Overview

Public Act 148 (Michigan, Public Acts of 2003) required the Department of Environmental Quality (DEQ) to create a “groundwater inventory and map” that includes eight specific products, a general requirement for a groundwater inventory, and a directive to make the map and inventory available to the public. The act required that the work be completed by August 8, 2005. DEQ created a cooperative research team involving groundwater and mapping experts from the U.S. Geological Survey (USGS) and Michigan State University (MSU). In a separate but related effort, Public Act 148 also created a Groundwater Conservation Advisory Council. The Council was charged to study the sustainability of groundwater resources in the State and report to the legislature by February, 2006 whether the state should provide additional oversight of groundwater withdrawals. The Council was informed of the progress of the Groundwater Inventory and Map (GWIM) Project, and the final inventory and map products have been made available to the Council to assist with the generation of their report.

Financial Support

This project was funded through a joint funding agreement between the DEQ and USGS in the amount of $900,000. The MSU team members were funded through the USGS State Water Resources Research Institute Program to the Institute of Water Research ($453,000 from the DEQ-USGS joint funding agreement). The USGS Cooperative Water Program provided additional funding for this study in the amount of $250,000. The total project budget, not including the in-kind staffing contributions from the DEQ, was $1,150,000.

In-kind staff contributions by the DEQ included oversight of the project by an engineer and geologist in the Water Bureau (WB). Extensive contributions to the project were made by WB management and other support staff. The DEQ technical advisory committee included representation from Environmental Sciences and Services, Office of Geological Survey, Remediation and Redevelopment, and Waste and Hazardous Materials divisions. The technical advisory committee met on a monthly basis. Overall, it is estimated that DEQ annual staff costs to administer this project was 2 FTEs. The extensive participation and oversight by DEQ staff resulted in many improvements and contributed to many enhancements of the products produced by the GWIM Project.

Project Team

The project team consisted of personnel from DEQ, MSU, and USGS.

Michigan Department of Environmental Quality

The team leaders were Brant Fisher and Joseph Lovato, directed by Wm. Elgar Brown. Project support was provided by Andrew LeBaron, Ronda Page and Dan
Diebolt, Source Water Protection Unit, Drinking Water and Environmental Health Section, Water Bureau. Ron Van Til, Water Use Program, provided required data for the mapping effort, as did Kristen Philip, Community Drinking Water Unit, who compiles these data for public water supplies. Chuck Thomas, Upper Peninsula District Office, provided a great deal of help on the aquifer distribution and use for the Upper Peninsula. Mike Gaber and Dave DeYoung, Well Construction Unit, provided insight on the relationship between the mapping project and the Groundwater Dispute Resolution Program, which was established by Public Act 177 (Acts of 2003).

**Michigan State University**

The team leaders were Dr. David Lusch (Remote Sensing & GIS Research and Outreach Services – Department of Geography, and Institute of Water Research) and Steve Miller (Department of Biosystems and Agricultural Engineering, and Institute of Water Research). Dr. Jon Bartholic, Director of the Institute of Water Research facilitated the contract between MSU and USGS. Members of the research team included: Justin Booth, Bill Enslin, Bob Godwin, Ed Hartwick, Pam Hunt, JoAnn Render, Yi Shi, Andreanne Simard, Paula Steiner and Sharon Vennix.

**USGS Michigan Water Science Center**

The team leader was Dr. Howard Reeves. The team members included Steve Aichele, Beth Apple, Lori Fuller, Chris Hoard, David Holtschlag, Carol Luukkonen, Brian Neff, Cynthia Rachol, and Kirsten Wright.

**Technical Support**

To assist the research team, DEQ assembled a technical advisory panel of geologists, hydrogeologists, and engineers from different program areas within DEQ including, John Esch (Superfund Section), Kevin Kincare (Office of Geological Survey), Richard Mandle (Groundwater Modeling Program), Jeff Spencer (Environmental Science and Services Division) and Ron Stone (Waste and Hazardous Materials Division). The research team met with the technical advisory panel once a month to review progress and gather suggestions for research efforts. The project benefited greatly from the candid discussion and helpful suggestions of the technical advisory panel.

Data for the inventory and map were provided by agencies in addition to DEQ. Bob Pigg from Michigan Department of Agriculture (MDA) directed the data collection, provided the data, and reviewed the map for agricultural water use reported to MDA. Michael Kost, Ecology Program Leader from Michigan Natural Features Inventory, supplied the analysis and data for the groundwater dependent natural features listed in the Natural Features Inventory.

**Additional Project Review**

The Groundwater Conservation Advisory Council was briefed on two occasions – October 7, 2004 (Higgins Lake) and April 22, 2005 (Grand Rapids). A project overview and appraisal meeting was held March 1, 2005 at the Kellogg Center on the campus of MSU. Representatives from an array of stakeholder groups were invited including water
supply consultants, well drilling contractors, academic hydrogeologists, local environmental health and the DEQ technical advisory group. Preliminary copies of the Glacial Aquifer and Bedrock Aquifers Yield maps were displayed at the March 15, 2005 annual meeting of the Michigan Groundwater Association. About fifty people viewed the maps and twelve made written comments concerning groundwater conditions in their various service areas. Virtually all the verbal comments were positive.

**Summary of Products**

The final maps and inventory items assembled to comply with P.A. 148 are summarized in this report. Detailed descriptions of the procedures used to meet each requirement are provided in the companion Technical Report for this project that is available on the project web site (gwmap.rsgis.msu.edu/). This web site is an important feature of this project. All the assembled data and analysis derived from the raw data are available on this site, in addition to the final maps required by the legislation. Although the inventory and map products provide a wealth of valuable new information processed from the compilation of existing data, decisions regarding specific groundwater uses require site-specific studies that go beyond the scope of this project.

The inventory and map products are available to end-users in three ways. Each of these provide for interactive viewing and use of the data at larger scales not possible with the small-scale maps provided in this Executive Summary. The DEQ Water Bureau web site will provide links and explanations of use for all three distribution mechanisms:

1. Web-based mapping site hosted by Remote Sensing and GIS Research and Outreach Services at MSU (gwmap.rsgis.msu.edu/). The digital data are also available for download from this site.
2. Digital data provided on compact disc for use with the Map Image Viewer software (MIV), an easy-to-use GIS software package for viewing and analyzing spatial data. The Remote Sensing and GIS Research and Outreach Services group at MSU provides this mechanism. There is a charge for this service for users other than local health departments and the DEQ.
3. The digital data will also be available for download through the State of Michigan, Center for Geographic Information (www.michigan.gov/cgi).

P.A. 148, Section 32802 (Michigan, Public Acts of 2003) specified that the “groundwater inventory and map” include the following items (a) through (h). Compliance with the requirement was met, in part, by development of the summary maps noted in the following list and included in this report.

(a) **Location and water yielding capabilities of aquifers in the state.**

(b) **Aquifer recharge rates in the state.**  
Summary map: 6) Estimated Recharge to Glacial Deposits (p. 19)

(c) **Static water levels of groundwater in the state.**  
Summary map: 7) Estimated Depth to the Water Table (p. 20)

(d) **Base flow of rivers and streams in the state.**  
Summary map: 8) Estimated Base Flow of Rivers (p. 22)

(e) **Conflict areas in the state (as defined by P.A. 177).**  
Summary map: 9) Groundwater Use Conflicts (p. 24)

(f) **Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources that are identified on the natural features inventory.**  
Summary map: 10) Trout Lakes and Streams, and Groundwater Dependent Resources from the Michigan NFI (p. 26)

(g) **The location and pumping capacity of all registered industrial or processing facilities, all registered, non-agricultural irrigation facilities, and all public water supply systems that have the capacity to withdraw over 100,000 gallons of groundwater per day average in any consecutive 30-day period.**  
Summary maps: 11) Non-agricultural Groundwater User by Type (p. 27)

(h) **Aggregate agricultural water use and consumptive use, by township.**  
Summary map: 12) Agricultural Water Use, by Township (p. 29)

In fulfillment of the requirement to “collect and compile groundwater data into a statewide groundwater inventory ...” the project searched the available literature for relevant theses, journal articles, abstracts, conference presentations/papers, and government documents that described groundwater characteristics anywhere in Michigan. This “statewide groundwater inventory” is available to the public through a web application described at the end of this report.

**Recommendations**

There is still much to learn about the groundwater resources of Michigan and their stewardship. For this issue area, Michigan’s number one priority should be the maintenance and enhancement of the maps and data compiled by the GWIM Project. The team strongly recommends the following as necessary next steps to maintain, enhance, and expand upon this initial GWIM Project. Simply stated, this project would have been impossible without the extensive electronic database of water well records, Wellogic, which is maintained by DEQ. The Wellogic program is primarily supported by federal funding through Clean Water Act, Section 106 monies. As budgetary constraints continue to squeeze the DEQ, more Water Bureau programs are looking to this source of funding for support, threatening the long-term viability of the Wellogic program. Success
of site-specific studies and other future efforts also will depend on a vibrant Wellogic program. Refinement of the groundwater yield estimates will require field mapping of glacial geology at local scales, additional characterization of the full thickness of glacial deposits, and more hydraulic characterizations of aquifers in regions that currently are data poor.

Database issues
- Continue to maintain and add documents to the groundwater Inventory.
- Continue to maintain Wellogic adding new well records in a timely fashion.
- Enter data from the scanned historic well records (~800,000 available) into Wellogic, prioritizing areas where electronic well records are scarce.
- Continue to provide outreach and technology transfer on the use and importance of Wellogic.
- Pursue consistency in water-use reporting requirements. Current inconsistencies include reporting either capacity or use, reporting use by facility or well, and reporting use aggregated by township.
- Develop a process to streamline the mapping of water use and provide tools to DEQ and MDA to simplify the mapping procedure as new data are submitted each year.

Mapping issues
- Explore ways to obtain hydraulic characteristics of aquifers, especially in data-poor areas, with a priority on areas of potential future water resource development.
- Update the improved bedrock topography map and the improved thickness map of the glacial deposits that were created by this project. Much of the information required for this updating task was collected and scanned during the aquifer map and inventory project.
- Develop large-scale (i.e. local) 3-D maps identifying the major confined and unconfined aquifer zones in the glacial deposits. Such a task was considerably beyond the time-line and budget of this project.
- Support and expand the detailed glacial geology mapping of the Michigan Office of Geological Survey with a focus on relating this effort to groundwater resource management.

Water balance and impact data
- Maintain the existing groundwater-level monitoring program and expand it to include both background wells that provide information on the natural variability of water levels and wells in areas of active pumping to record induced changes. The network also should include wells in the major bedrock aquifers and in a variety of glacial settings.
- Study and report on the temporal trends in the existing groundwater-level data. This analysis would provide insight to areas of Michigan that are more or less sensitive to drought, and provide a water-use and climatological context to the reported static water levels.
• Expand surface-water gaging network to improve estimates of baseflow and recharge.
• Collect low-flow streamflow measurements for currently ungaged watersheds to confirm the baseflow estimates and provide additional data to improve these estimates.
• Research practical methods to link aquifer analyses, water-use information, and baseflow and recharge estimates to evaluate the ecological impact of future groundwater resource development.

Required Elements of the Groundwater Inventory and Map

Location and water-yielding capabilities of aquifers in the State

This requirement was the most challenging owing to difficulties in determining the location and extent of glacial aquifers and in quantifying the water-yielding capability of any aquifer. The water-yielding capability (i.e. yield) from the glacial deposits that cover most of Michigan was mapped separately from the yield for the various bedrock aquifers. Although there are important heterogeneities at local scales, the general configuration of the bedrock aquifers is better known compared to aquifers within the glacial deposits.

Yield from a location in either the glacial deposits or bedrock aquifers was mapped as the estimated pumping rate that would cause a fifty-percent decrease in water level in the aquifer in that locale. This fifty-percent threshold value accounts for the generally accepted manner that high-capacity water wells operate. The yield map should not be viewed as a guarantee of yield from a well at a specific location.

Companion maps for the glacial deposits and the bedrock aquifers were produced to show the estimated change in groundwater level within the aquifer at a distance of 500 feet from a specified withdrawal location on the yield maps after 100 days of continuous pumping. These drawdown maps illustrate the general response to a groundwater withdrawal at the estimated yield rate in different areas of the State – they should not be used for groundwater withdrawal design purposes. A site-specific analysis of both aquifer yield and the impact of a proposed groundwater withdrawal should always be performed, especially in the case of proposed high-capacity wells.

Additional information describing and characterizing portions of the various bedrock and glacial aquifers in Michigan can be obtained from the groundwater information database that can be searched on the project web site (gwmap.rsgis.msu.edu/). Details about this search function are given in the concluding sections of this document.

Glacial Deposits

Aquifers in the glacial deposits of Michigan tend to be complex and, in many areas of the State, are extremely heterogeneous. Most glacial aquifers are identified only from very site-specific (i.e. costly) studies, and the horizontal and vertical extent and continuity of individual glacial aquifers is generally unknown. The budget and time-line
of this project precluded focusing on individual aquifer units. Instead, the yield was estimated for the thickness of the glacial deposits typically used for water supply.

The major data sources used to estimate the yield from the glacial deposits included 1) *Wellogic*, an electronic database of water-well records maintained by DEQ; 2) a database of aquifer-test analyses developed and maintained by DEQ; and 3) a new glacial landsystems map compiled for this project. The glacial landsystems map provides the geologic framework that is used to regionalize the various data that were extracted from *Wellogic*. The landsystem map supported the classification of the State into areas where the anticipated amount of water that can be transmitted by an aquifer is low, intermediate, or high. The lithologies (sand, silt, clay, etc.) reported in *Wellogic* were used to develop equivalent hydraulic conductivity and transmissivity estimates that quantify the expected yield and show the heterogeneity within each landsystem.

The industry-standard minimum well yield for a small residential home is 10 – 15 gallons per minute (gpm). Several regions of minimal yield (<10 gpm) are obvious on Figure 1, notably in the areas northwest, south and southeast of Saginaw Bay, the tip of the “thumb”, and southeasternmost Lower Michigan. Many areas in Delta and Menominee counties in the Upper Peninsula also exhibit poor yields. Note that in these areas, some homeowners have wells in glacial deposits that yield sufficient water. Local-scale heterogeneity (lithologic variations within 10 – 1000 meters) is very difficult to quantify and display on a statewide map. As such, site-specific investigation is always prudent when planning high-capacity groundwater withdrawals.

The 70 gpm yield level is the current definition of a high-capacity well. Such wells are routinely possible throughout much of Lower Michigan (excluding the areas shown in red and orange). Zones of very high yield potential are located in southwestern and south-central Lower Michigan, in the core of the “thumb” (Oakland, Lapeer and southeastern Tuscola counties), in the Houghton-Higgins lakes district of northern Lower Michigan and across the “tip of the mitt.”

Areas of thin glacial deposits (<30 feet) that make legally-constructed water wells screened in the glacial deposits unlikely are shown in Figures 1 and 2. The no-data areas on these maps are defined as zones more than 2000 meters away from a well log in *Wellogic*. This 2000-meter buffer zone balances the desire to note areas that lack data in *Wellogic* with the need for a statewide estimate. If the buffer was set much smaller, the no-data areas would begin to dominate the map in the northern Lower Peninsula and across the Upper Peninsula.

The estimated drawdown map for pumping from glacial deposits (Figure 2) follows the general patterns noted for the yield map (Figure 1) with one interesting exception. Areas of low estimated drawdown (less than 5 ft) occur both where the estimated yield is moderate (70 – 200 gpm) and where it is low (< 10 gpm). In the low-yield areas, the small estimated drawdown results from the inability of the water-bearing materials to provide enough groundwater to impact a well 500 feet away. In areas of moderate yield, the available drawdown and transmissivity of the glacial deposits are such that the estimated yield can be obtained without significantly lowering the groundwater level 500 feet away. In these areas, a high-capacity well capable of pumping at a rate larger than the estimated yield might be possible (for example, by drilling a well much deeper than the typical wells in the area) and such a well could impact groundwater levels 500 feet away.
Figure 3 illustrates an example spatial analysis of the data displayed in Figures 1 and 2. Public Act 177 (Acts of 2003) established the Groundwater Dispute Resolution Program within the DEQ to investigate and resolve disputes arising from the impacts of high-capacity water wells (pumping capacity of 70 gallons per minute [gpm] or more) on small-quantity wells (pumping capacity less than 70 gpm). Figure 3 shows the estimated drawdown (data from Figure 2) resulting from groundwater withdrawals of 70 gpm or more in the glacial deposits. In many large areas of the state, the estimated drawdown exceeds 10 feet, which could adversely affect neighboring wells. It should also be noted, however, that problematic groundwater withdrawal impacts can, and do, occur in many areas of the state where the estimated yields (Figure 1) are less than 70 gpm.
Figure 1
Glacial Deposits - Estimated Yield

Yield (gpm)
- < 10
- 10 - 70
- 70 - 200
- 200 - 500
- 500 - 1,400
- > 1,400

- Glacial Deposits < 30 ft. thick
- No Data

Note: Yield is defined as the pumping rate necessary to produce an estimated 50% decrease in water level at a well, for the used thickness of the glacial deposits as derived from Wellogic well records.
Figure 2
Glacial Deposits - Estimated Drawdown

Drawdown (ft.) at 500 ft.

- **Blue**: 0 - 5
- **Light Blue**: 5 - 10
- **Green**: 10 - 15
- **Yellow**: 15 - 20
- **Red**: > 20

- Black: Glacial Deposits < 30 ft. thick
- White: No Data

Note: Drawdown at 500 ft. was calculated for each cell using the estimated yield values from Figure 1, assuming 100 days of continuous pumping and a storage coefficient of 0.0016 consistent with a leaky aquifer.
Figure 3
Estimated Drawdown in Glacial Deposits Resulting from High-Capacity Well Pumpage

Drawdown (ft)

- **0 - 5**
- **5 - 10**
- **10 - 15**
- **> 15**
- Wells generally not capable of producing 70 gpm or no data

Note: Estimated drawdown 500 feet from high-capacity (>=70 gpm) glacial wells pumping at their estimated yield (assuming 50% of available drawdown in the well) for 100 days.
Bedrock Aquifers

Four major sources of hydrogeologic data were available to characterize the properties of the bedrock aquifers in Michigan: 1) the DEQ aquifer-test database, 2) the USGS Regional Aquifer System Analysis (RASA) aquifer-test archive, 3) hydraulic properties listed in county hydrogeologic reports, and 4) specific capacity data from some wells in Wellogic. The configuration of the bedrock aquifers was characterized using the state bedrock geology map (Milstein, 1987), information from the USGS Michigan Basin RASA (Westjohn and Weaver, 1998), and information from the water-well records in Wellogic.

The bedrock aquifer yield map (Figure 4) depicts those areas of the state where groundwater is readily available from the bedrock. The highest estimated yields from bedrock aquifers occur in the central and southern portions of the Lower Peninsula especially in Jackson, Calhoun and Barry counties where high yields are associated with a productive sandstone unit (the Marshall Formation).

Lower yields are typical from bedrock aquifers in the Upper Peninsula, the northern swath of the Lower Peninsula and in the southeast corner of the state. These aquifers are generally comprised of sandstone and carbonate units in the Upper Peninsula and predominately carbonate strata in the Lower Peninsula.

In the Lower Peninsula, the white areas on Figure 4 are generally characterized by shale bedrock units that normally do not serve as aquifers, such as the Coldwater Shale that underlies much of southwestern and southeastern Lower Michigan and an arcuate swath from Mason to Alcona counties in the northern Lower Peninsula. Much of the western Upper Peninsula is dominated by hard-rock units that only produce groundwater along localized fracture traces. Nevertheless, there are residential wells in these areas of the State that derive water from fractures in the upper part of these “non-aquifer” units.

The estimated drawdown map for groundwater withdrawals from bedrock aquifers at the estimated yield rate is depicted in Figure 5. Comparing Figures 4 and 5, at least four groundwater withdrawal regimes across Michigan are apparent:

1. Low-yield areas exhibiting small drawdown values. In these areas, the estimated yields are so small that the groundwater withdrawal does not cause significant drawdown 500 feet away. This condition exists across a large portion of the Upper Peninsula, as well as in the northern swath and southeast corner of the Lower Peninsula.

2. High-yield areas with large drawdown values. In these locales, the aquifer characteristics allow for large yields at the expense of a great deal of drawdown. Such conditions occur in the central and north-central portions of Lower Michigan and in four restricted areas in Barry, northeastern Jackson, northern Ingham and northwestern Lapeer counties (associated with portions of the Saginaw Formation and the Marshall Sandstone).

3. High-yield areas exhibiting small drawdown values. In these places, the aquifer properties promote minimal drawdown values even at high rates of withdrawal. These conditions are common in a narrow band across northeastern Calhoun, southern Jackson and northern Hillsdale counties (all associated with the southernmost margin of the Marshall Sandstone).
4. **Moderate-yield areas with moderate drawdown values.** The hydraulic properties of some bedrock aquifers are such that both the estimated yields and the associated drawdown amounts are moderate. The Saginaw formation beneath portions of Shiawassee, Clinton, Eaton and Ingham counties exhibits these characteristics as does the Marshall Sandstone in parts of Sanilac and Huron counties.

Another noteworthy attribute of the bedrock aquifers in central Lower Michigan is shown by the gray and dark gray overprint on Figures 4 and 5. These are zones within the rock units where the dissolved solids concentrations in the groundwater exceed 1,000 milligrams per liter (more than twice the recommended drinking water limit). For lack of practical alternative water supplies, some residential well owners utilize this low-quality groundwater. This is especially common in the area around Saginaw Bay.

The map reader should take careful note of the white diagonal stripe pattern across large areas of central Lower Michigan and more restricted areas in the eastern Upper Peninsula on Figures 4 and 5. These parts of the state lacked sufficient data to accurately predict both the yield and the drawdown levels. The various colors beneath the stripe pattern (depicting yield or drawdown) are shown to indicate the areal extent of the various bedrock aquifers. The yield and drawdown values in these areas are notably unreliable.
Figure 4
Bedrock Aquifers - Estimated Yield

Composite Bedrock Yield (gpm)
- < 10
- 10 - 70
- 70 - 200
- 200 - 500
- 500 - 1,400
- > 1,400

Dissolved solids concentrations (mg/l)
- Brine >= 100,000
- Saline > 1,000 - < 100,000
- No Data

Note: Yield is defined as the pumping rate necessary to produce an estimated 50% decrease in water level at a well in the bedrock aquifer.
Figure 5
Bedrock Aquifers - Estimated Drawdown

Composite Bedrock Drawdown (feet)
- < 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- > 50

Dissolved solids concentrations (mg/l)
- Brine >= 100,000
- Saline > 1,000 - < 100,000
- No Data

Drawdown at 500 ft. was calculated for each cell using the estimated yield values from Figure 3, assuming 100 days of continuous pumping and a storativity of 0.004.
Recharge

Recharge typically refers to the amount of precipitation, either rainfall or snowmelt, that infiltrates through the ground and reaches the water table aquifer. Deeper aquifers generally are recharged with water from shallower systems. Groundwater discharge is water that leaves an aquifer through boundaries including rivers, wetlands, and lakes. The approach used to estimate recharge is based on statistical regression of groundwater discharge (baseflow) estimates derived from stream-gaging records. The assumption is made that recharge to the shallow aquifer system is equal to baseflow. The regression technique expands on the work for the lower peninsula of Michigan by Holtschlag (1996). This method is appropriate for the shallow aquifer system (typically in the glacial deposits) that delivers most baseflow to streams and provides a long-term (1 – 80 year) average estimate of recharge for moderate areas (up to 500 square miles) (Scanlon and others, 2002). Note that most bedrock aquifers in Michigan do not possess a strong hydraulic connection to the gaged streams and that the recharge map does not apply to the water delivered to bedrock aquifers from the overlying glacial deposits or through adjacent bedrock units.

The baseflow estimates discussed below were used to estimate recharge as detailed in the Technical Report. Note that although the spatial distribution of streamflow gages in the Lower Peninsula (totaling 162) was generally adequate to represent most landscape settings, only 46 gages were available in the Upper Peninsula. There were too few Upper Peninsula gages to provide an adequate number of observations to support the incorporation of land cover and surficial geology data into the models. This is why the recharge map (Figure 6) in the Upper Peninsula is notably less detailed than in the Lower Peninsula. This also means that the influences of surficial geology, such as the reduction in recharge and baseflow associated with the low-permeability lacustrine deposits in the eastern Upper Peninsula, as well as the effects of land cover, have been ignored in the estimation procedure undoubtedly leading to an overestimation of recharge in this part of Michigan.

A common misconception is that groundwater development can be designed such that pumping does not exceed recharge. Such a view fails to recognize that a withdrawal designed to pump all available recharge leaves no groundwater to provide baseflow to streams, support ecology, or prevent intrusion of poor-quality groundwater from adjacent geologic units. It also does not consider well-to-well interference such as that addressed by P.A. 177. The source of groundwater to wells must be recognized and the impact of pumping a well on the groundwater system must be understood in order to place the recharge estimate map in its proper context (Alley and others, 1999).

Before pumping, the groundwater system is in a state of dynamic equilibrium. Recharge into the system is balanced by discharge out of the system (this is the basis of the assumption used in equating estimated baseflow with long-term recharge). When recharge exceeds discharge, the groundwater level in an aquifer will rise and more water is held in storage in the system. When discharge exceeds recharge, groundwater levels decline and water is removed from storage. These changes in groundwater levels occur on seasonal, annual and long-term cycles. When a well is pumped, water will come from one or more of these three sources: (1) a change in storage in the system by lowering the
water level, (2) an increase in recharge to the aquifer, or (3) a decrease in discharge to surface water from the aquifer.

When a groundwater withdrawal occurs, water is first removed from storage and the water level in the aquifer adjacent to the well is lowered. The change in water level extends outward from the well some distance depending on the hydraulic characteristics of the aquifer. For most aquifer systems, a new equilibrium state is reached by associated decreases in discharge from the aquifer system, although in some cases recharge to the aquifer system may be increased (e.g. induced recharge from surface water). The balance between removal from storage, increase in recharge, decrease in discharge and the time required for these changes to occur after a well is pumped are all determined by the hydraulic characteristics of the aquifer system. The recharge rate plays a role in the behavior of the aquifer in response to pumping, but it cannot be used as the sole indicator of the water resources potential for an area.

Static Water Levels

Mapping static water levels for all aquifers of the State, as called for in P.A. 148, is problematic for two major reasons. First, although the static water level is recorded on many of the water well records in Welogic, the wells must first be grouped together by aquifer so that the various groundwater levels are not inappropriately mixed. Only rarely, and then only in small areas, are glacial-aquifer maps available due to the heterogeneity of the glacial deposits across much of Michigan. As a result, grouping wells that are screened in the glacial deposits by aquifer is very difficult. Second, the reported static water levels, even for wells in the same aquifer system, may vary considerably across the several decades of reporting in Welogic due to seasonal variability, climatic changes, changes in use, and inaccuracy of reported levels.

A greatly-improved, statewide water table map was compiled to partially fulfill this mandate (Figure 7). This mapping effort built upon a prototype version of a similar map that had been compiled by RS&GIS, MSU as part of the very successful Source Water Assessment Program (Michigan Department of Environmental Quality, 2004). The water table is the upper surface of the saturated zone of the earth. The water table map was compiled from several existing, digital, geospatial data sets, including surface hydrography, topography, soils, wetlands and selected well records from Welogic. The improvements over the previous version came primarily from the incorporation of newly available soils data, new analyses of the lithology data in Welogic that identified wells screened in unconfined glacial aquifers and improved computerized interpolation methods. The “data problem” areas, shown in red on Figure 7, result from interpolation artifacts in data-poor areas that coincided with high-relief terrain.

To supplement the water table map, approximately 200 plots of groundwater levels based on observations collected at USGS observation wells across Michigan are provided in order to document both natural and pumping-induced variations in groundwater levels in both glacial deposits and bedrock aquifers. These plots are available on the project web site (gwmap.rsgis.msu.edu) and to help illustrate the temporal trends in groundwater levels and show water levels in a number of bedrock aquifers not addressed in Figure 7.
Figure 6
Estimated Recharge
to Glacial Deposits

Recharge - in/year

- No Data
- ≤ 6
- 7 - 9
- 10 - 11
- 12 - 13
- 14 - 22
Figure 7
Estimated Depth to Water Table

Depth in feet
- Data Problems
- 0 - 15
- 15 - 30
- 30 - 45
- 45 - 60
- 60 - 75
- > 75

*Data problem areas result from interpolation artifacts in data-poor areas that coincided with high-relief terrain resulting in estimated water table levels above the ground surface.*
Baseflow of Rivers

The baseflow of a stream or river is the amount of groundwater discharged from an aquifer to the watercourse. This discharge occurs year-round, and fluctuates seasonally depending on the level of the water in the aquifer. Over the course of a year, assuming no change in the quantity of water stored in the aquifer, the total baseflow is assumed to equal the total groundwater recharge for a watershed. Baseflow is supplemented by direct runoff during and immediately after precipitation or melt events, resulting in peaks on a hydrograph showing stream flow through time. The process of dividing these peaks into base flow and runoff is called hydrograph separation.

Hydrograph separations were completed for all USGS stream flow-gaging stations in Michigan that had more than 10 years of daily records. Sites that were clearly affected by upstream impoundments (lakes, dams) were excluded. No attempt was made to detect or correct for trends in the data. This may lead to some errors in the comparison of streams with data from different time periods if there is an underlying temporal trend in the data, but inclusion of all records in the analysis was necessary to increase the data pool and provide better spatial coverage.

Watersheds were delineated for each of the 208 stream flow-gaging stations, and various characteristics of each watershed, such as topographic relief, surficial geology, land cover, growing degree days, annual and winter-season precipitation, and others were tabulated. Regression modeling, described in the Technical Report, was used to estimate the baseflow for each steam segment of the 1:100,000-scale National Hydrography Dataset as shown in Figure 8.
Figure 8
Estimated Baseflow of Rivers

BASEFLOW - cfs
- 0.0 - 0.5
- 0.6 - 1.0
- 1 - 5
- 5 - 20
- 20 - 50
- 50 - 500
- > 500

Note: Average annual mean baseflow rate in cubic feet per second (cfs) from period of record data from 208 gaging stations and extrapolated to streams on the 1:100,000 scale National Hydrography Dataset for Michigan.
**Conflict Areas Per P.A. 177**

A groundwater-conflict resolution procedure was established by P.A. 177 (Michigan, Public Acts of 2003). The Groundwater Dispute Resolution Program within the DEQ investigates and resolves disputes arising from the off-site impacts of high-capacity water wells. If a small quantity well (defined as a well capacity less than 70 gallons per minute [gpm]) fails to produce its normal supply of water or fails to produce potable water and the owner has credible reason to believe the problem was caused by a high-capacity well (70 gpm or more), a complaint can be filed with the DEQ, Water Bureau. An assessment of the affected water well by a licensed water well drilling contractor maybe required to rule out mechanical problems as the cause of the well failure.

The DEQ will investigate the complaint to determine if the problem is caused by the lowering of groundwater by a high-capacity well and then make a diligent effort to resolve the dispute. If the suspected high-capacity well is an agricultural well, the complaint is referred to the Michigan Department of Agriculture, Environmental Stewardship Division, for investigation. Resolution of a groundwater dispute typically involves restoration or replacement of the small-quantity water well or connection to a municipal water system, with the high-capacity well owner reimbursing the complainant and the DEQ for costs incurred.

As of July 27, 2005, a total of 43 complaints had been received by the DEQ Groundwater Dispute Resolution Program. Of these, 17 were determined to be invalid, another 17 have been resolved and nine complaints remain unresolved. Of the 17 valid and resolved complaints, 11 involved high-capacity wells used for quarry dewatering (located in Charlevoix and Monroe counties) and six involved high-capacity agricultural wells (all in Saginaw County).

Figure 9 shows the location of the 17 valid and resolved complaints, and the two declared conflict areas. As required by the statute, the Director of the DEQ declared four townships in Saginaw County and all of Monroe County as areas where there is the greatest risk for potential groundwater disputes.
Figure 9
PA 177 Groundwater Use Conflicts for 2004 -2005

Verified per PA 177 of 2003 as of July 27th, 2005
Trout Lakes and Streams and Groundwater-dependent Resources on the Natural Features Inventory

On October 12, 2000, the Director of the Department of Natural Resources ordered that certain lakes and streams or portions of streams be designated as trout lakes or trout streams. These designated trout lakes and streams are shown on Figure 10.

The Michigan Natural Features Inventory (MNFI) is a cooperative program of Michigan State University Extension and the Michigan Department of Natural Resources to identify, evaluate and map the locations of the rarest species and exceptional examples of natural communities in Michigan. MNFI manages the continuously-updated Biological and Conservation Database. This database lists and describes 74 natural communities currently recognized by MNFI, of which 28 are considered “groundwater dependent.” These also are shown in Figure 10. It should be noted, however, that there are numerous other groundwater dependent natural resources throughout Michigan that are not shown on this map because they have not yet been surveyed by the MNFI. Most persistent lakes, streams and wetlands are groundwater dependent.

Water Use Reported to Michigan Department of Environmental Quality

Thermoelectric power generation, industrial/manufacturing, public water supply, and non-agricultural irrigation facilities throughout Michigan report water use information to the DEQ. The data shown on Figure 11 represent groundwater withdrawals made during the 2003 calendar year, based on measurements or estimates made by facility personnel.

Water withdrawal data reported under Public Act 399 of 1976, as amended, include information reported through the water supply program at DEQ by all community public water systems that withdraw groundwater. Thermoelectric power generation, industrial/manufacturing, and non-agricultural irrigation facilities with a pumping capacity of more than 70 gallons per minute (100,000 gallons per day averaged over any 30-day period) are required to report to the DEQ under Part 327, P.A. 451 of 1994, as amended. All withdrawals in this data set are defined as groundwater for the purpose of this project. However, some withdrawals reported by non-agricultural irrigators come from combined well and pond sources and include a combination of groundwater and surface water.

The accuracy of the reported data varies from measured to estimated, with metering more frequent for community water supplies and thermoelectric power plants than for industrial/manufacturing facilities and non-agricultural irrigators. In some instances where groundwater withdrawal data were not reported for 2003, facility data from a previous year were used. Since non-agricultural irrigation water withdrawals typically occur only during the May to September period, comparisons with other facility types require careful scrutiny as the posted values are all annualized averages.
Figure 10
Trout Lakes and Streams and Groundwater-dependent Resources from the Michigan NFI
Figure 11
Non-Agricultural Groundwater Use by Type

Groundwater Use (Millions of Gallons/Day)

- 0.00 - 0.10
- 0.10 - 1.00
- 1.00 - 2.00
- 2.00 - 5.00
- > 5.00

Groundwater Users 2003

- Power Plants
- Industrial
- Non-Agriculture Irrigation
- Public Water Supply
Agricultural Water Use Reported to Michigan Department of Agriculture

Water use was reported to the MDA by agricultural producers in the state that met water pumping capacity thresholds (70 gpm) during the 2004 calendar year. At least 90 percent of the water use reported was for irrigation. This agricultural water use, aggregated by political township as required by P.A. 148, is shown in Figure 12. It is estimated that 27% of the reported water use was withdrawn from surface water sources. Michigan and the other Great Lakes states have agreed that 90 percent of agricultural irrigation water use is consumptive. The proportion of other agricultural water uses that is consumptive varies by use.

Water use reporting forms were mailed to all agricultural producers who registered with the MDA. Forms were also made available on the MDA web site. Data mailed back to MDA were entered into a database and water use was attributed to political townships. Water use was reported in a variety of units (gallons, acre-feet, and acre-inches), but these were converted to millions of gallons per day (MGD) for consistency with other water use reporting. Obvious errors made by reporting producers were corrected; otherwise, all data were entered as reported. Water use was then aggregated by political township.

In addition to the water use in this section being reported by township, agricultural water withdrawals typically occur only during May through September. To be consistent with the previous section (non-agricultural groundwater use), the mapped values are annualized averages. As mentioned above, the reported agricultural water use data include both groundwater and surface water withdrawals. As a result, comparisons with the facilities shown on Figure 11 require careful scrutiny.

An MDA comparison of the 2004 reported agricultural water withdrawals with the 2002 NASS irrigation survey reveals that MDA received reports covering 69.7% of the irrigated acres tabulated by NASS. By comparison, the non-agricultural groundwater use reported above has an estimated reporting rate exceeding 90%. This is the first year of agricultural water use reporting and, hopefully, the percentage of irrigators reporting will improve as the program continues.
Figure 12

Reported Agricultural Water Use

2004 Agriculture Water Use
(Millions of Gallons/Day)

- 0.00 - 0.10
- 0.10 - 1.00
- 1.00 - 2.00
- 2.00 - 5.00
- 5.00 - 6.08

Note: Water use aggregated by township as reported to the Michigan Department of Agriculture (MDA). It is estimated that 27% of the water use reported was from surface sources.
Groundwater Data Inventory and Bibliography

In fulfillment of the mandate by Section 32802 (1) of P.A. 148 to “collect and compile groundwater data into a statewide groundwater inventory ...” the project searched the available literature for relevant theses, journal articles, abstracts, conference presentations/papers, and government documents describing groundwater characteristics in Michigan. Over 220 documents and applicable map plates were digitally scanned and are available on the project web site (gwmap.rsgis.msu.edu/). The full bibliography containing 464 citations is also available on this web site.

Many of the scanned documents were categorized into the Groundwater Information Database that supports web-based queries to find 1) written summaries of the hydrogeologic characteristics for each county, 2) the type of wells, range of transmissivity and storativity, and amount of water used for each county, 3) reports pertaining to the groundwater resources in Michigan by location, author, watershed name or hydrologic unit code, or 4) aquifer data for wells listed in reports sorted by county, type of aquifer, and/or type of test. A brochure at the back of this Executive Summary highlights the components of this Groundwater Information Database.

Distributing the Groundwater Maps to the Public

All of the maps and supporting data from the GWIM Project have been made available to public through three mechanisms. Each of these provide for interactive viewing and use of the data at various scales not possible through the summary maps provided in this Executive Summary. The DEQ Water Bureau website will provide links and explanation of use for all the distribution mechanisms:

1. Web-based mapping site hosted by Remote Sensing and GIS Research and Outreach Services at MSU (gwmap.rsgis.msu.edu/). A brochure at the back of this Executive Summary highlights the main components of this mapping application.

2. Digital data provided on compact disc for use with the Map Image Viewer (MIV), a GIS software package for viewing and analyzing spatial data. The Remote Sensing and GIS Research and Outreach Services group at MSU provides this mechanism. There is a charge for this service for users other than local health departments and the DEQ.

3. The digital maps can also be downloaded from the State of Michigan, Center for Geographic Information web site (www.michigan.gov/cgi).

Literature Cited


