developed by DNR for broad use in fisheries, water quality, and watershed management applications (Zorn et al 2008). Research has shown that Michigan fish species assemblages are initially structured according to the two variables of stream size (drainage area) and summer (July mean) water temperature (Zorn et al. 2002). The classification employs three categories of stream size (stream, small river, and large river) and four categories of summer water temperature (Cold, Cold Transitional, Cool (or Warm Transitional), and Warm). Stream size categories were delineated by visual examination of Michigan distributions of fish species and assemblages known to prefer either small stream or large river habitats, along a gradient of stream size (Zorn et al. 2002; 2009). Temperature categories were similarly delineated by statistical analyses of distributions of fish species known to prefer either cold or warm temperatures, along a gradient of summer water temperatures (Lyons et al. 2009). The temperature analysis was only for wadable streams but the categories were extended to non-wadable streams as well. Cold Transitional was recognized as a separate temperature category as a result of this work. It is a cold stream, but very sensitive to small reductions in flow or small increases in temperature. These small changes can alter the ecosystem so it no longer will support cold water species.

This 3x4 matrix results in 11 ecological stream types (as no “cold large rivers” exist in Michigan). For each of the 11 types the expected “characteristic” fish species and the expected “thriving” fish species were determined by analysis of several representative stream segments per type (Zorn et al. 2008; characteristic fishes per type are online at: <http://www.miwwat.org/wateruse/regulations.asp>; January 2010). “Characteristic fish populations” for a segment are defined as the assemblage of fish species whose characteristic habitat (Index Flow and July Mean Water Temperature) distributions (within 1.5 standard deviations of the median habitat value for each species) include the habitat conditions expected for that segment. Abundance of characteristic fish species is generally greater than the statewide mean abundance for that species. “Thriving fish populations” are defined as those species whose optimum habitat distributions (within 1.0 standard deviations of the median habitat value for each species) include the habitat conditions expected for that segment; abundance of thriving fish species is generally twice that of the statewide mean abundance for that species. Only ~40 of the most common Michigan stream fish species were included in determining characteristic and thriving fish for each stream type (Zorn et al. 2008). For each ecological stream type, the sensitivity responses of the Characteristic and Thriving fish populations to potential reductions in Index Flow were also determined. So although there are ~4,800 WMAs (and associated stream segments) in Michigan, the WWAP only works with 11 different ecological responses to potential water withdrawal (Figure 2; Table 1).

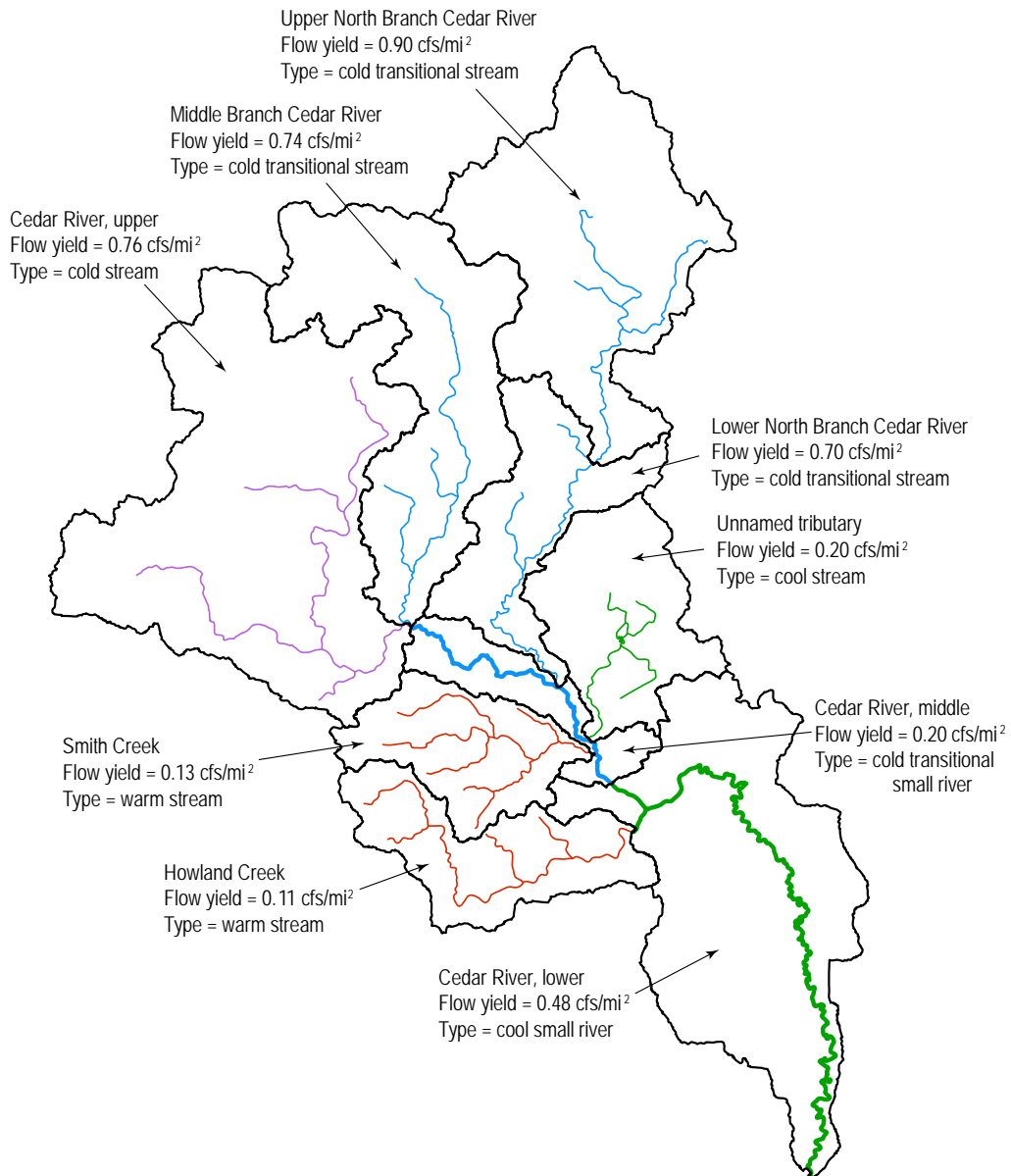


Figure 2.—Example of ecological type classifications for stream segments within the Cedar River (tributary to the Tittabawassee River and then the Saginaw River). Water Management Areas boundaries are shown in gray. Note that neighboring segments can be different types; this distinction is due to variation in groundwater contributions related to differences in surficial geology. Headwater tributaries drain coarse moraines and outwash that delivers high flow yields (0.67-0.90 cfs/mi²) and sustain cold systems, while lower tributaries drain fine lacustrine plains that provide low yields (0.11-0.20 cfs/mi²) and sustain cool or warm systems. The mid and lower mainstem ecosystems reflect the accumulation of all upstream tributary characteristics.

Table 1.–Ecological type classification for Michigan streams, by watershed size and July mean thermal limits, based on analyses of fish population distributions; and number of segments of each type for the groundwater withdrawal, Water Management database.

Ecological classification	Stream <80 mi ²	Small river 80 mi ² to <300 mi ²	Large river ≥300 mi ²
Cold <63.5°F	1,811	36	NA
Cold Transitional 63.5°F to <67.1°F	613	42	15
Cool (Warm-trans) 67.1°F to <69.8°F	970	134	44
Warm >69.8°F	876	142	126

Fish Population Response Curves

A key question in environmental management is "How much human-induced change can an ecosystem take before a threshold is reached where some unacceptable change occurs?" Fish populations can be used as indicators of threshold change in overall aquatic ecosystem functions that are dependent on a healthy flow regime. The focus is not on target or favorite fish species, but rather on metrics that describe the total assemblage of fish populations as a functional entity. Each river segment has "characteristic fish populations" that are best suited to its particular flow, temperature, and channel habitat.

The Fish Population Response Model was built using a combined dataset from DNR, the University of Michigan, and the U.S. Forest Service that describes abundance of fishes at about 1,700 stream locations in Michigan, gathered over the past 30 years; and the DNR Fisheries Classification GIS framework. Using statistical models, an expected list of characteristic and thriving fish species can be predicted for any segment in Michigan. Several example sites were selected to represent each of the 11 ecological stream types in Michigan. For the Index Flow and Mean July Temperature expected at each site, lists of characteristic and thriving fishes were predicted, and then Index Flow was hypothetically reduced by 10% increments and the resulting expected changes in species abundance were noted. The effects of reduced flow on temperature, and the subsequent effect on species abundance were likewise tracked. These analyses produced 22 Fish Population Response Curves; one highly sensitive "Thriving Species" (early warning flag) curve and one "Characteristic Species" population status curve for each of the 11 stream types (Figure 3); each type shows a fairly distinct response to flow reductions; some types show significant robustness to flow reductions while other types show highly sensitive responses (Zorn et al. 2008).

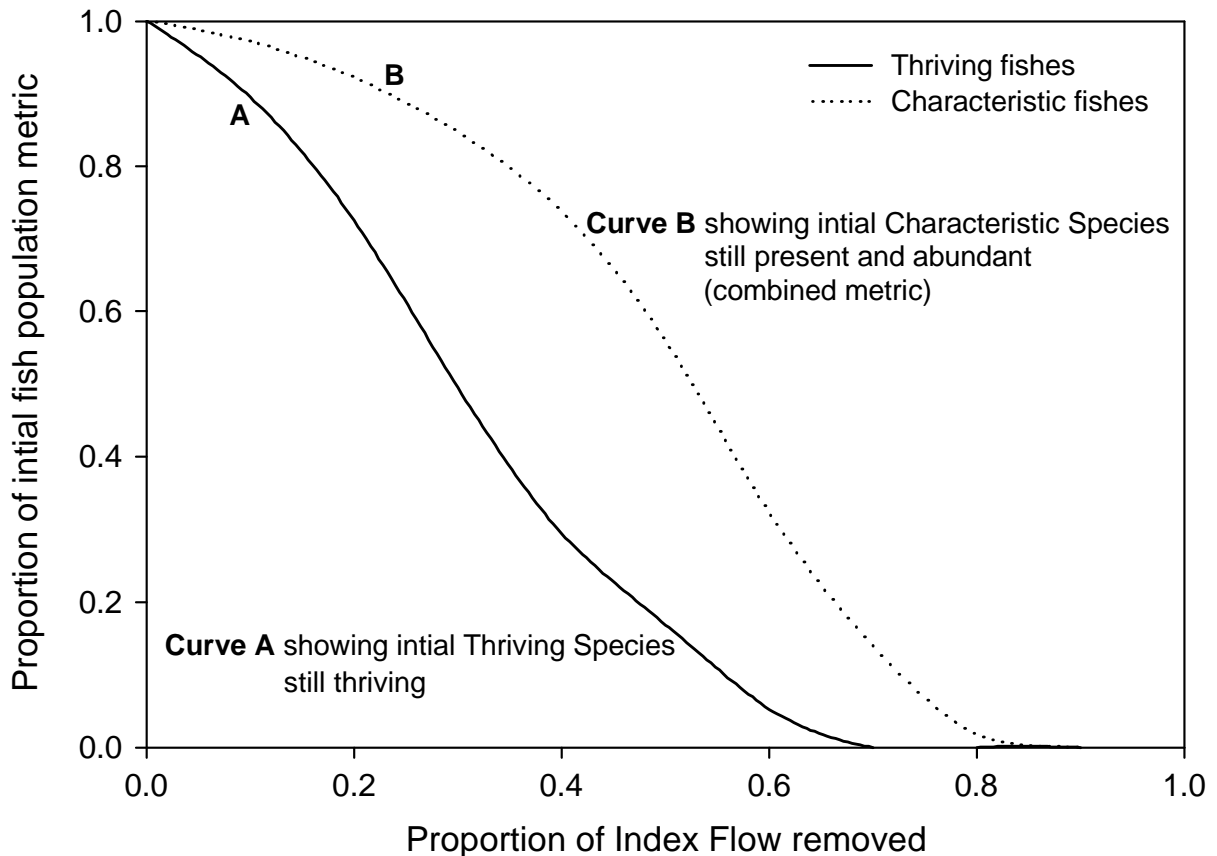


Figure 3.—Example of two curves, showing aspects of how fish populations respond to incremental removal of Index Flow, generated for each river type. Curve A was interpreted as a most-sensitive, early-warning flag. Curve B was interpreted as showing the actual decline in fish population functional integrity. A set of these curves was generated for each stream type.

Determining Acceptable Ecological and Streamflow Withdrawal Thresholds

The fish population response curves were used to frame the stakeholder and legislative discussions leading up to setting the management zones (sensu the ELOHA framework; Poff et al. 2010). The initial drop in the Thriving Species curve indicates the flow reductions where one might begin to be concerned. The overall drop in the Characteristic Species curve indicates where flow reductions would clearly alter the fish populations. The discussion generally took place between these points. Recognizing that these curves presented information on relative risks, rather than develop an absolute pass/fail line, the GWCAC recommended employing a series of four management zones to better reflect the gradient of ecological threats (Groundwater Conservation Advisory Council 2007). The first zone of little risk and the fourth zone of ARI were set as bookends; the second and third zones reflected intermediate and increasing ecological risk. The fact that the various stream types display a range of response slopes allowed for development of a related range of flow allocation standards and policies (i.e., more protective standards and policies were developed for the more sensitive and socially valued stream types).

Based on energetic discussions among societal water use interests, framed by the shape of the fish population response curves for the various river types and the geographic distribution of these river types, the state legislature determined the threshold at which a withdrawal causes an ARI. First the acceptable ecological threshold was considered (y-axis). This process was informed by the narrative

descriptions of ecological deterioration provided by the “Biological Condition Gradient” concept of EPA (Figure 4; Davies and Jackson 2006). The GWCAC concluded (Groundwater Conservation Advisory Council 2007) that by Step 4 of this sequential gradient, “notable replacement of sensitive species,” a stream fish community would have essentially lost its “functional integrity”, causing an ARI. The final legislative placement of the ARI threshold lines are generally consistent with Step 3, where “some replacement of sensitive species” is thought to occur.

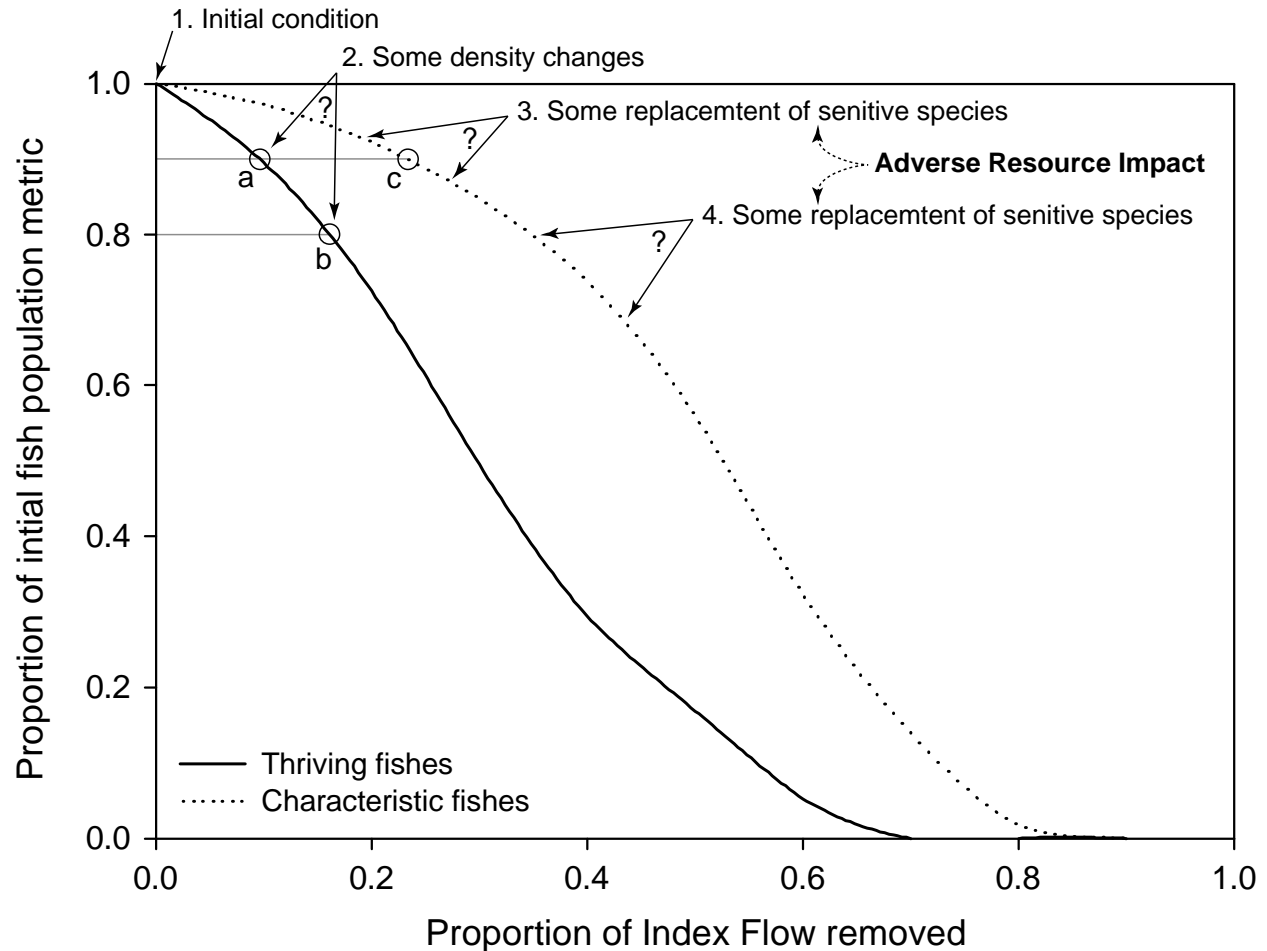


Figure 4.—Changes along the curves were used as the template for determining biologically acceptable (y-axis) thresholds related to ARI and intermediate risk policy zones. Narrative criteria from the Biological Condition Gradient concept (Davies and Jackson 2006), shown as steps 1-4, were used to help define meaningful regions of the curves. Somewhere between steps 3 and 4 was interpreted as Adverse Resource Impact. Also shown, as an example, is the GWCAC initial recommendation for biological thresholds, of 0.9 and 0.8 preservation of fish population metrics, and where these intersected with the curves.

The acceptable ecological thresholds (y-axis) can then be projected from the curves to determine the corresponding acceptable water withdrawal thresholds (x-axis). This was done for the concept of ARI, and for two intermediate risk thresholds, creating four sequential risk zones (Figures 5 and 6). During this process the legislature determined that under no circumstances should more than 25 percent of the Index Flow be depleted from the streamflow. As the expected risk increases, the degree of user responsibility and government oversight increases (Figure 6; Table 2). Water withdrawal

thresholds are thus set by the state legislature for each of the eleven stream types (Figure 7), creating a thoughtful array of allowable ecological changes and related water withdrawals (Tables 3 and 4).

Michigan’s Cold streams are a unique resource in North America. Cold Transitional streams are most sensitive to reductions in flow. Relatively small reductions in flow can dramatically alter these ecosystems so that they will no longer support cold water species like trout. Accordingly, withdrawals from these streams are very limited. For added protection, withdrawals from Cold Transitional streams require a site-specific review by DNR and DEQ staff. Other Cold stream types are afforded added protection through exclusion of Zone B, thereby requiring early notification of other users and interested parties that the watershed is no longer in Zone A.

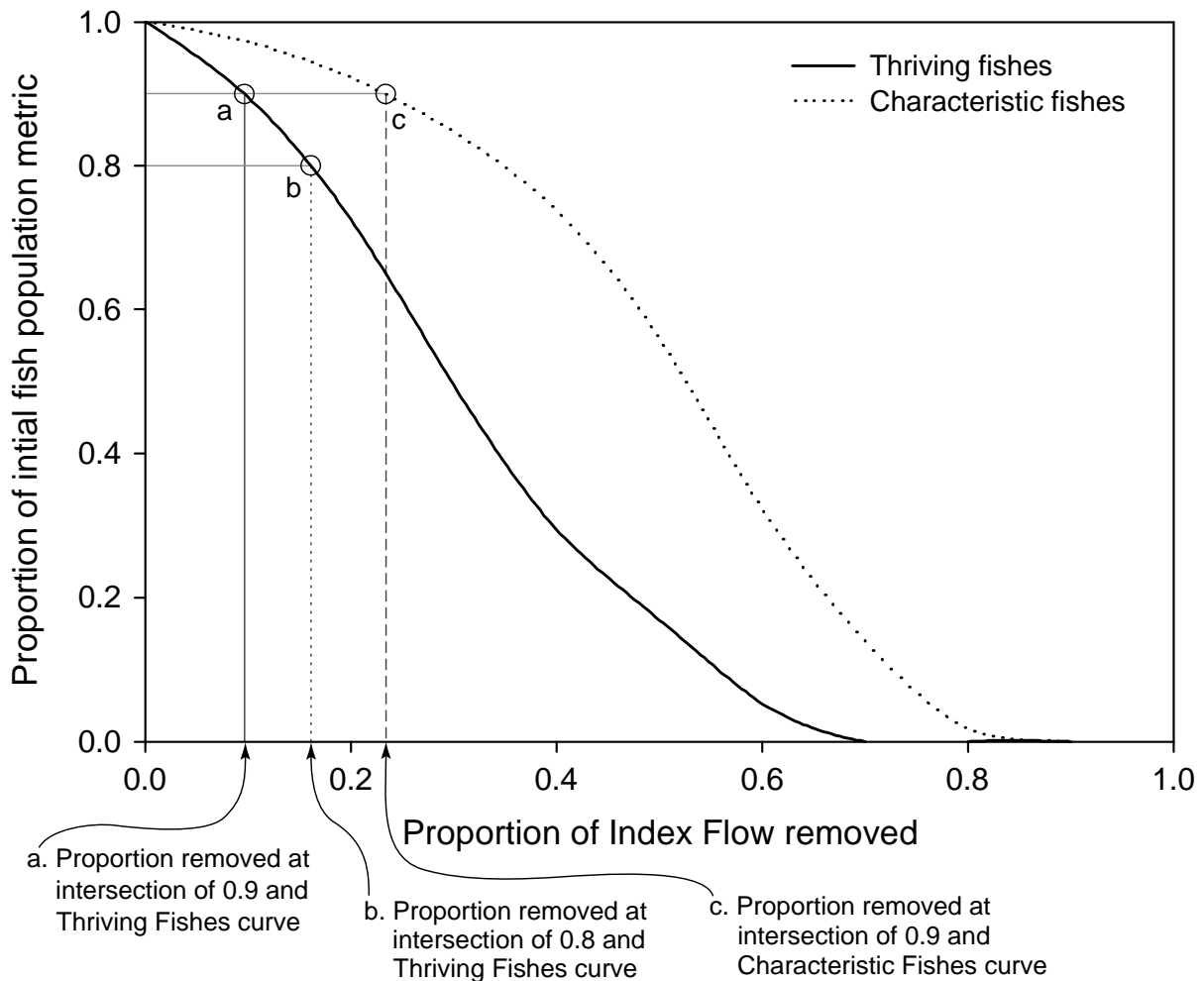


Figure 5.—Illustration of interpolating from the curves to identify 3 policy thresholds for proposed water withdrawals (thresholds A, B, and C along the x-axis). These 3 thresholds create four sequential risk zones that support sequential management rules. This example is based on the initial recommendation of the GWCAC.

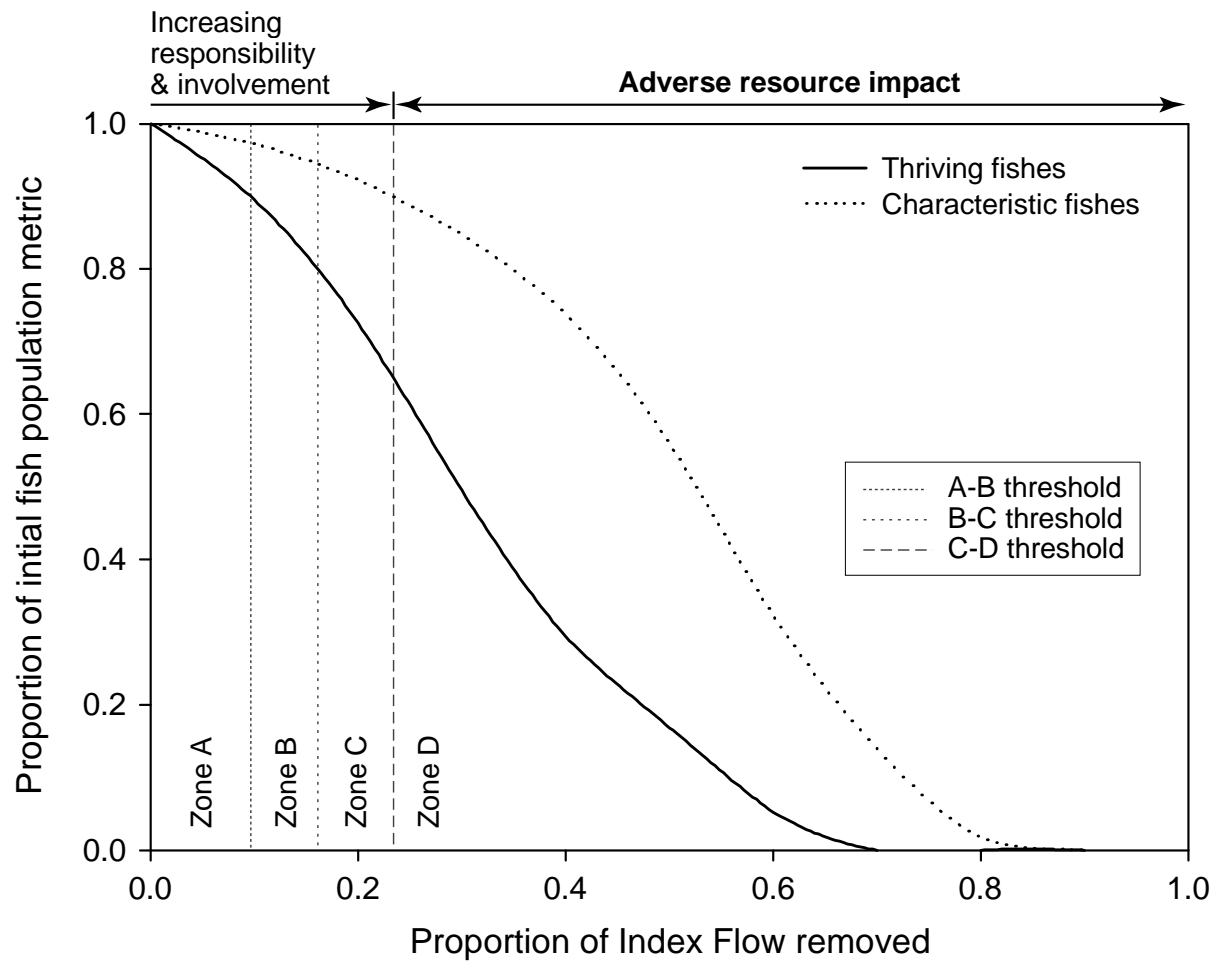


Figure 6.—Illustration of the four sequential policy zones, overlain on the fish population response curves. In this example the zone thresholds on the x-axis (streamflow removal) reflect the initial recommendation of the GWCAC.

Table 2.—Water withdrawal management zones and related management determinations and requirements. Illustrates increasing user involvement and responsibility.

Management zone	Determination and requirement
Zone A—little risk	<ul style="list-style-type: none"> • Register and proceed with proposed withdrawal.
Zone B—alert and attention	<ul style="list-style-type: none"> • Register and proceed with proposed withdrawal. • Cold Transition systems are automatically placed in Zone B and a site-specific review is required. • DEQ notifies: groups that have requested notification, such as: conservation district, regional planning agency.
Zone C—concern and prevention	<ul style="list-style-type: none"> • Site-specific review required. • Certify use of environmentally sound and economically feasible conservation measures. • DEQ notifies: large quantity users (of the same water source); and local governments and groups that have requested notification.
Zone D—Adverse Resource Impact	<ul style="list-style-type: none"> • Site-specific review required. • Cannot proceed if confirmed in Zone D. • Potential for “preventative measures”.

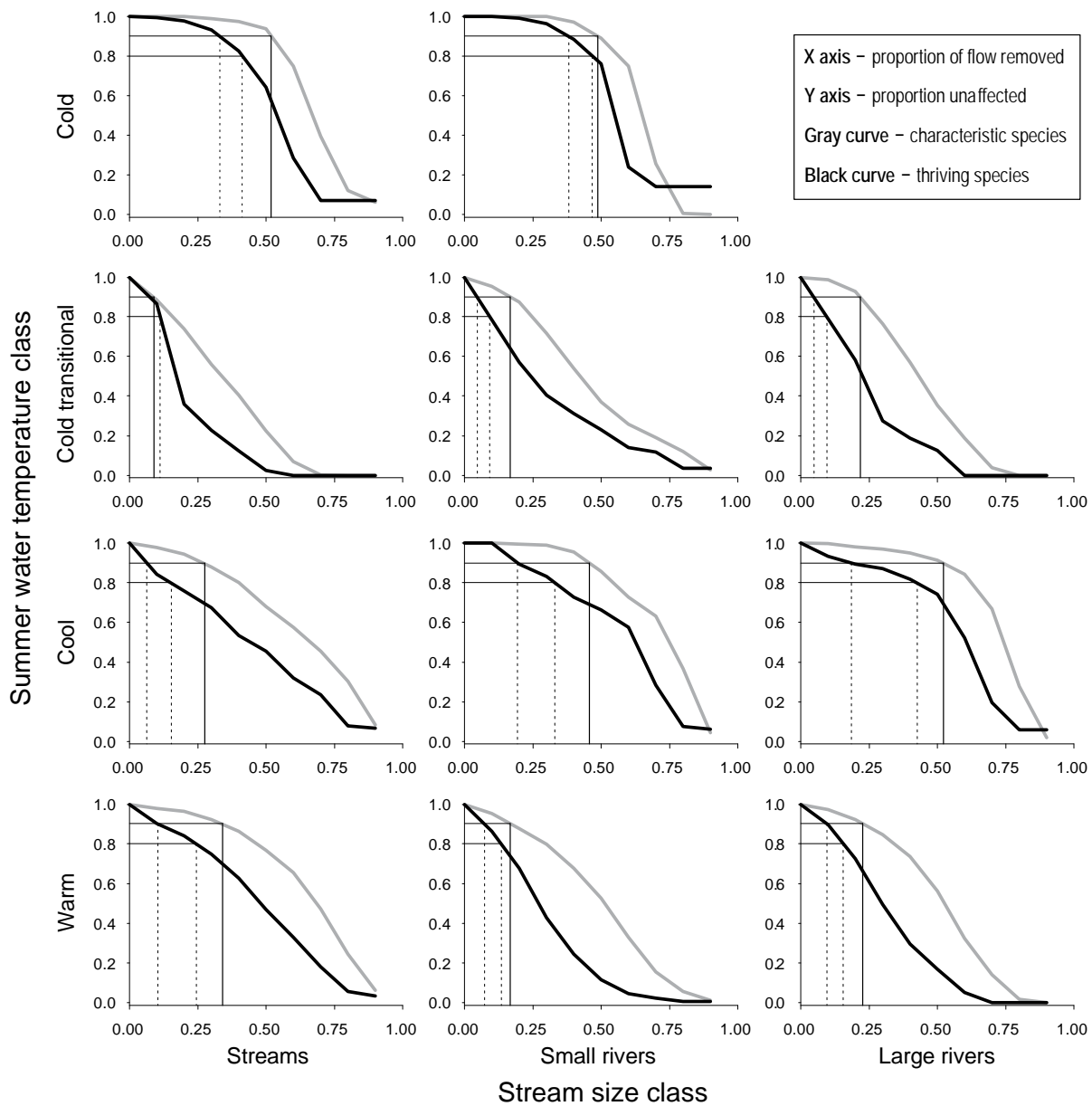


Figure 7.—Curves describing fish population responses to increasing water withdrawals for Michigan’s 11 stream types, as characterized by size and summer water temperatures. Axes labels are: x: Proportion of Index Flow removed; and y: Proportion of initial fish population metric. The black curve shows the proportion of Thriving Species still thriving, while the grey curve shows the mean of proportional changes in Characteristic Species remaining and their abundances. The 3 vertical lines show thresholds between, left to right: Zones A and B, Zones B and C, and Zone C and Adverse Resource Impact (Zone D). Note that these are not the final lines; they illustrate applying uniform standards to each stream type. The final legislative zones are described in tables 3 and 4.

Table 3.—Water Withdrawal zones used in the Michigan Water Withdrawal Assessment Tool, as defined by the potential reduction in stream fish populations caused by cumulative water withdrawals.

Ecological Stream Types		Water Withdrawal Management Zones			
		Zone A	Zone B	Zone C	Zone D (ARI)
Cold	Streams	Less than a 1% reduction in the density of Thriving Fish Populations	None	1-3% reduction in the density of Thriving Fish Populations	3% or more reduction in the density of Thriving Fish Populations
	Small Rivers	Less than 50% of the withdrawal that would result in an Adverse Resource Impact	None	50% or more of the withdrawal that would result in an Adverse Resource Impact, but less than a 1% reduction in the density of Thriving Fish Populations	1% or more reduction in the density of Thriving Fish Populations
Cold Transitional	Streams Small Rivers Large Rivers	None	Less than a 5% reduction in the density of Thriving Fish Populations	None	5% or more reduction in the density of Thriving Fish Populations
Cool	Streams	Less than a 10% reduction in the density of Thriving Fish Populations	10-20% reduction in the density of Thriving Fish Populations	20% or more reduction in the density of Thriving Fish Populations, but less than a 10% reduction in the abundance of Characteristic Fish Populations	10% or more reduction in the abundance of Characteristic Fish Populations
	Small Rivers	Less than a 5% reduction in the density of Thriving Fish Populations	5-10% reduction in Thriving Fish Populations	10-15% reduction in the density of Thriving Fish Populations	15% or more reduction in the density of Thriving Fish Populations
	Large Rivers	Less than a 8% reduction in the density of Thriving Fish Populations	8-10% reduction in the density of Thriving Fish Populations	10-12% reduction in the density of Thriving Fish Populations	12% or more reduction in the density of Thriving Fish Populations
Warm	Streams	Less than a 10% reduction in the density of Thriving Fish Populations	10-15% reduction in the density of Thriving Fish Populations	15% or more reduction in the density of Thriving Fish Populations, but less than a 5% reduction in the abundance of Characteristic Fish Populations	5% or more reduction in the abundance of Characteristic Fish Populations
	Small Rivers Large Rivers		10-20% reduction in the density of Thriving Fish Populations	20% or more reduction in Thriving Fish Populations, but less than a 10% reduction in the abundance of Characteristic Fish Populations	10% or more reduction in the abundance of Characteristic Fish Populations

Table 4.—Allowable percentage reduction in Index Flow used in the Michigan Water Withdrawal Assessment Tool.

Ecological Stream Types		Water Withdrawal Management Zones			
		Zone A	Zone B	Zone C	Zone D (ARI)
Cold	Streams	<14%	None	14 – <20%	≥20%
	Small Rivers	<10.5%		10.5 – <21%	≥21%
Cold Transitional	Streams	None	<4%	None	≥4%
	Small Rivers		<2%		≥2%
	Large Rivers		<3%		≥3%
Cool	Streams	<6%	6 – <15%	15 – <25%	≥25%
	Small Rivers	<15%	15 – <19%	19 – <25%	≥25%
	Large Rivers	<14%	14 – <19%	19 – <25%	≥25%
Warm	Streams	<10%	10 – <18%	18 – <24%	≥24%
	Small Rivers	<8%	8 – <13%	13 – <17%	≥17%
	Large Rivers	<10%	10 – <16%	16 – <22%	≥22%

Screening Tool

Groundwater Withdrawal Model—Run Dynamically in the Screening Tool

The Screening Tool assumes that surface-water withdrawals come directly from the stream segment associated with the WMA where the proposed withdrawal is located. In this case, the maximum withdrawal rate is subtracted from the “available water” portion of the Index Flow. This is because there is an immediate reduction in the streamflow equal to the instantaneous withdrawal.

For groundwater withdrawals, the situation is more complicated and requires use of a Groundwater Withdrawal Model. Effects of groundwater withdrawals on streams are not instantaneous; it may take weeks, or years for a groundwater withdrawal to affect streamflow. Groundwater withdrawals may affect only the closest stream segment or they may be distributed among adjacent stream segments. Intermittent groundwater withdrawals may have substantially less impact on streams than continuous withdrawals. The impact on a stream of a groundwater withdrawal from a sand-and-gravel aquifer will be substantially different than one from a confined limestone aquifer. Therefore, the Screening Tool must take into account the type of withdrawal (groundwater or surface water), the amount and continuity of the withdrawal, the depth of the well, the distance of the well from the stream, the aquifer properties of transmissivity and storativity, and the streambed conductance. The first four factors are input by a person wishing to make a withdrawal and the last three factors are calculated by the Groundwater Withdrawal Model. The result within the Screening Tool is a reduction in streamflow calculated for every affected nearby stream segment, given the specific characteristics of a proposed withdrawal.

An easy to calculate analytical model which uses simplified assumptions regarding aquifer geometry and properties was selected for the Groundwater Withdrawal Model (Reeves et al. 2009). This analytical model describes streamflow depletion by a pumping well, for a partially penetrating stream, in an infinite aquifer with streambed resistance between the stream and the aquifer. This analytical model is appropriate for Michigan streams, which typically do not fully penetrate the aquifers used for water supply, and it is sufficiently simple for statewide screening. For the Screening Tool, an Internet-accessible version of the analytical model was developed that includes the option to simulate intermittent pumping. This modeling approach is possible because of work that generalized

aquifer properties across the state in the Michigan Ground Water Inventory and Map (GWIM) database (Michigan Department of Environmental Quality 2005).

Streamflow depletion depends on aquifer and streambed properties, the distance from the well to the stream, and time. The aquifer is assumed to remain in hydraulic contact with the stream, which means that the pumping well does not cause the hydraulic head in the aquifer to be lower than the streambed. The aquifer is assumed to be infinite, and, therefore, no additional data regarding the aquifer geometry are required by the model beyond the distance between the well and the stream. The remaining model input includes transmissivity, streambed conductance, storage coefficient, pumping rate, and time desired for the evaluation. The GWIM database information is used to assign transmissivity, streambed conductance, and storage coefficient in the Groundwater Withdrawal Model.

Transmissivity is the measure of how easily water flows through the aquifer. The GWIM database includes estimates for aquifer transmissivity mapped to a 1-km by 1-km (3,280 ft by 3,280 ft) grid across the State for glacial deposits and bedrock aquifers. The median transmissivity for the GWIM grid cells within each WMA is assigned to the corresponding stream segment and used in the Groundwater Withdrawal Model. The median was selected as the representative statistic instead of the arithmetic mean because the median is less influenced by extremely low or high transmissivity estimates in the database and therefore may be the more reasonable statistic for screening-level estimation.

Streambed conductance is a measure of how easily water moves between the stream and the aquifer. It is affected by the vertical thickness of the aquifer between the well point and the stream, the width of the stream, and the vertical hydraulic conductivity. The distance from the bottom of the stream to the top of the well screen or open interval, is provided as the well depth by the user. For the statewide screening, the stream width is estimated by use of a regression equation developed to relate stream width to drainage area of a stream segment (T.G. Zorn, Personal Communication, DNR, Marquette). An estimate of the vertical hydraulic conductivity of the aquifer is computed by dividing the median transmissivity by the average thickness of aquifer material for each WMA. This thickness is estimated by interpolating the thickness used for the wells in the GWIM transmissivity-estimation procedure to a 1 km by 1 km grid over the state and then computing the mean estimated thickness for the grid cells within each WMA. To avoid dividing by zero in areas where glacial deposits are thin, a minimum value of 5 ft is assigned. A factor of 1/10 is included in the estimated streambed conductance to account for the anticipated increased resistance to flow in the vertical direction primarily because of layering of aquifers in Michigan. This factor is reasonable for aquifers without clay units and probably underestimates the resistance to flow in areas where clay layers are present, which would tend to make the model overestimate stream depletion in these areas. It is not currently possible in Michigan to identify the presence and impact of local clay layers. This level of detail is appropriately covered in site-specific review.

The storage coefficient is a measure of how much water is available in storage within the aquifer matrix. For a reasonable, yet conservative estimate that is consistent with the observed uncertainty in the estimated storage coefficients across the state, a constant value of 0.01, which is representative of a leaky aquifer, is used in the Groundwater Withdrawal Model.

Unlike direct surface water withdrawal, groundwater withdrawals potentially affect streams in neighboring WMAs. The analytical solution, however, estimates streamflow depletion only between the well and a single stream. The analytical solution was extended by assuming that the impact of pumping can be described by superimposing the solution to several individual streams. The total withdrawals was distributed between the neighboring WMAs using inverse distance weighting. The inverse distance method was selected for the Groundwater Withdrawal Model because (1) it produces a reasonable overall pattern of streamflow depletion compared to a numerical ground-water-flow model, (2) it is the most straightforward to implement in the Internet-based Screening Tool, and (3) it has some theoretical basis in steady-state analysis (Reeves et al. 2009).

Relationship Between Bedrock Aquifers and Streams

Bedrock aquifers are used for water supply in many parts of Michigan. To account for different potential bedrock conditions in the Screening Tool, the bedrock aquifers are grouped into four categories (Figure 8). In some areas of the state bedrock aquifers are separated from overlying streams by thick glacial deposits containing layers of material with low hydraulic conductivity, such as silt or clay. In these areas, the hydraulic connection between these aquifers and nearby streams is limited. Two of the categories have this characteristic. One has the potential to hit saline water with depth. The Screening Tool does not try to predict this, it simply groups these two categories together based on potential impact on streams. Bedrock wells in these areas, up to the amount that requires a permit, will receive a Zone A designation. In other areas, there may be a greater hydraulic connection between the bedrock aquifer and overlying streams. Finally, in some areas of the State, bedrock aquifers are not suitable for high-capacity wells. In these last two areas, the Screening Tool assumes a connection between the aquifer and streams and makes the depletion calculation as it does for glacial material. The user is given a disclaimer that the Screening Tool does not predict the quantity or quality of water that may be available from wells.

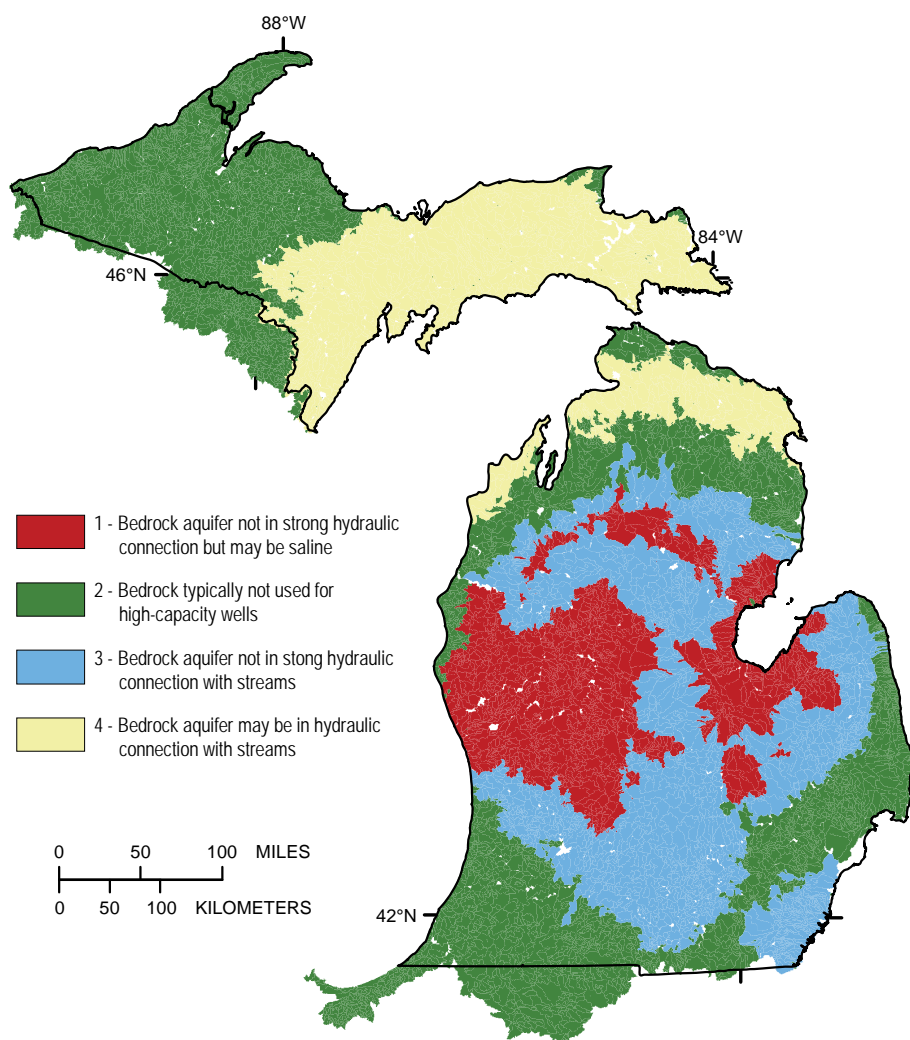


Figure 8.—Four bedrock categories used in Screening Tool. Aquifers in category 1 are typically not adequate for large quantity withdrawals. Aquifers in categories 2 and 3 have limited connection to the overlying streams, wells completed in these formations will receive a Zone A pass. Aquifers in category 4 may be hydraulically connected to streams; for these, stream depletion is calculated the same way as for glacial drift wells (Reeves et al. 2009)

Miscellaneous Assumptions Used in the Screening Tool

Shoreline watersheds.—Michigan contains about 600 small watersheds that drain directly into the Great Lakes. Many of these do not have defined streams. These are considered to be hydrologically well connected with the Great Lakes, so that any withdrawal in these areas takes the water directly from the Great Lakes. Any withdrawal, up to the larger amount that requires a permit, will receive an A zone pass.

Simulation period in Groundwater Withdrawal Model.—During the development of the Screening Tool, regional groundwater models were run to evaluate the appropriateness of some assumptions used in applying the analytical model here (Reeves et al. 2009). In general, it was found that the effects of large pumping wells reached a steady state impact on neighboring streams within one to two years. A five year simulation period is used in the Screening Tool; this is expected to yield a reasonable, yet conservative solution.

Streamflow depletion in neighboring WMAs.—All neighboring WMAs are identified that touch the source WMA. A streamflow depletion is calculated for each one based on the distance from the well to the nearest stream segment in each WMA. This method can yield nonsensical results, such as calculating depletions from streams that are far away when a major stream is nearby, or on the other side of a major stream. To minimize these situations and recognize that drawdown cones stabilize when they reach stream boundaries that can supply the withdrawal demand, withdrawal from individual WMAs are evaluated and withdrawals are applied in the WMA accounting only if the estimated depletion is more than half the maximum estimated depletion. This reduces the number of streams affected to those closest to the withdrawal point and limits the evaluation to those having the greatest potential to significantly contribute to the withdrawal. In addition, neighboring streams are only considered if the withdrawal triggers a Zone D response. Neighboring streams with Zone B or C responses are not flagged by the Screening Tool.

Possible ARIs in Cold Transitional streams downstream of Cold stream withdrawals.—The amount of water that can be withdrawn from Cold Transitional streams is restricted because of the sensitivity of these streams to small changes in flow or temperature. Proportionately much more water can be removed from Cold streams. Because of this combination of potential withdrawals, it is possible to cause an ARI in a Cold Transitional watershed that is downstream of a Cold stream where the withdrawal occurs. To prevent this, the maximum amount of water available in all upstream Cold streams is limited to no more than that available in the downstream Cold Transitional stream.

Withdrawal from a shallow pond.—The withdrawal is calculated as from a 10 foot deep well.

Example of the Screening Tool Calculation of Streamflow Depletion

The following is a hypothetical example to illustrate the computations used in the Screening Tool based on Reeves et al. (2009.) A 200 gpm well is proposed, screened at 150 feet deep in glacial drift. The well is located 2,500 ft from the stream within its source watershed, which has a drainage area of 29 mi². There are three neighboring watersheds; the well is located 4,000, 20,000, and 25,000 ft, respectively, from the closest stream in each watershed. The inverse distance method is used to determine the proportional contribution of each watershed to the pumping well. The fraction of pumping attributed to watershed(i) is:

$$Q_i = Q_w \cdot (1/d_i) / \sum(1/d_i)$$

where,

$$Q_w = \text{pumping well rate (gpm)}$$

$$d_i = \text{distance from well to closest stream point in watershed}(i).$$

Aquifer characteristics and streambed conductance must be determined to calculate the streamflow depletion. Streambed conductance is the product of the vertical hydraulic conductivity (K_v) and an effective stream width (w), divided by the thickness of the vertical resistance layer (well depth in feet). The effective stream width (in feet) is:

$$w = 3.28 \cdot (10^{((.522358 \cdot \log(DA \cdot 1.60932)) - 0.18786)})$$

where,

$$DA = \text{drainage area (mi}^2\text{)}.$$

For this example, the drainage area is 29 mi², therefore $w = 20$ ft.

The vertical hydraulic conductivity is 10% of the horizontal hydraulic conductivity (K), and $K = T/b$, where T is transmissivity (ft²/day), and b is the aquifer thickness (ft) used in calculating T for use in the Screening Tool. For this example, $T = 5000$ ft²/day and $b = 100$ ft, therefore $K = 50$ ft/day and $K_v = 5$ ft/day. The well depth is 150 ft. Note it can be different than the aquifer thickness used above, which is based on generalized data over a large area. The other parameters are the same as used in the Screening Tool: the aquifer storage coefficient (S) is 0.01, and the pumping duration (t) of the well is 1825 days (5 years). The streamflow depletion attributed to the stream in each watershed(i) is:

$$Q_s = Q_i \cdot (\text{erfc}(A) - \exp(B+C) \cdot \text{erfc}(\sqrt{B}+A))$$

where,

$$L = K_v \cdot w / \text{well depth}$$

$$A = \sqrt{S \cdot d^2 / (4 \cdot T \cdot t)}$$

$$B = (t \cdot L^2 / (4 \cdot S \cdot T))$$

$$C = L \cdot d / (2 \cdot T).$$

The results are found in Table 5. The streamflow depletion in neighbor watershed 1 is more than one half the maximum value found in the Source watershed. Therefore, the streamflow depletions from both the Source and neighbor 1 watersheds will be subtracted from the available water in the Water Accounting Database. The depletion values from the other two neighboring watersheds will not be used.

Table 5.—Example calculation results using the Screening Tool algorithms.

	Source watershed	Neighbor watershed			Sum
		1	2	3	
Distance of stream from well (ft)= d_i =	2,500	4,000	20,000	25,000	
Inverse distance= $1/d_i$ =	0.00040	0.00025	0.00005	0.00004	0.00074
Fraction of pumping = $f_i = ((1/d)/\text{sum}(1/d_i))$ =	0.54	0.34	0.07	0.05	1.00
Pumping from each watershed (gpm)= $Q_i = f_i * Q_w$ =	108	68	14	11	200
Q_s/Q_i =	0.70	0.68	0.44	0.38	
Stream depletion (gpm)= Q_s =	76	46	6	4	

Water Accounting Database

A Water Accounting Database is linked with the Screening Tool. It keeps track of how much water is available in each WMA, dynamically adjusting it as new withdrawals are registered. This allows users to have up-to-date water use information when they are planning new withdrawals.

The database is initially populated with: the initial estimated Index Flow at the downstream end of each WMA; a safety factor where the Index Flow is divided by two; and the amount of water available for withdrawal calculated according to stream classification. Operation of the Water Accounting Database is graphically illustrated with a hypothetical example in Figure 9. The regression equation predicts an Index Flow, and the management zones are proportionally set based on the stream type. In this case, 3000 gpm are available before reaching the Zone D (ARI). The values are divided by two and entered into the database, 1500 gpm are now available from the Screening Tool. The first registered withdrawal (W1) of 500 gpm reduces the available water to 1000 gpm and places the WMA in the Zone B. The next proposed withdrawal (W2) of 700 gpm would place the WMA into Zone C, therefore a site-specific review (SSR) is required. The review determines that the best estimate of the Index Flow results in 3600 gpm being available. Note the entire value is entered into the database, and since a detailed review was completed, there is no longer a need for the safety factor. When the two withdrawals are subtracted, 2400 gpm are now available, and the WMA is in the Zone B.

This database is updated every time a transaction is recorded. When a new use is registered, the withdrawal capacity is subtracted from the water available. It can be further adjusted to reflect actual water used after it is reported. When a site-specific review is performed, the water available is adjusted to reflect the more accurate Index Flow determinations for the WMA. All transactions are also recorded in a Transactions Table in the database. The tables are cross-linked allowing administrators to select a WMA and view all transactions that have occurred in that WMA, or view a registration associated with a particular transaction. In order to navigate and retrieve information more quickly from the database some pre-built queries were programmed.

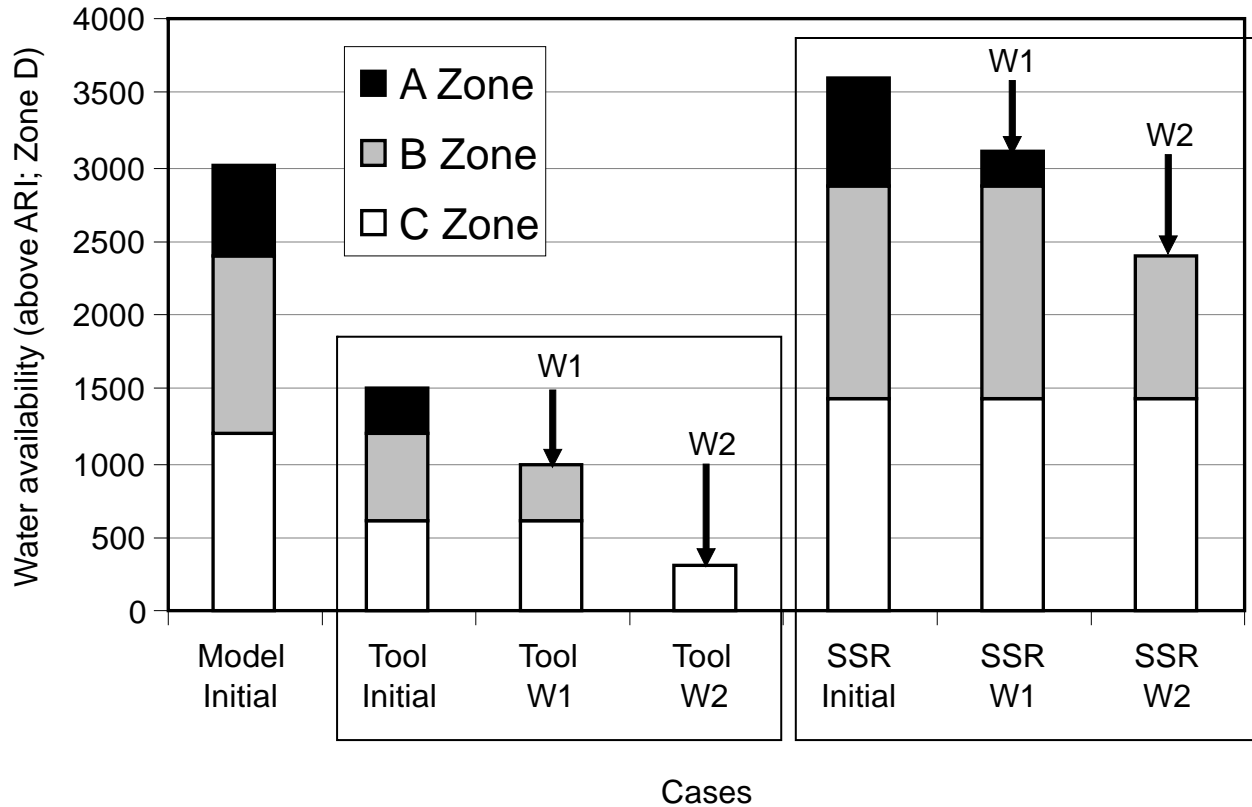


Figure 9.—Operation of the Water Accounting Database. This example illustrates how the initial estimate of the Index Flow is divided by two (as a safety factor) for use in the Screening Tool. Each time a new water withdrawal is registered, the associated streamflow depletion is subtracted from the water available in the affected Water Management Areas. When a proposed withdrawal lowers the available water into Zones C or D, a Site-Specific Review is required. The SSR may result in more or less water available than the initial regression model estimate. Since site specific factors are accounted for, there is no need to continue using a safety factor. The registered depletions are now subtracted from the water available based on the entire Index Flow determined in the SSR. Note it is expected that 90% of the time there will be more water available than indicated by the initial value used in the Screening Tool because of the safety factor.

Operation of the Internet-based Screening Tool

The water-withdrawal Screening Tool is designed to be accessed through the Internet. This access requires the integration of several technologies. The Screening Tool essentially implements the analytical model and inverse-distance weighting distribution method described above, but with different computer software than used in the testing and development. A brief list of steps illustrates how the Screening Tool operates. GIS software provides a map interface to the Screening Tool for the user (see also Figure 10):

- 1) When the user enters the location for a new withdrawal, the computer determines the WMA containing the proposed well (the source WMA).
- 2) If the proposed pumping rate is greater than 2 MGD, the user is notified that a permit may be required under the statute and directed to contact the department.

- 3) If a surface water withdrawal is specified, the Screening Tool goes to step 5 then step 9, considering that 100 percent of the withdrawal is removed from the source WMA (in a few cool and warm streams the WMA for a surface water withdrawal is smaller than for a groundwater withdrawal because of statutory requirements.)
- 4) The user specifies information about the proposed well: depth, pumping rate, pumping schedule, and if it is in glacial deposits or bedrock. If bedrock, then the bedrock type for the source WMA is identified. Certain types will receive a Zone A designation.
- 5) A GIS data file is accessed to gather the aquifer properties assigned to the source WMA. If it is identified as a Great Lake shoreline watershed, it will receive a Zone A designation.
- 6) The affected neighboring WMAs are similarly identified.
- 7) The distances from the proposed well to the nearest stream segment in each of the source and neighboring WMAs are computed.
- 8) The analytical model is run for the nearest stream segments in each of the source and neighboring water management areas. The calculation uses the aquifer properties for the source WMA containing the well and the distances computed in step 5. For steady pumping, the solution is evaluated after 5 years of pumping. If the user specifies intermittent pumping, then superposition is used to compute the maximum streamflow depletion during the 5-year evaluation period.
- 9) The streamflow depletion is distributed between the neighboring WMAs using inverse distance weighting. The total withdrawal is apportioned to each of the water management areas based on inverse distance weighting. The maximum depletion is determined, and any WMAs that have at least half this maximum value have that amount removed from the available water in the Water Accounting Database.
- 10) The results are compared to the amount of water available in the source and neighbor WMAs. Direction is given, depending on what zone will result from this proposed use. The management options, depending on zone are summarized in Table 2.

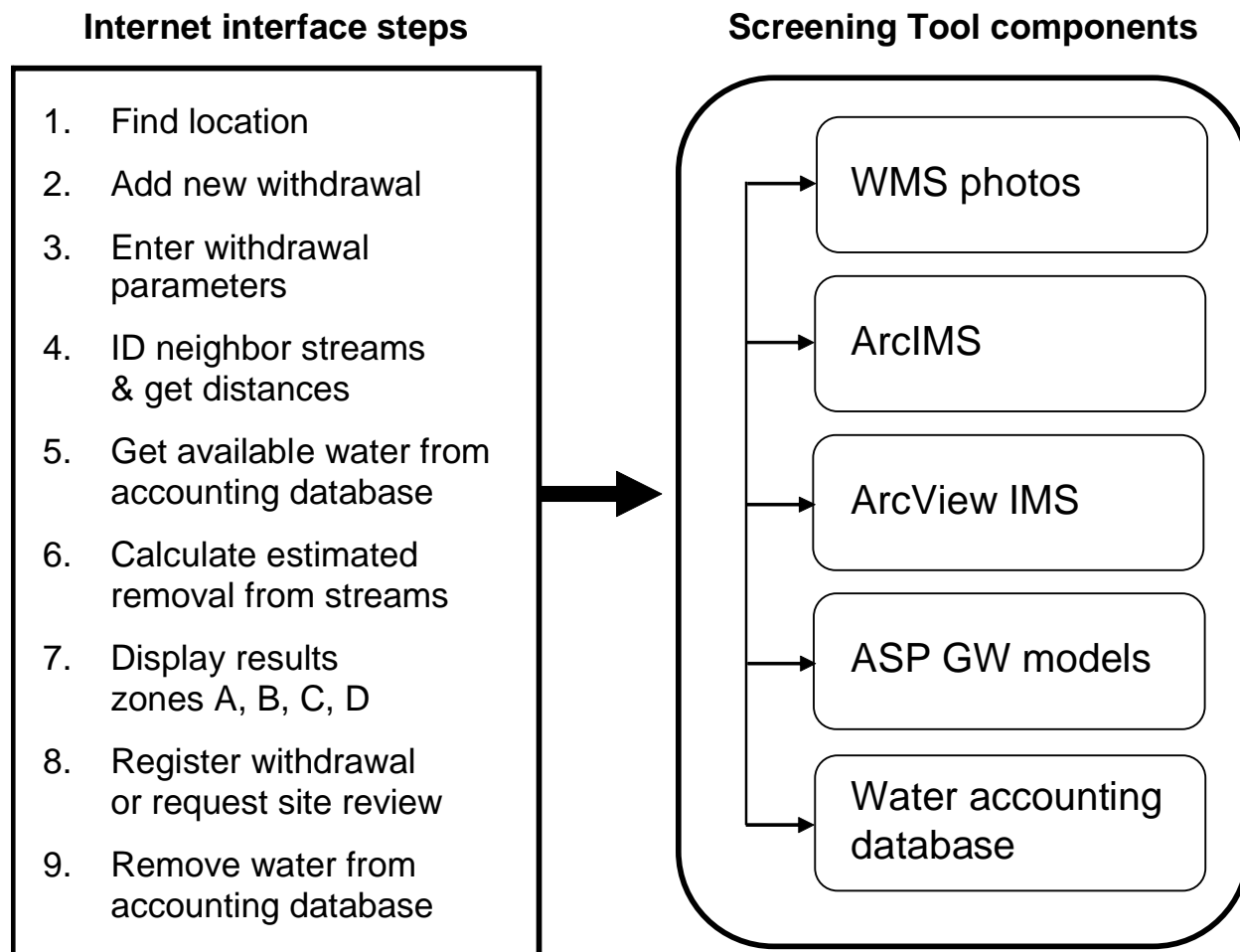


Figure 10.—Operational steps in the interface of the internet screening tool, and primary model components of the tool.

Screening Tool Evaluation

Whether the Tool Works Appropriately as a “Screen”—Testing Existing Wells

The Screening Tool is designed to provide users with results that will both protect the state’s water resources and efficiently authorize acceptable water withdrawals. To assure efficiency, the Screening Tool should authorize withdrawals that are small relative to the available water resources. To protect the aquatic environment, it should flag for site-specific review any proposed withdrawal that is so large relative to the available water that it has the potential to cause an ARI. Two performance tests were conducted before Screening Tool use became mandatory on July 9, 2009. Actual well information was entered into the Screening Tool and the results were evaluated. The expectation from the Groundwater Conservation Advisory Council was that water resources are abundant across most of the state but limited in specific areas, thus Screening Tool determinations should reflect this pattern.

In the first test, fifteen random large capacity wells were selected from each Michigan county using the entire Wellogic data base (water well logs filed with the state). If fifteen large capacity wells were not recorded in a county, the number available, if any, was used. This provided a

geographically distributed test. A total of 800 wells were used in this first test. The second test included all large capacity wells recorded in Wellogic since the water withdrawal legislation went into effect February 6, 2006. There were 545 wells used in the second test.

The results were very similar from the two tests (Table 6). The numerous cases where a proposed withdrawal will obviously not cause an ARI were identified and automatically authorized. Users can expect an “A zone” approval almost 80% of the time. Site-specific reviews can be expected because of a possible ARI only 10% of the time, and reviews because of Zone C or Cold Transitional watersheds only 7% of the time. The actual percentage of required site-specific reviews will likely be less because many users will be able to modify their proposal, based on information from the tool, so that they subsequently obtain approval through the tool.

Further review of 545 large capacity wells installed after February 2006, confirmed that these results are reasonable. Approximately 10% of the wells are located in bedrock that is isolated from streams or are in small watersheds immediately adjacent to the Great Lakes (flow directly into the Great Lakes); withdrawals from groundwater in both of these cases receive an automatic approval from the Screening Tool as not likely to cause an ARI. Roughly 68% of the wells are located in watersheds where the available water, before possibly causing an ARI (based on the hydrology model used in the tool), is at least eight times more than the projected streamflow depletion. Most of the remaining 22% of wells will either require a site-specific review, or fall within the Zone B where notification of watershed interests is required prior to developing the proposed well. When the tool becomes fully operational, it will also keep track of cumulative withdrawals, and identify those watersheds where the combined effect of all of the new or increased withdrawals may cause ARIs.

This review determined that Screening Tool determinations accurately reflect the distribution of water availability across Michigan. It gives an automatic authorization in 80% of typical cases statewide and further detailed inspection of these substantiated an abundant water supply. The Screening Tool flags a smaller set of cases either where proposed withdrawals are large enough to warrant further attention by DEQ staff or where aquatic ecosystems are especially sensitive; these cases receive focused attention by DEQ staff when requested. Thus the Screening Tool does: 1) provide an efficient statewide program tool; and 2) carry out the appropriate screening function.

Table 6.–Results from processing two sets of actual well data through the Screening Tool. Percentage results that highlight both ends of the assessment spectrum (Zones A and D) are highlighted in bold font. Note the consistency in the percentages from the two independent evaluations.

Screening tool results	From a stratified (by county) random set of wells across the state		Using actual constructed wells since Feb 2006 from the well registration data	
	Number	Percent (%)	Number	Percent (%)
Total number of wells used in the evaluation	800		545	
Over the ARI in source watershed (Zone D)	59	7	38	7
Over the ARI in neighboring watershed (Zone D) ^a	17	2	16	3
Total number flagged as over the ARI	76	10	54	10
Zone C in source watershed	18	2	10	2
Zone B in source watershed (cold, cool, or warm)	34	4	40	7
Zone B in source watershed (Cold Transitional)	40	5	26	5
Zone A in source watershed	649	81	431	79
without neighboring ARI ^a	637	80	417	77

^a The count in each zone was revised to subtract wells that cause an ARI in a neighboring watershed. Seventeen wells were over the ARI were in neighboring watersheds while 59 were in the source watershed for a total of 76 watersheds flagged or approximately 10%.

Comparing Screening Tool Response with Site-level Review

The Screening Tool is based on statewide information that involves many generalizations. The tool gives an accurate representation of general hydrologic conditions in various regions across the state. However, it is recognized that the Screening Tool cannot possibly reflect the specific conditions at every site in the state. Site-specific reviews are appropriate and necessary to resolve questions of potential environmental impact when the tool flags a concern regarding possible ARI. Site-specific review means using additional hydrologic and other information that is available for a particular site to most accurately determine the likely impact of a water withdrawal on the neighboring water resources. As part of our evaluation, site-specific reviews from nine sites were compared with the results from the Screening Tool, and lessons gleaned.

In every case, the Screening Tool results were logical and appropriate (Table 7). This can be effectively illustrated by describing two situations where the tool determined that an ARI was likely. The first example was a proposed surface water withdrawal from a relatively small stream. The tool appropriately determined there was not enough water in that stream to support the withdrawal. However the site-specific review, confirmed by a site inspection, found the location was in backwater from a dam located on a much larger river. Therefore, since the water would actually be from the large river, the impact would be in Zone A and the withdrawal could be approved. The second example was a proposed well located in the watershed of a large river but near a small cold stream. The Screening Tool indicated an ARI was likely to the cold stream. The site-specific review determined that the proposed well would be in a deep aquifer that is not connected to the shallow aquifer that sustains the cold stream. Therefore, the proposed well would not adversely impact the stream and it could be approved. This determination could not have been reached without the site-specific review. Both of these cases reflect the additional flexibility in allowing water uses from the site-specific review process as the Council and the legislation had envisioned.

Table 7.—Comparison of selected Screening Tool results with site specific evaluation results.

Number of Sites	Screening Result	Site-specific Result
2	Zone A; withdrawal authorized	Confirmed Zone A
3	ARI; site-specific review needed	Confirmed likely ARI
2	Zone C; site-specific review needed	Determination warranted site-specific review
2	ARI; site-specific review needed	Withdrawal allowed as a result of site-specific review

Results from the First Year of Operation

The full WWAP went into effect on July 9, 2009 when use of the Screening Tool became mandatory for everyone that proposed a large quantity withdrawal (LQW). In the first year of operation, 216 proposed LQWs were processed. Eighty four percent of these were for agricultural use. A total of 172 registrations were automatically approved and registered through the Screening Tool (80% of the total). An additional 44 Site-Specific Reviews (SSRs) were finalized and recorded in the Water Accounting Database. Details of the reasons the Screening Tool referred users to a SSR and the final determinations are shown in Table 8. The results are consistent with the test results generated during the process development. The Screening Tool was designed to be conservative, to

minimize the potential of overestimating the amount of water available and mistakenly authorizing an ARI. But it was also designed to authorize withdrawals where there was clearly an abundance of water relative to the proposed withdrawal. The comparison of the zones as determined by the Screening Tool and after professional review in the SSR confirms that the process is operating as designed (see Table 9). The vast majority of applications were automatically authorized, and a relatively small number required SSRs. After staff review, which frequently includes discussions with the applicant and adjustments to the proposed withdrawal, the vast majority of these determine an adequate amount of water is available.

Table 8.—The number of LQWs (large quantity withdrawals) processed, the reasons for referral to SSR (Site-Specific Review), the results from the SSR analysis, and the overall disposition of the proposed withdrawals.

	Number	Percent (%)	SSR Results			
			Zone A	Zone B	Zone C	Zone D
Total Number of LQWs processed in the first year	216					
Reasons Screening Tool referred to SSR:						
Possible ARI	25	12	15	7	1	2
Possible ARI in Cold Trans	3	1		3		
Cold Transitional watershed	4	2		4		
Zone C	12	6	8	4		
Total	44	20	22	18	1	2
LQWs authorized through:						
Screening Tool	172	80				
SSR	42	19				
Total	214	99				
Likely ARI	2	1				

Table 9.—Comparing the distribution of Zones based on the Screening Tool results and after the completion of a Site Specific Review.

Zone	Distribution of Zones (%)	
	From Screening Tool results	After SSR
A	58	69
B	22	29
C	6	<1
D	14	1

Discussion

The Michigan Water Withdrawal Assessment Program is one of the first comprehensive applications of the suggested ELOHA framework (Poff et al. 2010). Our initial experiences confirm that the ELOHA steps of science elements (statewide flow database, stream classification, and biological response curves) in support of social elements (choice of ecological and streamflow

thresholds, and implementation) is a strong model for implementation of state level environmental flow standards. Our work did not include one important ELOHA element, the development of an index of flow alteration for all state stream segments, which is subsequently used to develop biological response curves. Several other states recently developed this index and are using it to develop response curves (e.g., MA, Archfield et al. 2009). It will be useful to develop an index of flow alteration for Michigan streams and compare results between methods.

We emphasize that the Michigan WWAP is an initial product, developed over a short time frame (1.5 yr) using readily available ideas and datasets. The GWCAC, in their recommendation to the Michigan legislature stressed that “Any implementation [...of the recommended WWAP] must include a plan for ongoing, periodic field testing and review and revision of the process and tool.” (Groundwater Conservation Advisory Council 2007). We echo this imperative for the foundational science to be periodically reviewed and updated, incorporating new field data and improved modeling approaches. Estimates of Index Flow must be improved through incorporation of miscellaneous streamflow measures, strategically placed streamflow gaging, and improved spatial modeling approaches. The stream classification map and the fish response curves must be periodically updated based on new field surveys of stream temperatures and fish assemblages, and on the hydrologic alteration analysis described above. And as called for in Michigan law, we will need to explore how best to incorporate coverage of lake, wetland, and rare ecosystems into the assessment process.

We anticipate that other Great Lakes states, as well as states around the U.S., will soon develop parallel tools and processes, and we hope to learn from their experiences, as the science of environmental flows continues to grow and converge. Hopefully the two currently active organizations, the Instream Flow Council and The Nature Conservancy’s Environmental Flows Program, will continue to serve as information clearinghouses and sources of guidance through time. This initial Michigan WWAP is a rational, workable product but the clear expectation should be for significant improvements in approach and accuracy in years to come.

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