

**DEVELOPING TOOLS FOR ASSESSING  
THE IMPACTS OF WATER  
WITHDRAWALS IN THE GREAT LAKES-  
ST. LAWRENCE BASIN**

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**Limno-Tech, Inc.**

Ann Arbor, Michigan

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## EXECUTIVE SUMMARY

The Governors and Premiers of the Great Lakes States and Provinces have long recognized the need for a regional water management system for the Great Lakes. In 1985 they signed the Great Lakes Charter, which outlines principles for managing this expansive but finite resource. A later amendment to the Charter called the Great Lakes Charter Annex, or Annex 2001, outlined a framework for a set of guiding principles for reviewing proposals for new and increased water withdrawals. The principles include conservation measures, no significant adverse individual or cumulative impacts, and an improvement to the waters and water-dependent natural resources of the Great Lakes. The amendment also directed that a decision support system be developed to ensure access to, and use of, best available information.

The States and Provinces, through the Council of Great Lakes Governors, are currently in a three-year process of turning Annex 2001 into regional water management standards. The Great Lakes Protection Fund (GLPF) is supporting this effort by funding several projects that build technical tools, or test various decision-making processes. This paper describes one of these projects, which involves the development of a linked modeling framework to assess the ecological impacts of withdrawals and diversions in a Great Lakes tributary.

The application of mathematical models provides the potential for evaluating water withdrawal impacts at the full range of spatial and temporal scales to address management issues. However, existing models generally address only part of the overall problem, such as watershed hydrologic response, channel hydraulics, sediment transport, water quality, or ecological effects. No existing model by itself directly links a water withdrawal to ecological endpoints, or addresses the broad range of potential ecological responses resulting from water withdrawal scenarios.

To address the need for this type of decision support tool, we developed a prototype modeling framework that permits direct evaluation of how hydrologic changes associated with water withdrawals affect important ecological aspects of a river-based watershed. The modeling framework links the Hydrologic Simulation Program – FORTRAN (HSPF) model to a habitat-based ecosystem sub-model developed based on an existing stand-alone ecosystem model. The prototype model was field-tested on the Muskegon River watershed, located in northwest Lower Michigan. Water withdrawals in this watershed can potentially impact flow regime and water temperature in mainstem and tributary reaches, thus affecting the habitat of brown trout and other important species in the system.

An important objective of this work was to explore issues and challenges to developing a model of this type. Challenges we encountered related primarily to data processing and availability. The large size of the Muskegon River watershed required that we collect and synthesize a large volume of data and information, which proved to be a time-consuming process. Furthermore, certain types of data and information, such as information related to ecological effects and processes were very limited or

non-existent. The proliferation of control structures in the Muskegon River watershed also posed a challenge for modeling. We also explored the applicability of this type of model to other watersheds. This model has broad potential applicability, but site-specific modifications to the model will always be necessary, particularly for the ecosystem components, due to the complexity of the watershed as well as data availability.

The ultimate objective of our work is to develop a user-friendly, linked model framework that can be applied to a wide range of Great Lakes basin watershed systems. This prototype model represents a first step toward meeting that objective. Follow up work should build on this project by refining, further developing, and applying this modeling framework to a wider range of river systems within the basin. This should include the development of a decision support interface for the model suite to support effective development, assessment, and comparison of different water withdrawal scenarios by decision-makers.

The utility of the technical tools developed through this and other efforts will be considered for use by parties responsible for making decisions concerning new water withdrawal applications in the context of the Great Lakes Charter Annex. It is envisioned that these approaches as implemented in a specific watershed could be used as an adaptive management tool by incorporating results of ongoing monitoring, thereby providing a synthesis tool and a methodology for assessing cumulative impacts of multiple flow modifications. In addition, models for individual watersheds could potentially be linked to form a larger Great Lakes Basin assessment tool.

## **1. INTRODUCTION**

### **1.1 BACKGROUND**

The Great Lakes Charter Annex, signed in 2001, seeks to develop water resource management practices in the Great Lakes-St. Lawrence Basin that guarantee the long-term sustainability of the basin's water resources. Long-term sustainability involves preserving the quantity and quality of the region's abundant water resources to maintain and enhance its ability to provide social, economic, and environmental services to all of the inhabitants of the basin ecosystem. One of the main tenets of any water resource management approach with this goal is to prevent human withdrawal and use of the waters of the basin from having adverse ecological impacts on the Great Lakes ecosystem.

In specifying its concern about preventing adverse ecological impacts of water withdrawals in the Great Lakes, Directive #3 of the Great Lakes Charter Annex invokes the establishment of a new decision-making standard that the States and Provinces will use to evaluate proposals related to establishing new water withdrawals, or increasing existing water withdrawals from the Great Lakes Basin. Implementation of such a decision-making standard in a fair and equitable way requires, among the many knowledge domains, a quantitative understanding of the relationship between water withdrawals (or diversions) for human uses and the cumulative ecological response of the system. Over the past few years, several research efforts have focused on the development of technical and policy tools to address these management questions (Great Lakes Commission, 2003; Great Lakes Protection Fund, 2002).

Technical tools currently under development in support of the Great Lakes Charter Annex range from relatively simple evaluations to more complex model applications. The application of mathematical models provides the potential for evaluating water withdrawal impacts at the full range of spatial and temporal scales to address management issues. Models can also address the question of the capacity of a water body to endure cumulative withdrawals without suffering from adverse ecological impacts. However, existing model frameworks generally address only individual components of the overall problem, such as watershed hydrologic response, channel hydraulics, sediment transport, water quality, or ecological effects. No existing model by itself directly links a water withdrawal to important ecological endpoints, or addresses the broad range of potential ecological responses resulting from water withdrawal scenarios.

### **1.2 SCOPE OF WORK**

To address the need for a decision support tool, we developed a prototype modeling framework that permits direct evaluation of how hydrologic changes associated with water withdrawals affect important ecological aspects of a river-based watershed.

The modeling framework links the *Hydrologic Simulation Program – FORTRAN* (HSPF) model (Bicknell, 2003) to a habitat-based ecosystem sub-model developed based on an existing stand-alone ecosystem model. Presented in this document is a description of our conceptualization and approach for developing the prototype watershed ecological model, a description of the configuration, application, and field testing of the model to the Muskegon River watershed (Michigan), a discussion of the benefits and limitations of the modeling framework for support of decision-making with regard to water withdrawals in watersheds throughout the Great Lakes basin, and, finally, a set of recommendations for further development and application of the model for use within the Annex 2001 implementation process.

## **2. PROJECT APPROACH**

The first step in model development was development of a broad conceptual model that illustrates conceptually all the cause-effect relationships that might exist between potential water withdrawal-induced physical (hydrological and hydraulic) changes in river-based watersheds in the Great Lakes Basin and ecological impacts that might result from those changes. This helps create a vision of what needs to be done when evaluating water withdrawals; it also aids managers and applicants in identifying potential issues of concern. The second step was development of a prototype linked-model framework specific to a Great Lakes river-based watershed system, through which we identified issues, technical needs and obstacles, and tested the model framework's general applicability. This model was built around a modeling support interface that allows easy model input and graphical model output visualization. It serves as a demonstration of the feasibility and efficacy of this type of model for assessing water withdrawal proposals.

The first step in development of the conceptual model was to create a list of system stressors and assessment indicators. A list of performance measures for each assessment indicator was then prepared. The measures that were identified were those that were considered important for river systems. Network diagrams were then prepared that illustrate the interactions between the system stressors and assessment indicators and measures.

The conceptual model was constructed to be as comprehensive as possible and to include all conceivable interactions and measures of indicators. It provided the basic framework for the prototype model, but the prototype model only quantified a subset of the information/data flow pathways conceived in the broader conceptual model. The ability of the chosen suite of ecological assessment indicators to capture the important overall ecosystem response to changes in water flow regimes is system-specific. Therefore, the utility and feasibility of including various transfer pathways and associated processes in the prototype version was based on site-specific considerations and data availability.

Field testing of the prototype model was conducted in parallel to model development to insure the integrity of model linkages. Several Great Lakes watersheds were considered for field testing, and the Muskegon River was selected based on selected criteria.

### **2.1 DEVELOPMENT OF BROAD CONCEPTUAL MODEL**

The primary purpose of the conceptual model is to illustrate all the possible cause-effect relationships that may exist between potential water withdrawal-induced physical (hydrological and/or hydraulic) changes in river-based watersheds in the Great Lakes basin, and ecological impacts that might result from these changes. This conceptual model:

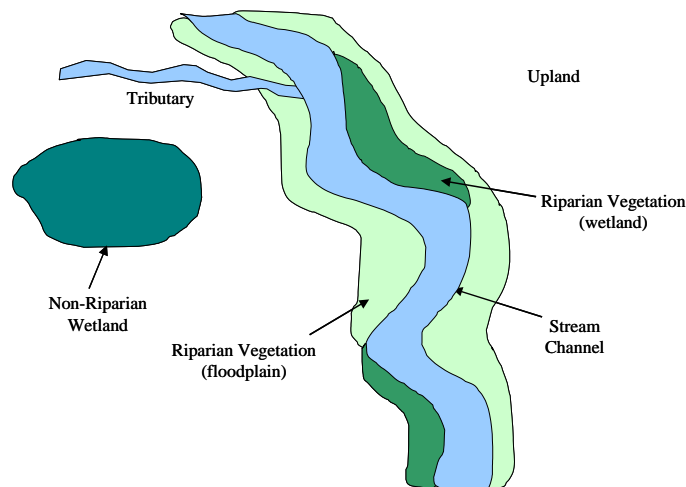
- Helps create a vision of what needs to be done when evaluating water withdrawals;
- Assists in identifying potential areas of concern; and
- Provides a basis for developing the prototype modeling framework.

Two literature reviews conducted as part of related research projects were valuable in developing the conceptual model: *Development of a Framework for a Decision Support System for Water Management* (Limno-Tech, Inc. and Slivitzky, 2002); and *Implementing an Integrated Ecological Response Model (IERM) for the IJC LOSL Study* (Limno-Tech, Inc., 2002b). In addition, we applied knowledge gained through experience at other sites, and through discussions with other researchers.

The objective of the conceptual model is to organize information of various components of the ecosystem into a single framework that relates the impact of system stressors to a series of ecosystem response variables. System stressors are external functions or variables of nature that can influence the state or can change the functioning of the ecosystem. They can be physical (e.g., armoring the shoreline), biological (e.g., exotic species) or chemical (chemical inputs and loadings). They can be human-induced (e.g., drainage, filling and dredging, shoreline modifications, regulations, nutrient and contaminant inputs, water level changes, etc.) or natural (e.g., water level changes, sediment supply and transport, ice and storms, climate change impacts). Ecosystem response variables are ecosystem performance measures that can be measured in the field and are intended to be calculation endpoints of a quantitative model. One or more of these response variables can be used to form what are termed ecological assessment indicators. An assessment indicator is an index of the measures that characterize or assess one of the critical components of the ecosystem to changes in water supply. The performance measures of assessment indicators include biological, chemical or physical attributes that quantify the ecological condition of the system.

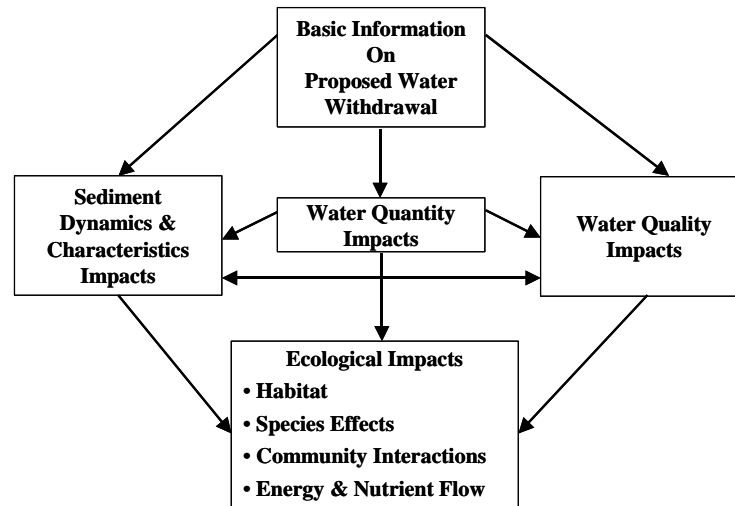
The conceptual modeling framework uses different performance measures for every assessment indicator. For example, water quality is an assessment indicator, and measures of this indicator could include concentrations of nutrients, biochemical oxygen demand (BOD), dissolved oxygen (DO), total suspended solids (TSS), pH, dissolved solids, contaminants, bacteria or other measures of water quality. These parameters can measure the response of water quality to changes in water levels or flows. Before developing the linked modeling framework based on this conceptual model, particular response variables of concern, for each ecosystem assessment indicator were chosen. The conceptual model is intended to provide the general flow of data/information from system stressors (i.e., natural hydrological and climatological forcings, other management actions, channel modifications, cumulative water use, drainage basin properties) affecting water flow regimes to a series of ecosystem response variables (model calculation endpoints) that may be related to ecosystem assessment indicators of concern.

Figure 1 shows the ecosystem components representing various geomorphological areas of a fluvial system. The ecosystem is contained within the watershed boundaries, and is organized into the following areas: upland, tributaries and streams, riparian vegetation (both wetland and floodplain areas), non-riparian vegetation, and the mainstem, the main river channel that ultimately exports water and materials in the water from the watershed. The figure does not depict groundwater, but the groundwater flow regime is an important component in fluvial systems within the Great Lakes Basin. A complicating factor is the potential for groundwater to move between surface water drainage basins. Since the prototype model is based on a Great Lakes Basin river system, the system components are chosen in such a way that they interact with the river channel directly or indirectly and affect the river system. Tributaries contributing to main channel flow will be considered as a part of the drainage basin. Non-riparian wetland vegetation areas could be linked hydrologically with the stream main channel via seepage through groundwater, and, in turn, can be influenced by the flow in the main channel.



**Figure 1. Conceptual Representation of Physical System**

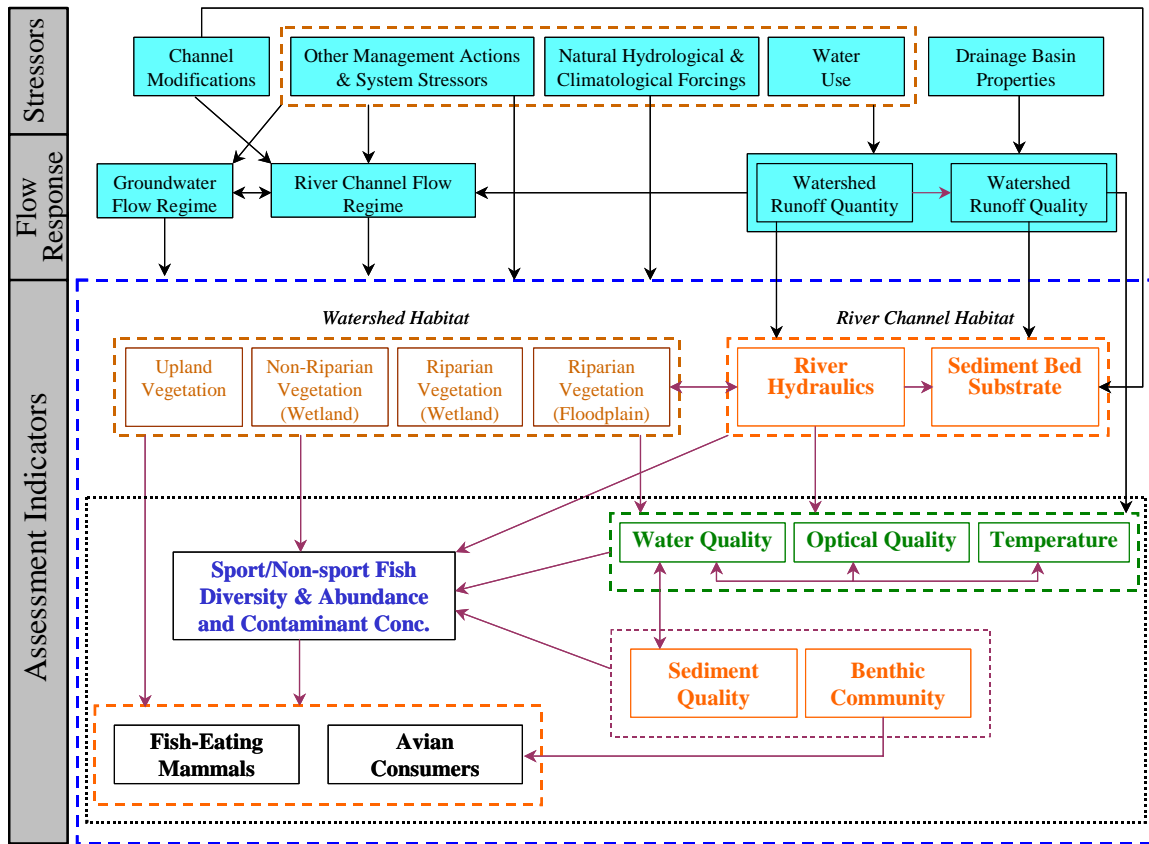
Figure 2 shows a very simple representation of the linkages between a proposed water withdrawal and the potential impacts on ecosystem components. This is a broad conceptualization of the flow of information that provides a starting point for development of the conceptual model. As depicted, a withdrawal may impact water quality and quantity, sediment transport and bottom sediment properties; and these changes may in turn impact the ecology of the ecosystem. The arrows show that there are interactions among various components of the system, and the impacts can be directly or indirectly related to the water withdrawal. For example, a water withdrawal may directly impact where sediment is deposited in the river system or how much sediment is exported from the watershed, or it may impact erosion of sediments from the drainage basin, which in turn can impact sediment deposition and export rates.



**Figure 2. General Framework for Assessment of Water Withdrawals**

The conceptual model assists in identifying the important processes that need to be simulated by the quantitative assessment modeling framework. In order to simulate the impact of a water withdrawal scenario, the framework must represent the flow of information depicted in Figure 2 and therefore must include: a hydrologic model for the watershed; a hydraulic model for the main stem river system; a watershed loading model for the water quality parameters of concern, sediments, and ancillary parameters; a water quality (transport and fate) model for the receiving river system; and an ecological impact model that quantifies the selected performance measures for each desired assessment indicator. There may be several ecological endpoints or indicators of interest, potentially requiring a variety of models or techniques.

The conceptual model builds on Figure 2 by providing a more detailed network diagram of model components and the process-related linkages between various stressors and assessment indicators. An overview of the conceptual model is shown in Figure 3. The flow of information is from system stressors (top of figure), to the effects on different habitats and other system components including fish and terrestrial consumers (bottom of figure). The conceptual model components depicted in Figure 3 are divided into the following categories: System Stressors; Watershed; Physical Habitat; and River Ecosystem.



**Figure 3. Conceptual Model**

System Stressors (which are used to develop inputs to the model) include channel modifications, natural hydrological and climatological forcings, other management actions and system stressors, water use, and drainage basin properties.

The lower portion of Figure 3 (unshaded boxes) presents the assessment indicator web, which is comprised of a series of ecological assessment indicators and the interactions among those indicators. A suite of indicators can respond to changes in flow regimes and other important forcing functions. For example, changes in habitat can be an assessment indicator for water level changes, and can also impact consumers at the higher trophic levels. Watershed runoff quantity can impact river hydraulics, which can in turn impact sport and non-sport fish diversity and abundance. The vegetation in various areas of the fluvial system can be impacted by the river channel flow regime, which can impact sport and non-sport fish diversity and abundance. These examples illustrate that changes in an indicator could result from a direct effect or through a series of indirect effects. The interactions among various indicators and species are complex and require ecosystem level understanding to examine the effects of multiple stressors on multiple endpoints in a river ecosystem.

## 2.2 DEVELOPMENT OF PROTOTYPE MODEL

The conceptual model contains a description of the range of pathways for information/data flow through a series of ecosystem components. The river-based watershed prototype model developed in this study quantifies only a sub-set of the information/data flow pathways conceived in the broader conceptual model. The selection of sub-models to be incorporated into the prototype model was based on the identification of ecological indicators to be included in the prototype, and on the possible pathways by which those indicators can be impacted. Therefore, the first step in this process was to develop a prototype conceptual model, which is a subset of the larger conceptual model.

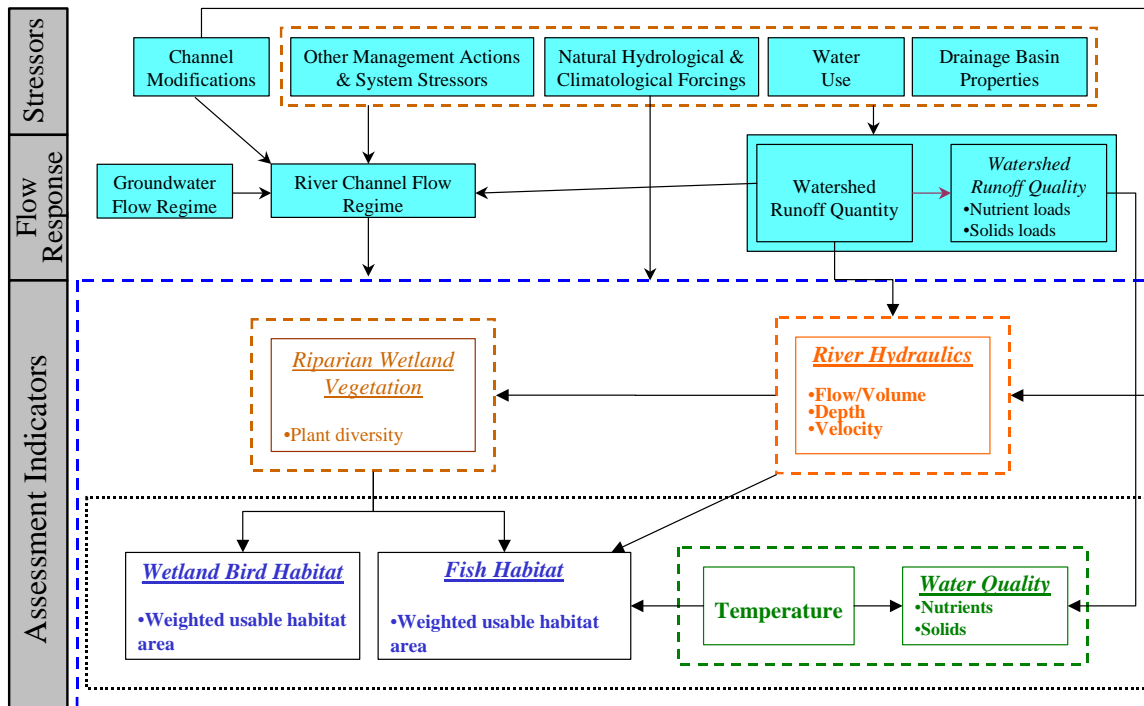
The selection of conceptual model components to be included in the prototype model was driven in large part by anticipated data limitations. Based on the conceptual model, general knowledge of watersheds within the Great Lakes basin, and logistical considerations, the following components were selected for inclusion in the prototype linked modeling framework:

- Watershed runoff and loading;
- Channel hydraulics;
- Water temperature (in-stream);
- Water quality (in-stream);
- Fish habitat supply;
- Riparian wetland plant diversity; and
- Wetland bird habitat supply.

The flow of information between these components in the prototype conceptual model is depicted in Figure 4. Ultimately, the extent to which each of these components can be modeled for a particular watershed will depend on the availability of site-specific data available for model configuration (and ultimately calibration). For example, the modeling of water temperature requires a variety of meteorological inputs, some of which may not be available for all watersheds. However, the prototype components were selected with the expectation that many watersheds do have adequate data to support some level of modeling for each component.

The watershed runoff and channel hydraulic components are essential to the modeling framework because these components will serve as a significant driving force for ecosystem responses in any watershed in the Great Lakes basin. Temperature and water quality components were also included in the prototype conceptual model because these components are important determinants of food availability and bioenergetic response for various faunal groups. The three ecosystem elements (fish habitat, wetland plant diversity, and bird habitat) were selected because they have universal applicability and importance for watersheds in the Great Lake basins. Wetland plant abundance and diversity are the primary determinants of habitat quality for many faunal groups. For example, reproduction success of some fish and bird

species is strongly dependent on the diversity and spatial configuration of wetland plant communities.



**Figure 4. Prototype Conceptual Model Diagram**

## 2.3 BUILDING THE MATHEMATICAL MODEL

The next phase of the project involved converting the prototype conceptual model into a quantitative mathematical Great Lakes Ecosystem (GLECO) model. Since there has been previous model development for individual components of the overall ecosystem response model, our approach was to select existing model frameworks for linking into an overall system model rather than building the ecosystem response model from scratch. The development of an appropriate user interface to facilitate the application of this prototype assessment tool was also part of the model development phase of this project.

### 2.3.1 GLECO Model Components

A number of existing models were evaluated for potential use as sub-models in the linked ecological modeling framework. The list of potential models was derived from the Model Inventory Report prepared as part of the Water Resources Management Decision Support System project (Limno-Tech, 2002a). Characteristics that were considered desirable in a sub-model included:

- Representation of important state variables and associated processes;
- Ability to simulate a range of spatial and temporal scales (to meet site-specific needs);
- Flexibility in terms of simulation complexity;
- Accessibility of model code and input/output structures (e.g., public domain status); and
- Efficiency of input/output design.

The review of existing models revealed that no collection of existing ecological models was adequate to meet the requirements of the ecological components of the linked modeling framework. Existing ecological models that were evaluated were typically too general, too specific to a particular environmental region (e.g., Everglades Landscape Model) and/or specific to a faunal species (e.g., salmonid populations). The lack of appropriate ecosystem component models illustrates the challenges inherent in modeling the highly complex and site-specific biological processes and interactions occurring in a given watershed environment. Given the importance of site-specific considerations, it is essential to evaluate current and historical ecological data for a given watershed before determining the group or species to be modeled. For this project, we determined that the most efficient approach for developing the ecosystem component was to construct a relatively simple habitat response model based on principles applied in existing ecosystem models rather than attempting to directly incorporate one or more of those models.

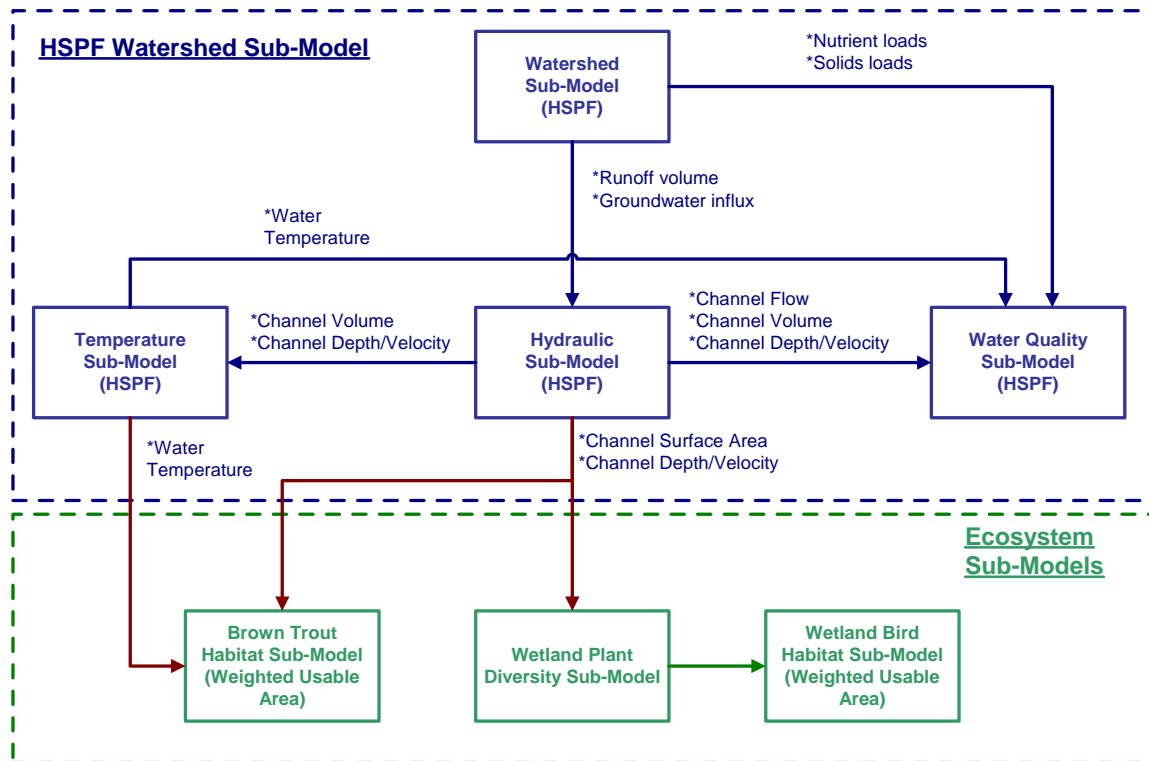
The prototype configuration was conceived as an application of the Hydrologic Simulation Program in FORTRAN (HSPF) model to collectively simulate the watershed hydrology and constituent export, river hydraulics, and in-stream temperature and water quality components of the modeling framework. HSPF is a public domain model that has been successfully applied to a large number of watersheds nation-wide. The selection of this model to simulate watershed and in-stream processes provides a number of advantages over linking several individual sub-models:

- HSPF eliminates the need to develop and fully test complex linkages between multiple sub-models;
- HSPF provides a better representation of watershed and groundwater dynamics and is better suited to simulate large watershed areas (such as the Muskegon River watershed) than the GWLF watershed model; and
- HSPF provides considerable flexibility in configuring the complexity of simulated processes and pathways to an appropriate level based on the availability of site-specific data.
- HSPF has widespread acceptance and support, has undergone extensive peer review, is supported by EPA through BASINS, and is currently being used for the Chesapeake Bay modeling.

The proposed flow of information between various internal components of the HSPF model and the ecosystem components is shown in Figure 5. Potential approaches for

incorporating ecosystem sub-models for fish habitat, wetland plant diversity, and bird habitat were evaluated based on existing models.

Brown trout was identified as an important sport fish in the Muskegon River watershed; therefore, a habitat sub-model was developed for this species based on the Instream Flow Incremental Methodology (IFIM) approach outlined by the U.S. Fish & Wildlife Service (USFWS, 1986). The IFIM approach utilizes habitat suitability curves to compute the relative suitability of a potential habitat locale on a scale of 0-1. This approach has commonly been used to evaluate stream habitat for a variety of fish species and locations.



Asterisks represent those properties computed by HSPF that respond to water withdrawals and, in turn, drive brown trout spawning success.

**Figure 5. Conceptualized Prototype Sub-Model Linkage Diagram**

After reviewing relevant literature and model documentation, it was determined that insufficient data are available to support a wetland plant diversity sub-model, or the wetland bird habitat sub-model, which is dependent on the plant diversity model. Riparian wetland plant diversity is driven by the frequency and duration of flooding within the wetland structure, which is in turn controlled by a variety of complex driving factors, including site-specific geomorphology, groundwater table behavior, hydrology of adjacent upland areas, and hydraulic behavior in the adjacent stream (Mitsch & Gosselink, 1986). Although there is an abundance of literature documenting the importance of these and other factors on riparian wetland vegetation

diversity, quantitative linkages between plant diversity and these driving factors apparently have not been established. The lack of quantitative algorithms for calculating riparian wetland plant diversity is likely due to the complexity and site specificity of surface water and groundwater interactions. Because wetland plant community diversity and composition is critically important to the habitat of a number of faunal groups (e.g., wetland birds, fish, amphibians), we recommend that potential approaches for representing wetland plant response in mathematical models be further explored.

### **2.3.1.a GLECO Model Linkages**

The selection of HSPF to model watershed runoff, hydraulics, in-stream temperature, and water quality helped to minimize the number of between-model linkages required to develop the overall model framework. The HSPF model is coded in a series of linked FORTRAN libraries. The built-in flexibility of the HSPF model structure allows the model source code to be used directly without modifications. The customized ecosystem component for brown trout habitat is coded in Microsoft Visual Basic 6.0 (VB6).

The linkages between HSPF and the brown trout habitat sub-model are accomplished via a “wrapper” program coded in VB6. The wrapper program allows the user to modify reach-specific settings for withdrawals and land cover, runs the sub-models in sequence, and utilizes a Microsoft Access 2000 database to store and transfer the necessary input/output data elements. The brown trout sub-model requires reach-based daily output from HSPF for water temperature, stream depth, and stream velocity. The habitat model also requires information on bank vegetation cover and substrate type for each reach. These variables were not modeled explicitly in HSPF; therefore, constant values for vegetation cover and substrate were established and entered into the GLECO database for each reach based on available information for the Muskegon River watershed.

The IFIM-based brown trout habitat model implements piecewise linear functions that are used to compute the habitat suitability index (HSI) on a daily basis for each reach and brown trout life stage, including spawn, fry, juvenile, and adult. The minimum HSI computed for each of the five variables was considered to be the limiting condition for habitat suitability and was multiplied by the reach surface area to generate a daily weighted suitable area (WSA) estimate. Daily WSA estimates were aggregated over the course of a calendar year to provide annual estimates of habitat area in units of hectare-days. The model evaluates juvenile and adult habitat over the entire calendar year, but only computes spawning and fry habitat during the time period relevant for those life stages.

### **2.3.1.b Configuration to River System**

The configuration of the model framework to a watershed system was originally conceived to occur following the complete development of the model linkages.

However, extensive testing and evaluation of the modeling framework is required as various components are added to ensure that the flow of information is occurring as it is intended. The most efficient way to evaluate the performance of the linked model framework is to use actual data to develop inputs for the model. Therefore, the most logical approach was to configure the model to site-specific data in parallel to developing the model components and linkages. In addition, since data availability and physical and ecosystem properties vary substantially between watersheds, consideration of site-specific conditions has a significant influence on the selection of components and linkages represented in the modeling framework. For example, the brown trout habitat sub-model was selected for inclusion in the GLECO model because brown trout is an important sport fish in the Muskegon River watershed, which was selected as the site for testing the prototype linked model framework.

### **2.3.1.c User Interface**

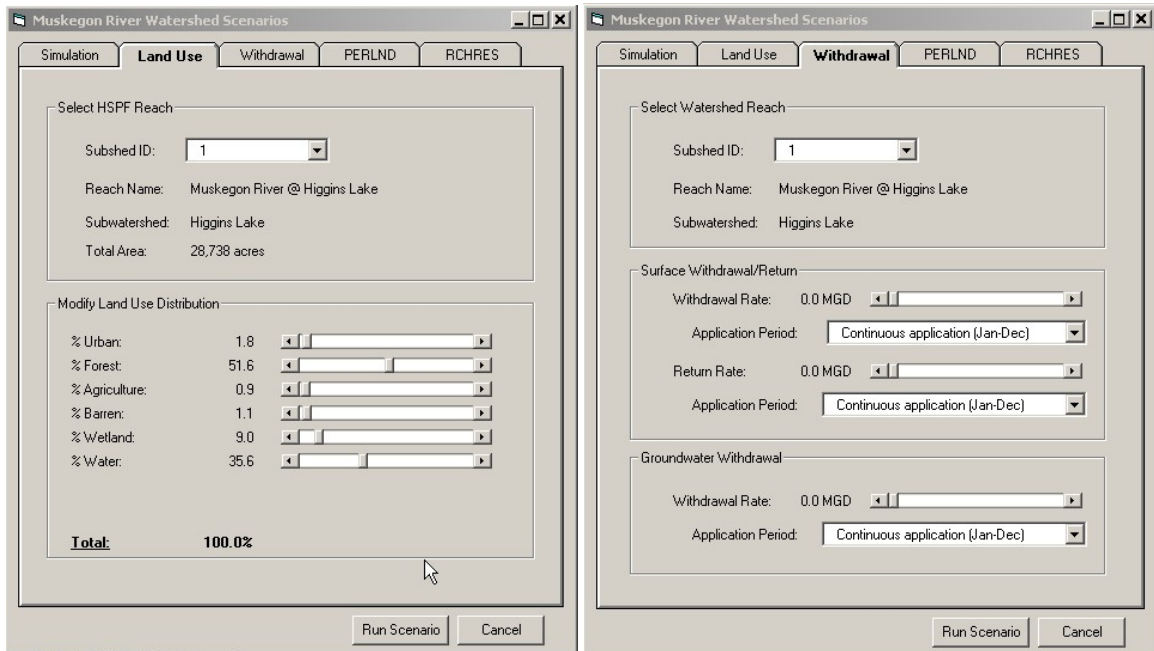
The GLECO model utilizes Microsoft Visual Basic 6.0 (VB6) for its wrapper program, which links the sub-models via a Microsoft Access 2000 database. VB6 is a powerful and versatile programming language that is ideally suited for the development of this linked prototype model. In addition to allowing the model developer to incorporate a range of third-party component libraries, it can be used to seamlessly integrate existing DOS-based applications compiled in other languages (FORTRN, C++, etc.) into a user-friendly, windows-based environment. This feature of VB6 was critical to the successful development of the prototype, because it allowed us to utilize existing HSPF source code without actually recoding the algorithms implemented in this model in the Visual Basic language.

Standard VB6 forms were used to develop a main menu where the model user may navigate to build a scenario, or visualize results from an existing scenario that has been previously simulated. When the “build scenario” option is selected on the main menu, the user is prompted to specify a number of scenario inputs, including:

- Simulation start and end dates;
- Surface water and groundwater withdrawal quantities for each reach;
- Surface water return flow quantities;
- Land cover distribution for each reach; and
- HSPF water quantity/quality variables to output for each model reach.

Screenshots of the model graphical interface for specifying land use distribution and withdrawal/return rates are shown in the left and right panes of Figure 6, respectively.

By selecting the visualization option from the GLECO main menu, the user invokes a graphics interface that allows her/him to compare model time series output for two scenarios for the selected reach and output variable. The user may use this interface to view time series results for any of the water quantity/quality variables output by HSPF in addition to the annual habitat time series output generated by the brown trout habitat sub-model.



**Figure 6. GLECO Model Interface for Building a Scenario**

In addition to providing a graphical interface to visualize model time series output, the model shell allows the user to visualize results geographically, provided that the necessary software is installed. The model “wrapper” program interfaces with the “MapControl” ActiveX component, which is distributed by Environmental Systems Research Institute (ESRI) with its ArcGIS software package. This control encapsulates the same basic functionality as the ArcGIS, a powerful application that is designed for effectively visualizing data and model results geographically. A number of recent watershed models have been built within GIS software in order to take advantage of the high level of mapping and visualization functionality it provides. Because of the spatial analysis capabilities offered by ArcGIS, building the core functionality of this GIS package into the model framework provides the foundation for developing an even more powerful tool in the future. For example, a more sophisticated version of the model might allow the user to modify land use for parcels of land directly in ArcGIS and then feed those changes into the HSPF watershed sub-model to provide an interactive management analysis capability.

## 2.4 TESTING OF PROTOTYPE ON MUSKEGON RIVER

A review of available data and information on candidate Great Lakes river-based watersheds was conducted to select an appropriate river system for testing the coupled model. The criteria for selection included: sufficient amount of data, both physical and biological; good data on watershed delineation; presence of USGS gages with reasonable flow records; moderate size watershed; differing flow regimes; and

mixture of non-urban land uses in the watershed. Based on these criteria, the Muskegon River in Michigan was selected for testing.

#### **2.4.1 Data Used for Testing**

Data for the Muskegon River watershed were collected from a variety of sources, including existing watershed reports, several websites on the Internet, and contacts with researchers working on the watershed. Data elements are organized and discussed in major categories, including watershed GIS data, stream flow data, and meteorological data.

##### *Watershed Spatial Data*

A majority of the spatial watershed data were obtained from the Michigan Geographic Data Library (MiGDL) website (<http://www.mcgi.state.mi.us/mgdl/>). Data were generally available by county, so it was necessary to merge datasets for multiple counties within ArcGIS. A brief description of each major watershed dataset used to parameterize and calibrate the HSPF model is provided below.

- **Watershed Delineation**: Polygon data delineating the Muskegon River watershed and 40 subcatchments were obtained from the MiGDL along with outlet points for each subcatchment. These data were used to estimate surface area and connectivity of subcatchment areas and served as the basis for developing pervious land segments in the HSPF watershed sub-model.
- **Stream Delineation**: Coverages were obtained for the Muskegon River and its tributaries. These data were used to determine hydraulic properties, including the length of each stream reach and reach connectivity.
- **Land Cover**: The National Land Cover Dataset (NLCD), developed in 1992, was used to develop land cover distributions for each modeled subcatchment. NLCD provides coverages for 19 different land cover types, including a variety of agricultural and urban types. For the purpose of parameterizing land cover in the watershed model, these 19 cover types were aggregated into the following categories: forest, wetland, agriculture, barren, urban, and water.
- **Soils**: The Michigan STATSGO dataset was used to estimate the distribution of soils in individual subcatchments based on Soil Conservation Survey (SCS) classification system. Soil distribution data were used to parameterize infiltration rates in the watershed model.
- **Digital Elevation Model (DEM)**: A digital elevation GRID with 30-meter resolution was developed based on a series of county-based GRIDs. The DEM was used to calculate land slope within individual subcatchments and to estimate the slope of mainstem and tributary stream reaches where no other data were available.

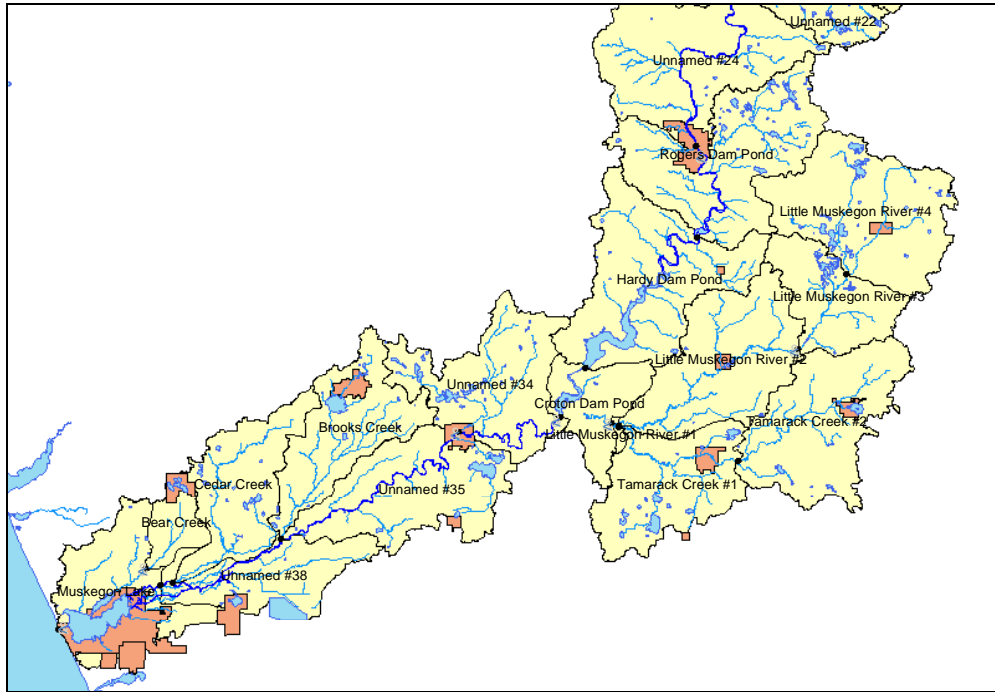
Detailed maps illustrating the Muskegon River watershed subcatchment delineation and stream network are provided in Figures 7-9.



**Figure 7. Upper Muskegon River Watershed**



**Figure 8. Middle Muskegon River Watershed**



**Figure 9. Lower Muskegon River Watershed**

A number of other GIS datasets were obtained to facilitate conceptual understanding of the physical watershed, including urban areas, dam locations, a fish atlas, and wetland delineations based on the National Wetland Inventory database.

#### *Meteorological Data*

Meteorological data are a crucial component of any watershed model. Daily precipitation, air temperature, and potential evapotranspiration (PET) data were obtained from the National Climatic Data Center (NCDC) Summary of the Day database for three locations within the watershed: Lake City, Big Rapids, and Muskegon County Airport. These locations were used to specify inputs for the upper, middle, and lower portions of the Muskegon River watershed. Other meteorological data required to build the HSPF watershed model were obtained from the standard database supplied with the EPA-supported Better Assessment Science Integrating Point and Non-Point Sources (BASINS) model, which includes HSPF as part of its modeling toolbox. A summary of the meteorological datasets is provided in Table 1.

**Table 1. Muskegon River Watershed Meteorological Data Summary**

Dataset Type	Interval	Station/Locations	Source
Precipitation	Daily	Lake City, Big Rapids, Muskegon County Airport	NCDC
Air Temperature	Daily	Big Rapids Waterworks	NCDC
Evapotranspiration	Daily	Muskegon County Airport	NCDC
Precipitation	Hourly	Muskegon County Airport	BASINS
Dewpoint Temperature	Hourly	Muskegon County Airport	BASINS
Solar Radiation	Hourly	Muskegon County Airport	BASINS
Wind	Hourly	Muskegon County Airport	BASINS
Cloud Cover	Hourly	Muskegon County Airport	BASINS

*Streamflow Data*

Stream flow data were obtained from the United States Geologic Survey (USGS) website for several mainstem and tributary gage located within the watershed (Table 2).

**Table 2. USGS Gage Locations in Muskegon River Watershed**

Station ID	Station Description	Catchment Area (mi <sup>2</sup> )	Latitude	Longitude	Start Date	End Date
04121000	Muskegon River near Merritt, MI	355	44.336	-84.890	10/1/46	12/31/73
04121500	Muskegon River at Ewart, MI	1,433	43.899	-85.255	11/17/30	9/30/01
04121650	Muskegon River at Big Rapids, MI	1,751	43.694	-85.468	10/1/99	9/30/01
04121970	Muskegon River near Croton, MI	2,313	43.435	-85.665	10/1/95	9/30/02
04122000	Muskegon River at Newaygo, MI	2,350	43.422	-85.801	7/1/08	9/30/93
04122150	Muskegon River at Mouth at Muskegon, MI	2,680	43.231	-86.330	4/1/94	10/31/95
04121300	Clam River at Vogel Center, MI	243	44.201	-85.217	6/1/66	9/30/01
04121900	Little Muskegon River near Morley, MI	121	43.503	-85.343	10/1/66	9/30/96
04121944	Little Muskegon River near Oak Grove, MI	345	43.431	-85.596	10/1/95	9/30/01
04122100	Bear Creek near Muskegon, MI	16	43.289	-86.223	10/1/65	9/30/01

*Receiving Water Quality Data*

Historical data for the 1970-2000 period were obtained from the EPA STORET database for several water quality constituents. The STORET database serves as a nationwide central repository for water quality, biological, and physical data. Based on the STORET data extraction, varying quantities of water quality data are available

for the following constituents: water temperature; dissolved oxygen; biochemical oxygen demand; ammonia, nitrite, nitrate, and total organic nitrogen; dissolved and total phosphorus; total dissolved solids; total suspended solids; and fecal coliform.

#### **2.4.2 Model Testing Procedure**

The model testing procedure involved several steps that would be required for configuring the model to any Great Lakes watershed including parameterization of the watershed and ecological (habitat) sub-models, calibration of the watershed model, and applying and evaluating the impacts of water withdrawal scenarios. Each of these steps is described in detail below.

##### *HSPF Watershed Sub-Model Parameterization*

The necessary data required to build the HSPF watershed sub-model were obtained from a variety of sources, as described above. Spatial data were processed using the ArcGIS software package and used to parameterize the watershed sub-model. Spatial datasets that were directly used to parameterize the model include subcatchment delineation and connectivity, land cover, soils distribution, and stream network configuration. Stream reaches were constructed for each of the 40 subcatchments identified in the watershed to form the stream network in the model. Data provided with the BASINS model framework (described above) along with field measurements conducted by LTI were used to parameterize the stream reach geometry in the model. Parameterizing the geometry and hydraulic behavior in the three major impoundments (Rogers Pond, Hardy Pond, and Croton Pond) associated with hydropower dams operated by Consumer's Power presented a challenge. Very few data were readily available for these areas; however, sufficient information for model parameterization was collected through direct contact with Consumer's Power personnel and review of existing watershed reports (O'Neal, 1997; U'Ren, 2002).

##### *Ecological Sub-Model Selection and Parameterization*

The selection of an ecological sub-model was based on a review of available literature and reports for the Muskegon River watershed. A fisheries report issued by the Michigan Department of Natural Resources (MDNR) provides a detailed description of fish, bird, mammal, amphibian, and reptilian species that utilize various portions of the Muskegon River watershed for habitat (O'Neal, 1997). In general, fish species are most dependent on changes in hydrologic/hydraulic changes in a watershed system; therefore, fish habitat was selected as the primary ecological sub-model component. O'Neal indicates that game fish species of interest in the watershed include walleye, northern pike, smallmouth bass, rainbow trout, and brown trout. Brown trout in particular are a popular species for fishing in the watershed, and portions of the Clam River and Middle Branch River (both tributary streams) are classified as Blue Ribbon trout streams. In addition to being a popular fish species, brown trout have a documented dependence on basic hydraulic attributes, including stream depth and velocity (USFWS, 1986).

Based on the factors described above, a brown trout habitat suitability model was selected for incorporation into the GLECO model. The model computes habitat weighed suitable area (WSA) on a daily basis for four life stages of brown trout – spawn, fry, juvenile, and adult. Habitat WSA for the juvenile and adult life stages is computed for the entire calendar, while the spawn and fry WSA calculations are only performed during the timeframes relevant to those life stages. Spawning is assumed to occur during the last 3 months of the calendar year (October – December), while fry development is assumed to occur during the first 5 months of the calendar year (January – May) based on guidelines provided in the literature (USFWS, 1986).

The brown trout habitat model requires reach-specific information for five stream channel parameters: water temperature, depth, velocity, substrate type, and vegetative cover along the stream bank. The HSPF watershed model was used to predict water temperature, depth, and velocity for each reach associated with a specific reach location. Substrate and vegetative cover were not explicitly modeled within the HSPF framework; therefore, it was necessary to develop reach-specific values for these parameters based on existing information in the literature.

Watershed reports (O’Neal, 1997; U’Ren, 2002) indicate that much of the stream bank area along major tributaries and the mainstem are well-vegetated. The USFWS habitat suitability index (HSI) model suggests that optimal brown trout habitat (e.g., HSI = 1.0) is associated with greater than 40% vegetative cover along the reach stream bank. For the purpose of the habitat sub-model, it was assumed that vegetative cover would not be a limiting factor in the suitability index calculation; therefore, all reaches were assigned a constant value of 50%. If necessary, these cover estimates could be refined by performing a site evaluation, or reviewing aerial photographs of the channel where available.

In general, substrate is expected to remain relatively constant over a 10-30 year period at a given location. However, it is important to correctly assign the appropriate substrate type to each reach because brown trout require specific conditions for spawning and fry development. O’Neal (1997) characterizes the substrate for a number of tributary and mainstem locations in the Muskegon River watershed. The information provided in this fisheries report was sufficient to assign each reach to a particular substrate type, although professional judgment was required for some reach locations. Brown trout spawning and fry development occur exclusively in areas where gravelly substrate dominates (typically tributary streams). Therefore, emphasis was placed on assigning gravel substrate to the appropriate locations, including the Clam River, Middle Branch River, and the Little Muskegon River.

#### *Calibration and Field Testing of the HSPF Watershed Model*

The hydrologic/hydraulic components for the HSPF watershed model were calibrated using USGS stream flow data for multiple gages located within the watershed boundary (Table 2). Stream flow data were available for several tributary and

mainstem locations, which made it possible to calibrate the model at several different points within the system. The Clam River and the Little Muskegon River are major tributaries in the watershed that have USGS gages with a long period of record. In addition, long-term USGS gage data are available for Bear Creek, which is located in the lower portion of the watershed near Muskegon Lake. A number of USGS gages have been operated on the Muskegon River mainstem over the past 100 years, but only the gages at Ewart and Newaygo had a significant overlap with the period of interest for modeling (1970-1995). These gages were used primarily as calibration locations within the model. Additional gage data available for shorter periods at Merritt, Big Rapids, Croton, and Muskegon Lake were used to verify the results of the tributary and mainstem calibration.

The HSPF watershed model contains a number of water quality modules that can be used to simulate the transport and fate of a range of constituents on land surfaces and within the receiving stream network. Water quality constituents represented in the prototype linked modeling framework include: water temperature, dissolved oxygen (DO), biochemical oxygen demand (BOD), total suspended solids (including fractional sand/silt/clay components), and components of the nutrient cycle (dissolved nitrite, nitrate, total ammonia, and phosphate; particulate ammonium and phosphate). A formal calibration of these water quality constituents was beyond the scope of this project; however, "field testing" of the water quality components was conducted by performing a general comparison of the model results to available water quality data.

The HSPF model is capable of simulating additional water quality components, including pH, phytoplankton, benthic algae, and zooplankton. However, it was not possible to include these components in this version of the model due to data and time constraints. If adequate data and budget were available to support inclusion of these components, they could add considerable value to the linked modeling framework in terms of evaluating eutrophication issues and food production in the stream network.

#### *Definition and Simulation of Baseline Condition*

After the watershed and ecological sub-model were appropriately parameterized and calibrated (or field tested) to the extent possible, the next step was to generate a complete model simulation to provide a set of "baseline" results against which scenario results might be compared. Given the long-term hydrologic/hydraulic variability in the Muskegon River watershed (and the Great Lake Basin in general), it was desirable to run the baseline condition for multiple decades to capture the full range of potential water withdrawal impacts under various water supply conditions. The primary constraint for defining the baseline simulation period was the availability of meteorological data to drive the watershed sub-model. Precipitation, air temperature, and evapotranspiration data were available for the 1970-2000 period. However, other meteorological datasets (solar radiation, wind, cloud cover) were only available for 1970-1995. Therefore, the 26-year period covering 1970-1995 was selected as the simulation time period. The baseline simulation was conducted for the 1970-1995 period based on historical meteorological forcing functions, current land

cover (consistent the 1992 NLCD dataset), and no withdrawals applied in the watershed.

### *Building and Simulating Water Withdrawal Scenarios*

The final step in testing the GLECO prototype model for the Muskegon River watershed involved defining hypothetical water withdrawal scenarios and simulating those scenarios within the linked modeling framework. For this application of the GLECO model, the groundwater-based withdrawals were assumed to be 100% consumptive. The model also provides the capability to specify surface water withdrawal or return flow for any of the reach locations within the watershed. In addition, the user may modify the land use distribution for any subcatchment represented in the model. Therefore, the GLECO model provides an integrated framework that can be used to evaluate the cumulative impacts of water withdrawals/returns and land use changes in a watershed system.

## **3. MUSKEGON RIVER TESTING RESULTS**

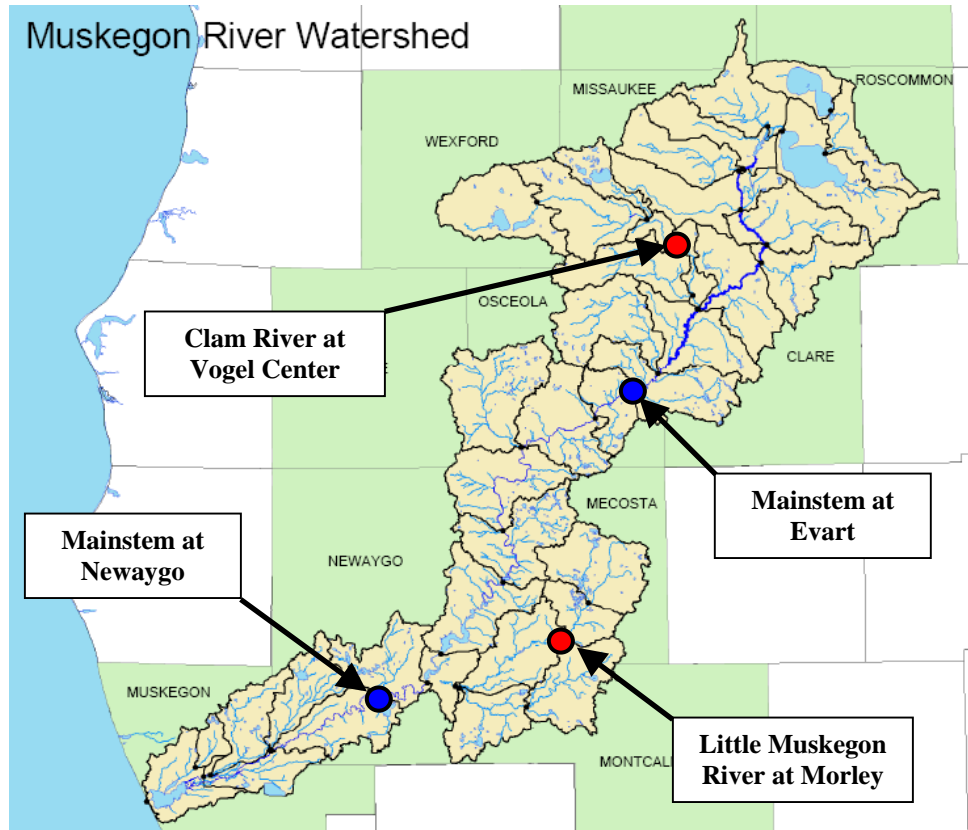
### **3.1 FIELD TESTING AND PRELIMINARY CALIBRATION**

Since this modeling framework is a prototype system and because there has been no coherent and comprehensive data collection program on the Muskegon River for the purpose of model calibration, it was not possible to conduct a full and formal calibration of our model. We did, however, conduct what we term a preliminary calibration and field testing of the model as a means of demonstrating its feasibility and utility for examining water withdrawals in Great Lakes watersheds. Flow at several gage locations in the watershed was calibrated to the extent possible to ensure that the flow balance was reasonable. Calibration of other model state variables was outside the scope of this effort; however, qualitative comparison with available data for water quality and ecosystem response variables made up the field testing of the model.

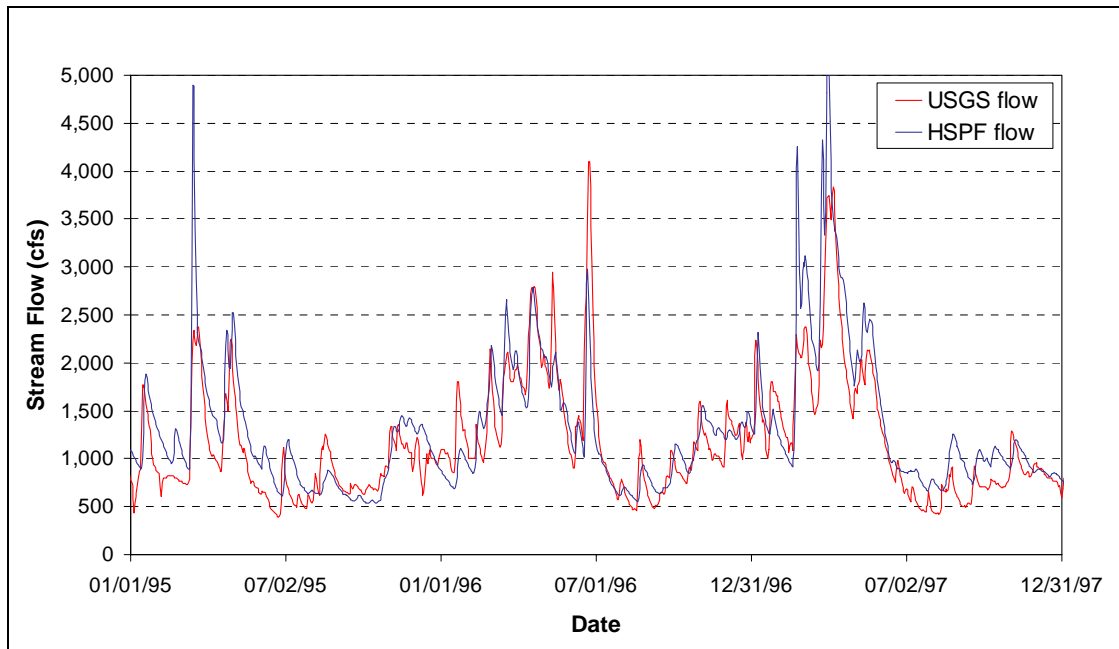
#### **3.1.1 Results of Flow Calibration**

Stream flow was calibrated at two mainstem and two tributary locations within the Muskegon River watershed where long-term USGS gage data were available. Mainstem gage locations include the Ewart gage located at river mile (RM) 112, and the Newaygo gage located at RM 34. Tributary gage locations include the Clam River at Vogel Center gage, and the Little Muskegon River at Morley gage. USGS gage locations are shown on the map in Figure 10. Several other mainstem and tributary USGS gages located in the watershed were used to verify the stream flow calibration, including the Bear Creek gage; the Little Muskegon River at Oak Grove gage; and the mainstem gages at Merritt (RM 186), Big Rapids (RM 81), and below Croton Dam (RM 47).

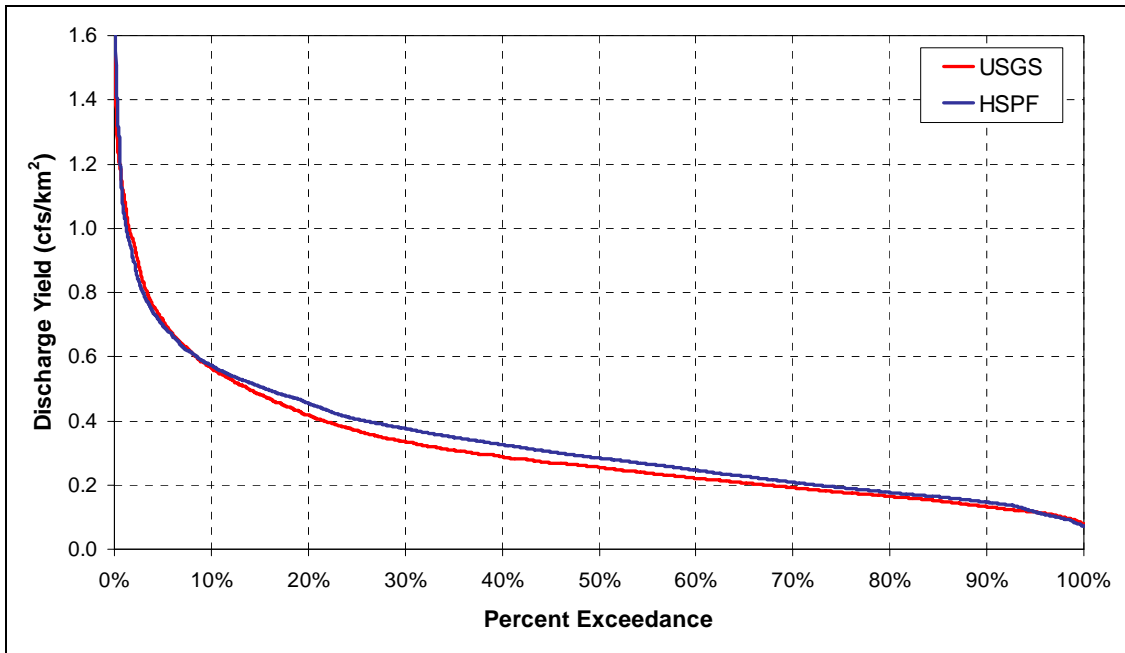
The stream flow calibration focused primarily on the 1990-1995 time period because the NLDC land cover dataset was collected in 1992 and, therefore, the model is expected to generate results that are most consistent with USGS gage data during that period. Calibration work included modifying parameters related to snow accumulation and melt; land surface interception, infiltration, and interflow; groundwater storage and recession; and evapotranspiration processes. Calibration results for the mainstem Muskegon River at Ewart (RM 112) are shown in Figures 11 and 12 as a time series comparison and a flow duration curve comparison, respectively. Flow duration curves provide an indication of the distribution of flow observed (or simulated) at a specific location in a watershed system by plotting the discharge yield against flow exceedance. Calibration of the model to higher flow events was problematic due to a number of factors including the timing of snowmelt events. However, the watershed sub-model consistently reproduces the gage data at low and moderate flow conditions, which are the conditions under which habitat quality in a stream reach is most likely to be degraded by a water withdrawal.



**Figure 10. Muskegon River Watershed USGS Gage Locations for Calibration**



**Figure 11. Muskegon River Flow Calibration at Evart (Time Series)**

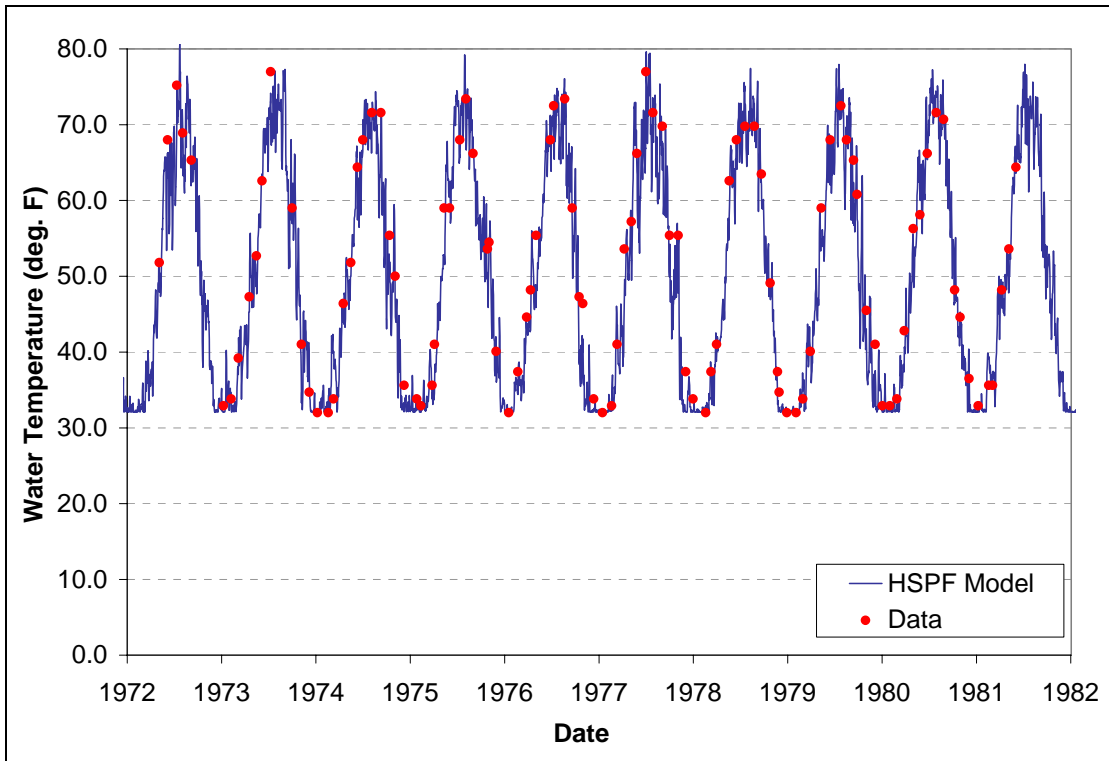


**Figure 12. Muskegon River Flow Calibration at Evart (Flow Duration Curve)**

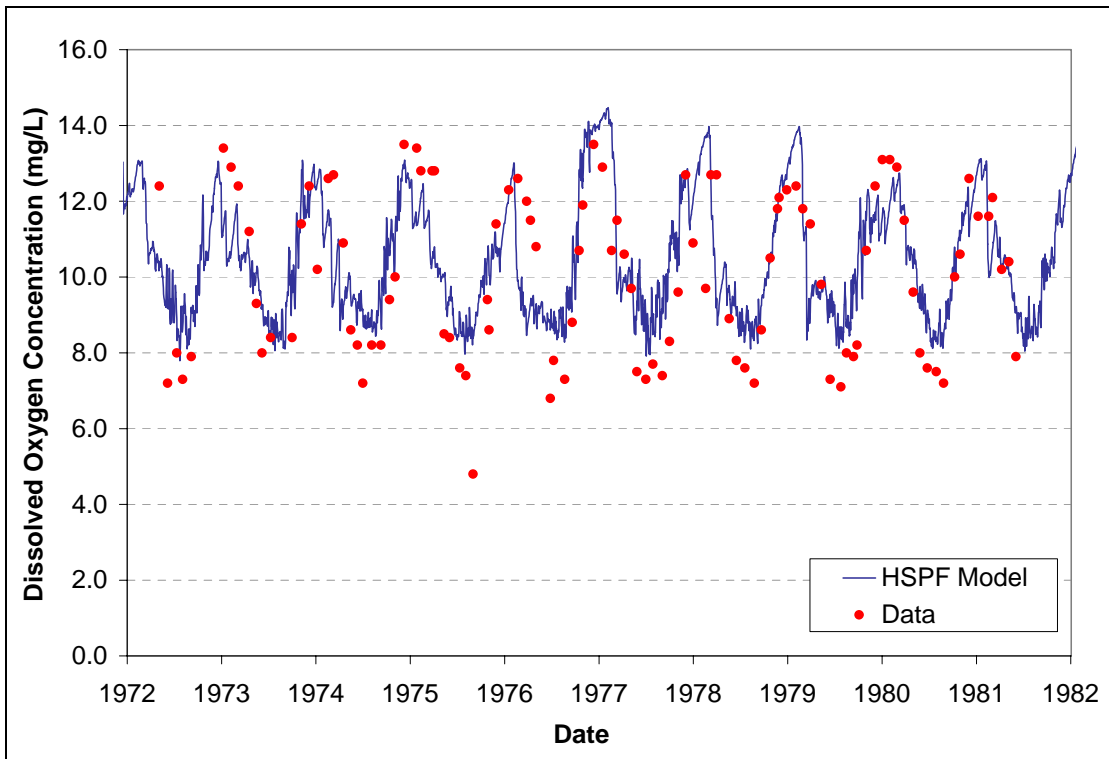
### 3.1.2 Results of Model Field Testing

In addition to calibrating the hydrologic/hydraulic component of the HSPF watershed sub-model, results generated by the water quality component of the model were compared against existing data obtained from EPA's STORET database. The STORET database contained water quality data at a limited number of locations on the mainstem. Initial STORET queries did not yield any data for tributary locations; however, it is likely that some existing water quality data is available from other sources for some of the larger tributary streams, such as the Clam River and the Little Muskegon River.

Several years of data for water temperature and dissolved oxygen downstream of Newaygo near the river's mouth at Muskegon Lake. Time series model-data comparisons were constructed for water temperature and dissolved oxygen at RM 2.5 (located near US-31) for the 1972-1981 period (Figures 13 & 14).



**Figure 13. Model-Data Comparison of Water Temperature at RM 2.5**



**Figure 14. Model-Data Comparison of Dissolved Oxygen at RM 2.5**

Uncalibrated model predictions for water temperature are in good agreement with data collected at the mainstem sampling location (Figure 13). This is not unexpected because temperature models generally require very little calibration if sufficient meteorological data (e.g., air temperature, solar radiation, cloud cover) are available to drive the simulation.

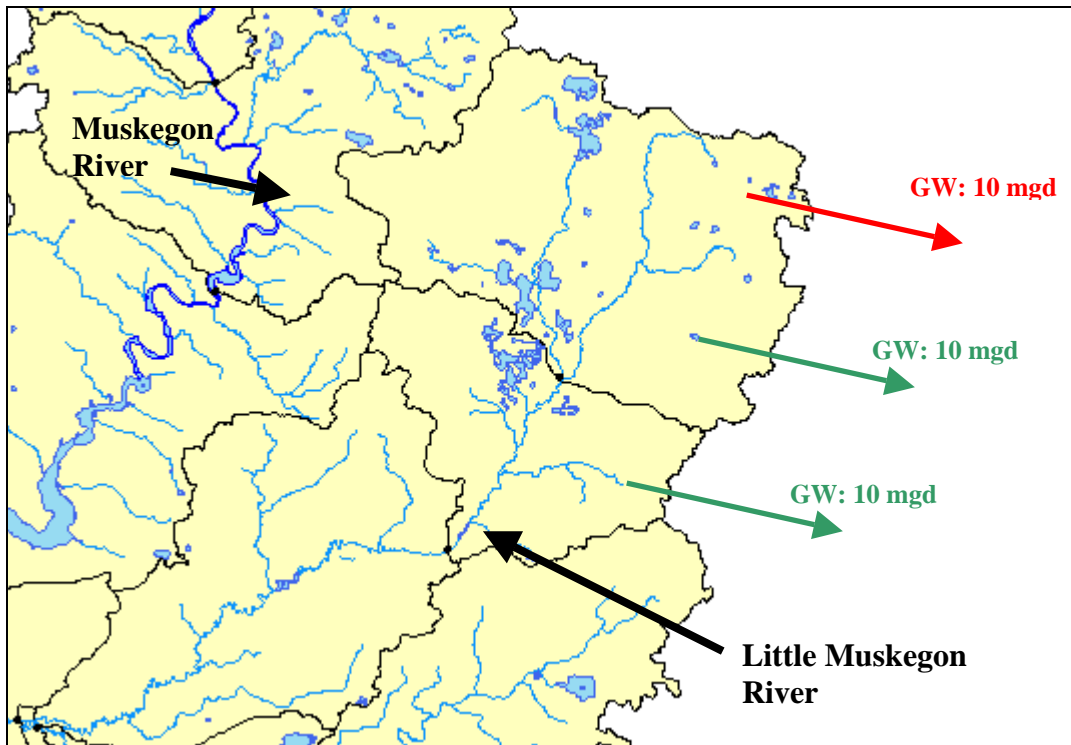
Uncalibrated model results for dissolved oxygen generally compare well to data collected at RM 2.5 (Figure 14). The dissolved oxygen data for 1972-1981 range from 7-14 mg/l, while the model results range from 8-14 mg/l. It is evident from Figure 14 that the model typically overpredicts dissolved oxygen during the summer months when minimum daily levels are generally observed. Discrepancies between the model output and data during these time periods are likely the result of “missing” pollutant loads in the watershed sub-model. Although the Muskegon River watershed is largely rural, a number of point sources do exist along the mainstem and tributaries. For example, wastewater treatment plants have been operating for decades in Cadillac, Big Rapids, Reed City, Howard City, Marion, and Newaygo. In addition to discharges from municipal treatment facilities, there are likely several industrial discharges impacting the system, particularly near the mouth at Muskegon Lake and within Muskegon Lake. Limited data are available for point sources through EPA’s Permit Compliance System (PCS); however, these data are often incomplete and may not reflect actual loading conditions in the system. The existing version of the GLECO application for the Muskegon River watershed does not include point source loads; however, these inputs could be added if additional resources were available to collect and process the required loading data.

Overall, these field testing results demonstrate that the HSPF watershed model sub-model is capable of reproducing water quality data in the receiving water system. These results indicate that it would be feasible to perform a formal calibration the water quality module to better reflect actual stream conditions in the watershed; however, data for additional watershed locations and constituents would be critical to building confidence in the calibration and the application of the water quality module to evaluate water withdrawal and/or land use scenarios.

### **3.2 WATER WITHDRAWAL SCENARIOS**

The final step in testing the application of the GLECO model to the Muskegon River watershed involved developing and applying hypothetical water withdrawal scenarios. One of the benefits of a process-based watershed model is that it provides the capability to evaluate cumulative impacts of water withdrawal and land use changes. In order to illustrate this feature of the model framework, two hypothetical groundwater withdrawals were conceptualized for the Little Muskegon River, a major tributary to the mainstem Muskegon River. Scenario “A” consisted of a 10 mgd withdrawal from a single Little Muskegon River subcatchment, while Scenario “B” consisted of 10 mgd withdrawals from the two Little Muskegon River subcatchments (Figure 15). For the purposes of this test simulation, the withdrawals in each of these

scenarios were assumed to be 100% consumptive; therefore, no return flow was specified in the model.

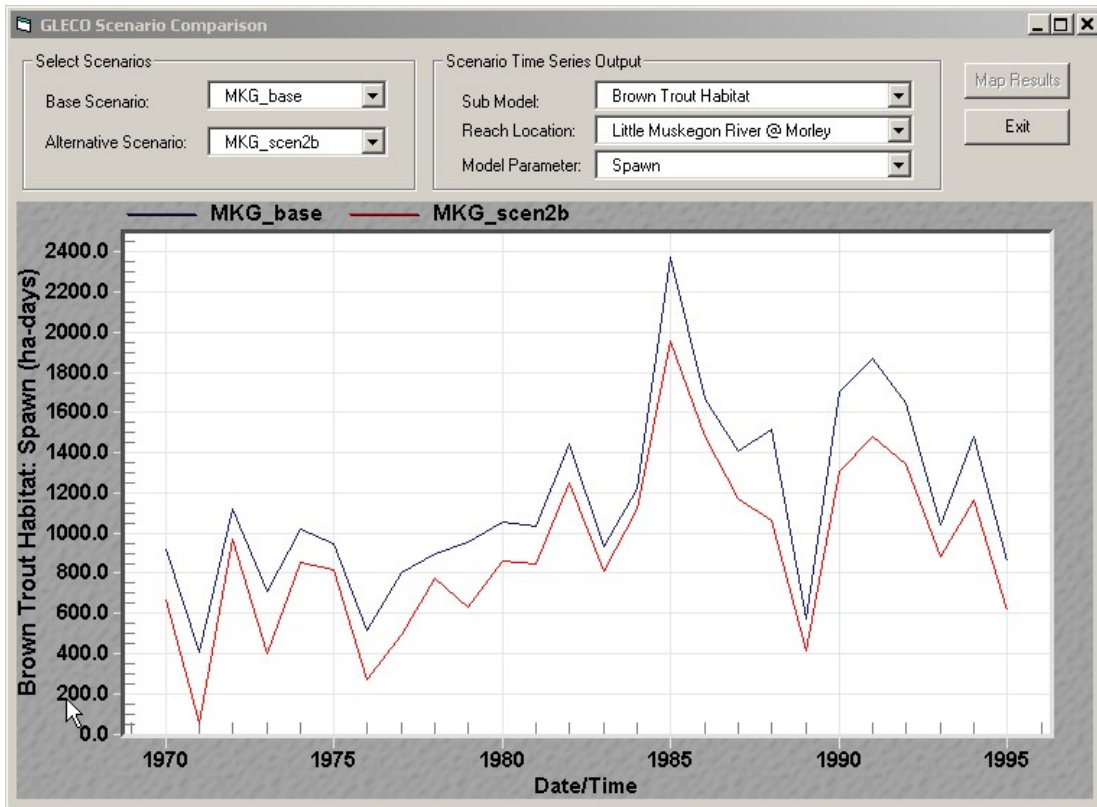


**Figure 15. Little Muskegon River Withdrawal Scenarios  
(Scenario “A” – red; Scenario “B” – green)**

Although the prescribed withdrawal scenarios were only applied to the Little Muskegon River, it is straightforward to apply a withdrawal to, or change the land cover distribution of, any of the 40 reaches represented in the model using the customized graphical user interface. Likewise, the model interface allows the user to specify any or all reach locations for model output. Therefore, the model framework provides the user with maximum flexibility for applying and evaluating withdrawal scenarios.

### **3.2.1 Model Display of Scenario Testing**

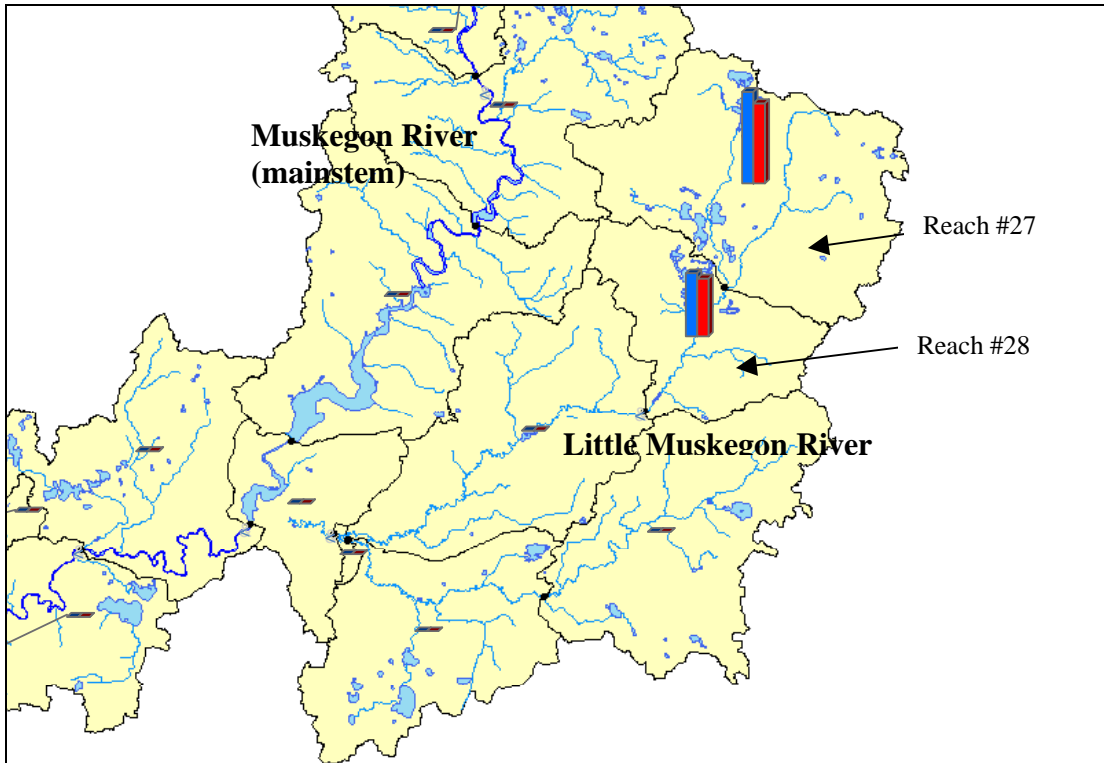
As described in Section 2.3.1.c, the GLECO model framework provides built-in tools for visualizing and comparing model scenario output. The time series comparison tool allows the user to interactively select scenarios and the sub-model (e.g., watershed, brown trout habitat), parameter, and reach location of interest. For example, an annual time series of spawning habitat weighted suitable area (WSA) could be compared for two scenarios by selecting the scenarios of interest, “brown trout habitat” as the sub-model, and “spawn” as the model parameter. Scenario 1b (10 mgd from each catchment) is compared with the baseline condition in Figure 16.



**Figure 16. GLECO Interface for Visualizing Scenario Time Series Results**

The built-in capability for graphically comparing model time series results provides the user with a concise, straightforward manner in which to evaluate scenario results. This feature of the GLECO model is in contrast to many models where few, if any, graphics capabilities are streamlined into the model framework. In most cases, the user is forced to spend a considerable amount of time and effort in processing and plotting the model output in a separate spreadsheet software package, such as Microsoft Excel.

In addition to the time series comparison tool, the GLECO model allows the user to launch a map interface that displays results time-averaged annual results for the selected sub-model and output parameter (Figure 17). This powerful built-in mapping capability allows the user to quickly compare scenario results between any of the reach locations represented in the model. For example, the time series output shown in Figure 16 demonstrates that a withdrawal scenario in one Little Muskegon River reach significantly impacts that brown trout spawning habitat in that reach. The map shown in Figure 17 provides additional insight into the impacts of this withdrawal scenario in other locations – it is clear from the bar charts in this figure that the relative impact (e.g., percent difference) between the baseline simulation and Scenario “A” is more significant for the reach where the withdrawal is applied (Reach #27) than for the next reach downstream (Reach #28).



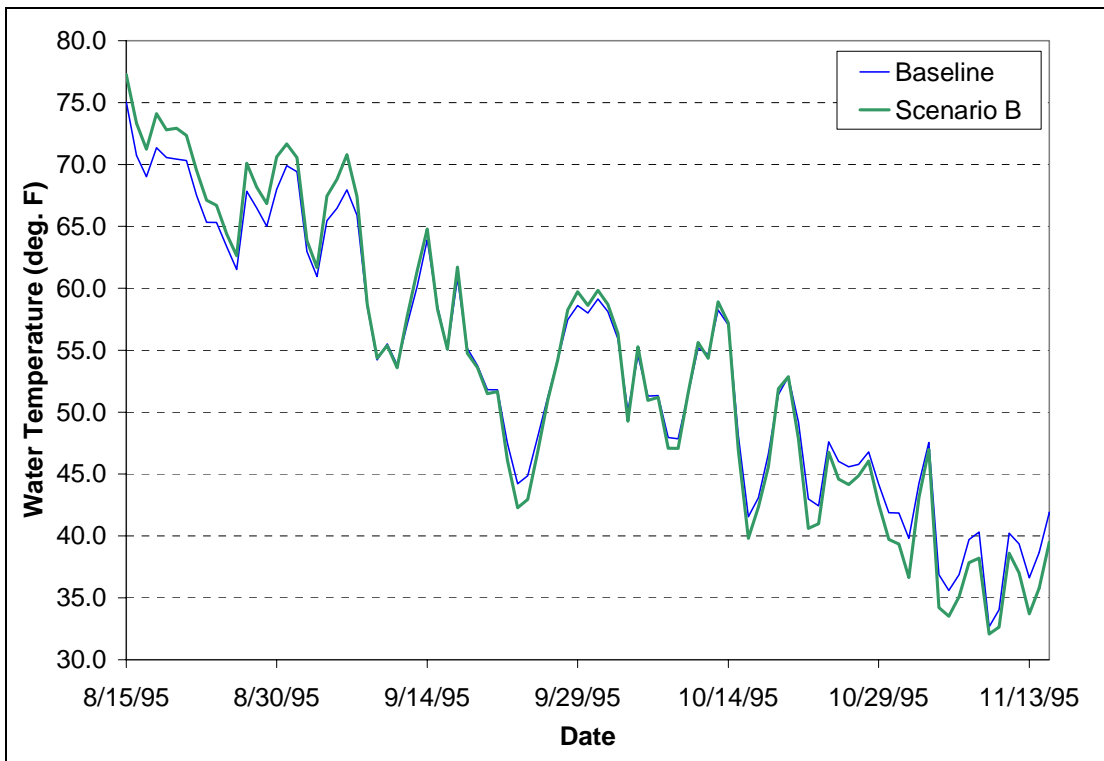
**Figure 17. GLECO Map Interface for Visualizing Time-Averaged Results**

### 3.2.2 Results of Scenario Testing

Water withdrawal scenarios “A” and “B” (Figure 15) were run through the GLECO model and results were generated for the upper two reaches in the Little Muskegon River subwatershed (Reach 27, 28 as indicated in Figure 17). Selected hydraulic and water quality output variables for the watershed sub-model for these simulations included daily average reach depth, reach velocity, surface area, water temperature, and dissolved oxygen concentration. Output variables for the brown trout habitat sub-model included total annual habitat weighted usable area (WSA) for four major life stages: spawn, fry, juvenile, and adult.

Predicted water temperature in Reach 28 for the baseline and withdrawal scenarios is shown in Figure 18 for the August 15 – November 15 period in 1995. These results illustrate the potential impact of withdrawals on temperature regime during different seasons. During the August-September period, the predicted water temperature in Reach 28 for Scenario “B” is roughly 5% higher than the predicted temperatures for the baseline scenario. The elevated temperatures observed for the withdrawal scenario are due to the depletion of groundwater storage, which in turn reduces the quantity of colder groundwater baseflow delivered to the reach. Because there is less total water volume and the cooling effect of the groundwater output has been reduced, the water in the reach is subject to larger temperature increases when it receives

energy input from solar radiation and heat exchange with the overlying air. The opposite effect is observed in the late fall months. Figure 18 shows that the predicted water temperature for Scenario “B” is lower than that for the baseline condition for the October 15 – November 15 period. During this time, the reduction in reach water volume reduces the ability of the reach to retain heat energy. Brown trout have very specific temperature requirements for various life stage activities, and spawning in particular. Therefore, the ability of the HSPF watershed sub-model to accurately represent these shifts in thermal regime is key to the performance of the brown trout habitat sub-model.



**Figure 18. GLECO Water Temperature Results for Reach 28**

As discussed in Section 3.2, the hypothetical water withdrawals were designed specifically to demonstrate the cumulative impact of water withdrawals on water quantity/quality and brown trout habitat. Brown trout spawning habitat results for the baseline, Scenario “A”, and Scenario “B” simulations are shown in Figures 19 and 20. The results in Figure 19 demonstrate that differences between the annual WSA results for the three simulations vary from year to year depending on the thermal and hydraulic conditions in this stream reach. For example, the reduction in spawning habitat WSA for Scenario “B” relative to the baseline condition was 86% in 1971, but only 8% in 1984.

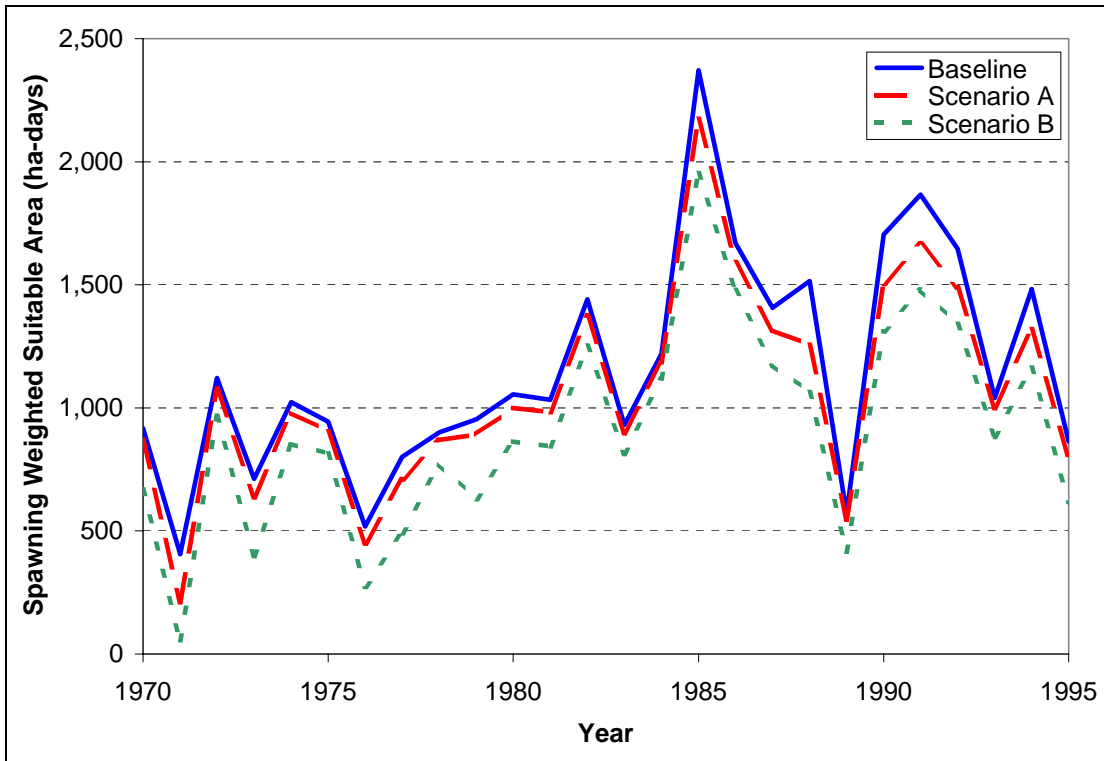


Figure 19. GLECO Brown Trout Spawning Habitat Results for Reach 28

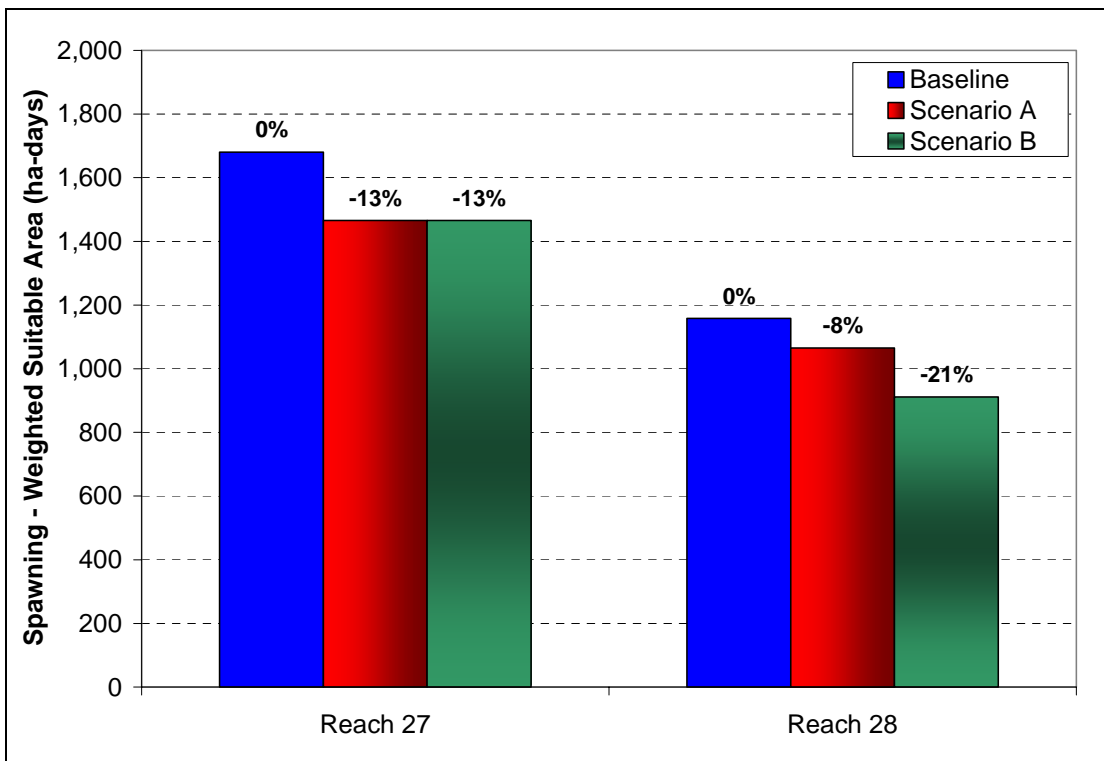


Figure 20. GLECO Brown Trout Spawning Habitat Results (Time-Averaged)

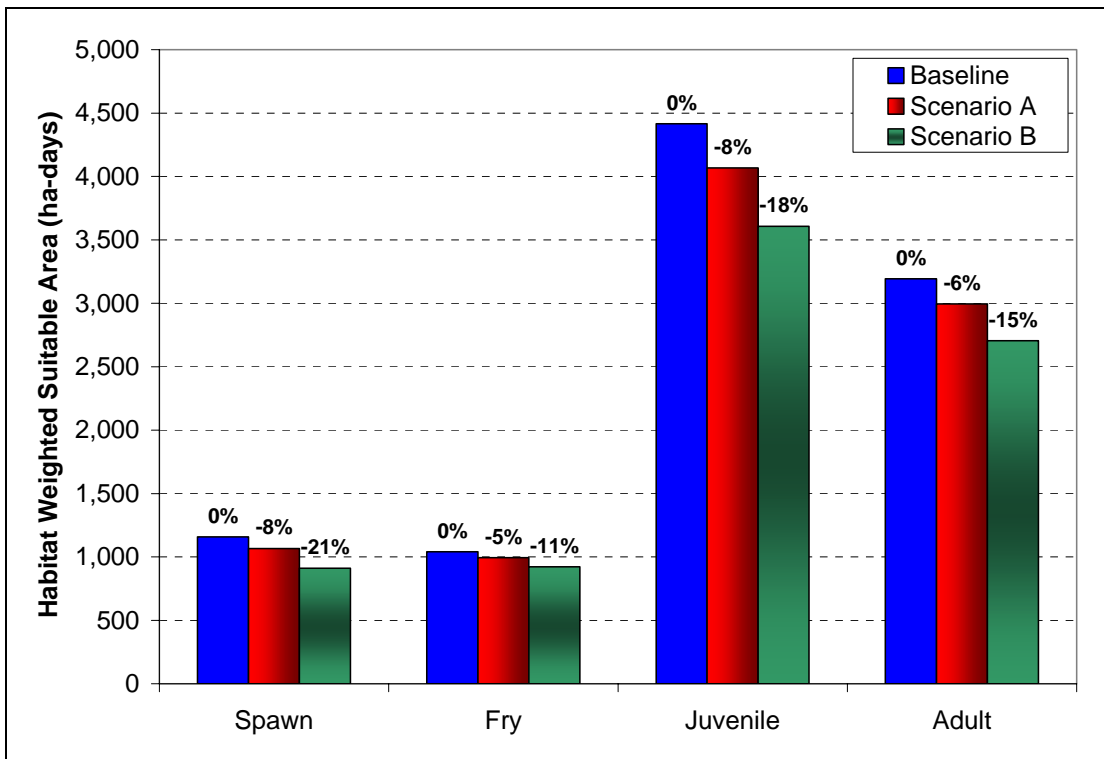
The cumulative impact of the two water withdrawals specified in Scenario “B” can be realized by comparing the results for Reach 27 and Reach 28 shown in Figure 20. Spawning habitat WSA predictions for the two scenarios are identical for Reach 27 because the same 10 mgd withdrawal is being applied to the groundwater storage in this reach in both cases. However, the results for Reach 28 indicate a substantial decrease (13%) in spawning WSA for Scenario “B” relative to Scenario “A”.

One of the major benefits of using a full-scale watershed sub-model in the linked model framework is that the impact of a particular set of withdrawals can be evaluated at any point in the system. The results shown here for the withdrawal scenarios indicate a potentially significant impact on spawning habitat in the reaches immediately downstream of the withdrawal location. However, the impact of those withdrawals will lessen at locations further downstream in the Little Muskegon and below its confluence with the mainstem as additional water is supplied to the system. The GLECO model allows the user to explore the spatial impacts of a set of withdrawals by providing simulation results at any desired reach location downstream of the withdrawal point(s).

GLECO simulation results for all brown trout life stages (spawn, fry, juvenile, and adult) are compared for the baseline condition and the two withdrawal scenarios in Reach 28 in Figure 21. These results demonstrate that reductions in habitat WSA for the various life stages for the two withdrawal scenarios are similar, although the greatest percent reductions are observed for spawning habitat. Total annualized habitat quantity for spawning and fry development are substantially less than habitat quantity for juveniles and adults. One reason for the large discrepancy is that juvenile and adult habitat are evaluated over the entire calendar year, while spawning and fry habitat are only computed during the time period relevant for those life stages. Brown trout are fall spawners (USFWS, 1986); therefore, spawning is assumed to occur during the last three months of the year (October 1 – December 31) in the habitat sub-model. Brown trout fry develop during the late winter months and typically emerge in the spring (USFWS, 1986). To be conservative, fry development in the habitat sub-model is assumed to occur during first five months of the calendar year (January 1 – May 31).

Although habitat predictions for the separate life stages provide important insight into potential impacts, it is admittedly difficult to evaluate the *overall* impact of the withdrawal scenarios for brown trout based on the habitat sub-model output alone. A habitat sub-model provides information on the suitability of a particular reach location for activities such as spawning, but it does not integrate that information into a “complete” evaluation of the species performance under stresses imposed by a withdrawal. However, an *assessment population sub-model* could be added onto the existing habitat sub-model to provide an integrated response to stresses induced by withdrawals. Population models combine quantitative habitat metrics (e.g., annual or daily WSA) and other parameters important to the life cycle of a species. For example, the life stage WSA results shown in Figure 21 could be used along with bioenergetics parameters, such as temperature- and density-dependent growth and

mortality rates, to predict the total abundance of surviving young-of-year fish at the end of each season. Young-of-year abundance predictions could in turn be used along with juvenile/adult mortality rates to compute the abundance of fish in each age class and total abundance of fish on an annual basis. Depending on the availability of data to parameterize and calibrate the watershed sub-model, the population model could even utilize water quality module output for primary production and zooplankton production to simulate food chain processes.



**Figure 21. GLECO Brown Trout Habitat Results for Reach 28 (Time-Averaged)**

## 4. DISCUSSION

A primary objective of this work was to identify the issues and challenges associated with development of a linked modeling framework of this type. Below, we discuss challenges related to model development and application, and applicability to other watersheds in the Great Lakes.

### 4.1 CHALLENGES RELATED TO MODEL DEVELOPMENT AND APPLICATION

The large size of the Muskegon River watershed required that we collect and synthesize a large volume of data and information. This was a time consuming process, compared to a smaller, less complex watershed. Initially we addressed the large data requirements by developing the model for the mainstem only. However, our review of site-specific information on habitats indicated that most critical fish habitats are located along tributaries. For this reason, we decided to include Muskegon River tributaries in the model, and HSPF helps considerably in this regard. In modeling Muskegon River tributaries, we found it difficult to characterize the flow regime in catchments containing significant lentic (i.e., ponded) water systems. These catchments contained insufficient flow data to permit characterization of the impact of these lake systems on the catchment hydrologic regime.

In addition to the fish habitat sub-model, we had originally planned on developing a wetland plant diversity sub-model, and a wetland bird habitat sub-model, which would be dependent on the plant diversity model. However, we found that sufficient data and information are not available to support these types of models. Our work identified the need for research to define the quantitative relationships between riparian wetland plant diversity and the range of factors that influence it. Because wetland plant community diversity and composition is critically important to the habitat of a number of faunal groups (e.g., wetland birds, fish, amphibians), we recommend that potential approaches for representing wetland plant response in mathematical models be further explored. This effort should draw on the outcomes of the ongoing Lake Ontario-St. Lawrence Study, which is exploring the effects of alternative regulation plans on various endpoints including environmental indicators. The web page for the study is at: [www.losl.org](http://www.losl.org).

Finally, the proliferation of control structures in the Muskegon River watershed (approximately 100) poses a challenge for modeling. Control structures that have been constructed for hydropower operations or wildlife floodings on tributary reaches can impact the magnitude, timing, and water quality of runoff from the local watershed. In most cases, negative impacts on water temperature, dissolved oxygen levels, and sedimentation will be of greatest significance. Also, the impact of control structures on fish movement in the system is another important ecological impact (Poff, et al., 1997; Rutherford, et al., ongoing research). We have found that the large number of tributary dams in the Muskegon River watershed act for the most part as

run-of-the-river reservoirs; therefore, they have relatively small impacts on the flow regime in the system. Most of their impacts are related to their impacts on biota migration and sediment trapping.

## **4.2 APPLICABILITY TO OTHER WATERSHEDS**

For any given watershed, the complexity of the modeling approach will be heavily influenced by data availability and the constraints associated with program objectives and resources. For this reason, it is important not to develop a model that is more complex than the available data. Site-specific modifications to the model will always be necessary, due to the complexity of the watershed as well as data availability. A benefit of using HSPF in this type of model is that it is scalable in its spatial, temporal, and process complexity (i.e., can be applied at different levels of complexity).

Limited information on ecological effects/processes in general will present challenges in applying this type of model to other watersheds. Ecological endpoints of most concern will be site-specific, and there is a possibility that model modifications in the ecological response modules will have to be made to apply the model to other watersheds.

In assessing ecological responses to alteration of flow regime in Great Lakes watersheds, there is a need to factor in the effects of other stressors (e.g., land use activities on nutrient and contaminant levels, non-native species invasions, climate change impacts) on ecosystem health and integrity. Also, our prototype does not characterize watershed sediment erosion (both from the drainage basin and from river banks) and associated transport dynamics. For watersheds in which this process poses a significant ecological threat, the modeling framework needs refinement to fully evaluate the impact of flow regime alteration on sediment dynamics and associated impacts.

Watersheds that have significant groundwater-surface water interaction will require an improvement of that component of the hydrology of the system relative to our current prototype. This is true especially if water withdrawals scenarios involve withdrawals from ground water and return to surface water or vice versa. Also, regional groundwater flow inventory and analysis will be necessary to delineate groundwater aquifer boundaries (i.e., groundwater-shed) from the traditional surface watershed.

The model was developed for rivers, and cannot be applied as is to watersheds that have a lake or chain of lakes as the primary receiving water body, because lake systems are characterized by very different hydrologic/hydraulic and ecological responses as compared to riverine systems. The Rogers, Hardy, and Croton impoundments in the Muskegon River behave like a series of lake systems. We handled these dams as run-of-the-river for simplicity.

Finally, many of the watersheds in the Great Lakes basin are largely urban watersheds, within which a significant fraction of their drainage area consists of impervious land serviced by stormwater or combined sewer systems. This has a very important impact on watershed hydrology and its response to additional water withdrawals. These systems will likely pose a different set of ecologically important resources and associated responses relative to largely rural watersheds, such as the Muskegon. Another class of watersheds in the Great Lakes basin includes those that are comprised largely of agricultural land use. Again, these systems have their own set of hydrologic and ecologic characteristics that must be considered. We therefore recommend that our prototype model be developed and field tested for these types of watersheds in addition to those represented by the Muskegon River application.

#### **4.3 FEASIBILITY AND UTILITY OF DEVELOPING A GREAT LAKES WATERSHED ECOLOGICAL RESPONSE MODELING SYSTEM**

We have demonstrated in this project via the development and application of a prototype watershed ecological model (GLECO) that it is both feasible and useful to apply this approach for assessing ecological impacts of water withdrawals/diversions within the context of the Great Lakes Charter Annex. Our prototype model suggests that it is feasible to develop a quantitative relationship between alteration of flow regime in a Great Lakes watershed and the various ecological impacts that that flow alteration might impose. We have illustrated a real impact on fish spawning in a catchment of the Muskegon River watershed; but there are many other potential impacts, which we have discussed and presented in our general conceptual model. A full assessment of flow alteration on the ecology of a watershed would consider all of these potential impacts.

In order to apply this approach to the Great Lakes basin as a whole, a separate watershed modeling framework would be required for each watershed in the basin. As we have indicated, it is not feasible to develop a single, generic model that could be used without modification on all Great Lakes watersheds. A framework like the one presented in this report, however, could form the basis for developing the various watershed-specific models that would be required. In order to accomplish this vision of each major Great Lakes watershed having its own planning and management model, we would require data and resources that may not be available for all systems. However, the acquisition of the necessary data and resources are certainly justified by the potential utility of such a planning tool on an individual watershed scale as well as on a basin-wide scale. And that justification will not only come from the implementation of the Annex but from the potential value for a wide range of watershed planning and management activities (e.g., TMDLs) in the Great Lakes basin.

## 5. NEXT STEPS

This project represents a first step toward meeting the ultimate objective of developing a user-friendly, linked modeling framework that can be applied to a range of Great Lakes basin systems. Future related efforts should be directed at building on this work by refining, further developing, and applying this modeling framework to a wider range of river systems and ecological endpoints within the basin. An important refinement identified in this study is the improvement of the simulation of groundwater – surface water interactions in a watershed so as to better assess the impacts of groundwater withdrawals on watershed ecology. The next phase of work should also include the development of a decision-support interface for the model suite to support effective development, assessment, and comparison of different water withdrawal scenarios by decision-makers.

The phased approach addresses the full range of possible hydrologic systems, in order of increasing complexity and integration level. Later phases of work may involve the development of a linked-model framework for inland lake systems, and for the Great Lakes themselves. Different types of water bodies have different hydrologic, water quality, and ecological responses of concern; therefore, a different modeling framework will be required for evaluating water withdrawals in each. Eventually, a planning and assessment watershed model framework like our prototype should be developed for each major Great Lakes watershed. Then assessments for the Great Lakes themselves can be made by developing a lakewide hydrologic – ecologic model that receives inputs from all its tributary watersheds.

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