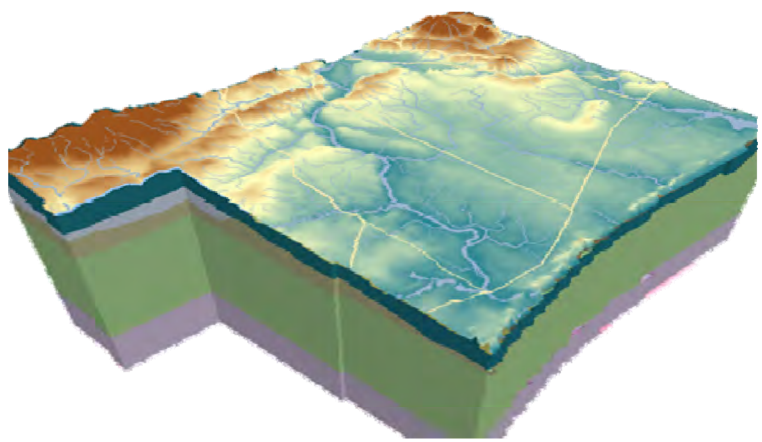
OTTAWA COUNTY WATER RESOURCE STUDY

FINAL REPORT



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May 24, 2013

ACKNOWLEDGEMENTS

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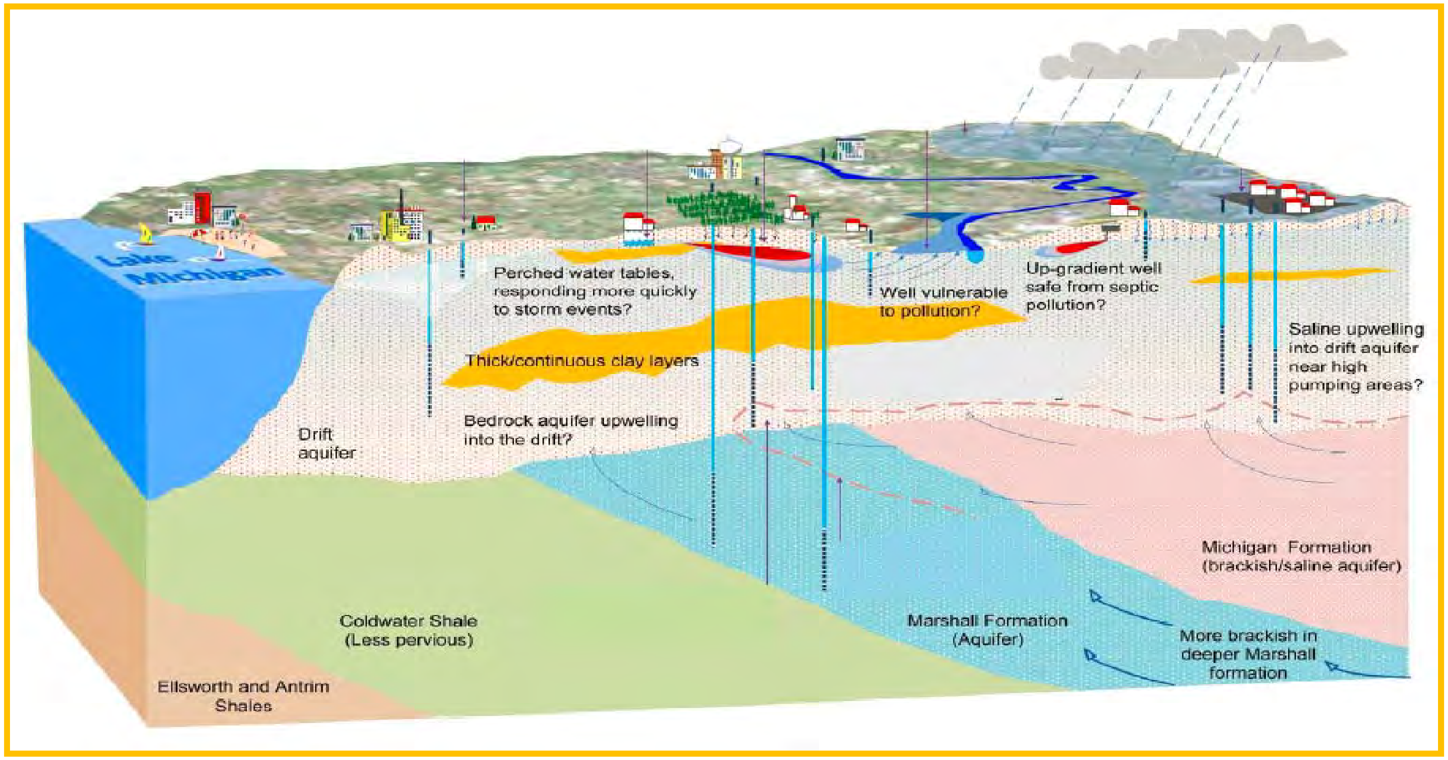
EXECUTIVE SUMMARY

Introduction

In recent years Ottawa County has experienced several issues related to groundwater. These problems included unreliable groundwater availability (quantity) in certain areas of the County, impaired groundwater quality (high brine and nitrate concentrations) in certain areas of the County and clustered occurrences of basement flooding (thought to be due to an elevated water table level).



A conceptual sketch illustrating some key water resources issues facing Ottawa County.

To gain a better understanding of the groundwater resource status in the entire County and provide preliminary decision support tools for County and township officials, Ottawa County contracted with the MSU Institute of Water Research (IWR) to carry out a comprehensive groundwater resource study and develop an interactive, on-line, water resources decision support system. A team of experts from the Department of Civil and Environmental Engineering, the Department of Geography and IWR were assembled to ***accomplish all the objectives specified in the contract***.

The specific groundwater objectives of the study, developed by the MSU Team, were to:

- Describe the aquifers beneath Ottawa County and evaluate their ability to sustain current and future water withdrawal demands.
- Map the static water levels in the aquifers of Ottawa County and their change across the period of the available well records.
- Evaluate the recharge areas to the aquifers of Ottawa County in terms of size, location and relative recharge rates.
- Characterize the groundwater quality in the aquifers of the County, especially regarding their salinity and nitrate concentrations.

The MSU team conducted a comprehensive groundwater resource study based solely on existing data in state databases such as Wellogic, Groundwater Inventory and Mapping Project (GWIM) and WaterChem. In order to stay within the allocated budget, no new data were collected in the field nor developed from laboratory analyses.

Aquifers

The Phase-1 study has documented that there are two extensive aquifers in Ottawa County: a shallow unconfined aquifer in the glacial deposits, and a deep, confined aquifer in one of the bedrock formations beneath the County. In most places within Ottawa County, these two aquifer systems are separated by an extensive, thick clay layer.

Static Water Levels

The static water levels (SWL) for both the glacial and bedrock aquifers were mapped for two periods (1960-1999 and 2000-2012). Since 1999, the static water levels in both the glacial and the bedrock aquifer have modestly declined in the central region of Ottawa County. The decline in the glacial aquifer SWL in south-central Blendon Township appears to be one of the most significant in the County. Such declines suggest that the current volume of withdrawals from the glacial aquifer in this part of Ottawa County may not be sustainable in the long run.

In south-central Allendale Township and north-central Blendon Township, the decline in the SWL within the bedrock aquifer appears to be one of the most significant SWL changes in the County, suggesting that the current volume of groundwater withdrawals from the Marshall Sandstone may be unsustainable in the long run.

Mapping the temporal trends in static water levels is problematic in areas with temporally variable data densities. Interpolating across each of two point data sets with notably different spatial distributions of sample points can cause significant spatial variations in the estimation uncertainty.

Further study will be necessary in order to forecast the sustainability of groundwater withdrawals from either aquifer.

Recharge

The master recharge areas for the unconfined, glacial aquifer occur in Chester and Wright townships in northeastern Ottawa County and in Jamestown Township in the southeast corner of the County. Due to the heterogeneous nature and generally finer textures of the glacial sediments in both of these areas, recharge to the unconfined glacial aquifer is limited. Groundwater replenished by the recharge area in Chester and Wright townships discharges primarily to the Grand River. Thus, the NE master recharge flow does not contribute groundwater to the areas south of the Grand River, where groundwater withdrawal needs are the greatest. Groundwater replenished by the Jamestown Township recharge area discharges, in part, to the Macatawa River and Rush Creek. As a result, this recharge also does not appreciably help the central County region.

The master recharge area for the confined, bedrock aquifer occurs in Jamestown Township in the southeast corner of the County. Due to the heterogeneous nature and generally finer textures of the glacial sediments in this area, however, recharge to the confined, bedrock aquifer from this landscape is limited. It is most likely that the majority of recharge to the Marshall Formation occurs outside of Ottawa County to the northeast, east and southeast.

Groundwater Quality

The groundwater in the glacial aquifer, but especially in the bedrock aquifer, is becoming more saline as shown by increasing chloride concentrations through time. Prior to 2000, generally less than 4% of all the groundwater quality samples in Ottawa County showed chloride concentrations above 250 mg/l (the recommended water quality standard). In the 2000 – 2010 period, however, 6 – 10% of the samples showed chloride concentrations above 250 mg/l.

A depth *vs.* concentration analysis showed that the chloride concentrations in both the glacial and bedrock aquifers are not a surface contamination problem (*e.g*., road salt). In both aquifers, chloride concentrations increase with depth indicating a deep, subsurface source. Evaluation of a small-scale map of generalized groundwater heads in the Marshall Formation suggests that hypersaline groundwater is upwelling within the Marshall Formation and discharging beneath Ottawa and Muskegon Counties. It is likely that increasing withdrawals from the bedrock aquifer over time have allowed hypersaline groundwater from deeper in the Marshall Formation to migrate upward at an increased rate beneath central Ottawa County.

The WaterChem data also show that nitrate concentrations are elevated (*i.e*., > 3 mg/l) in many areas of the County. There are numerous hotspots throughout the County, especially in the areas just east of Ferrysburg and Grand Haven, south and southeast of Zeeland, in central and western Allegan Township, in central Georgetown Township, and in southwest Jamestown Township. In many of these hotspots, the nitrate concentrations in groundwater are 2 - 5 times the drinking water standard of 10 mg/l. However, there is no strong temporal trend in the nitrate concentrations, thus suggesting that the nitrogen sources are persistent and prevalent, at least in and near the hotspot areas.

Decision Support System

Utilizing results from the MSU groundwater study together with numerous public , geospatial data gathered from the State and Ottawa County, the IWR team developed the Ottawa County Interactive Web-based Water Resources Decision Support System (IWDSS). The IWDSS uses a state-of-the-art, web-based environment with GIS capabilities and provides interactive plan-view maps and cross-sectional plots of portions of the County to: (a) determine the aerial extent and large-scale variation in aquifer characteristics, (b) provide a depiction of the general groundwater flow regime (direction and rate), (c) map the concentrations of sodium, chloride, nitrate, and arsenic from water well samples, and (d) determine the fluctuations of water table depth.

The system includes five inquiry scenarios that assist users in exploring selected groundwater issues in Ottawa County:

- Glacial Aquifer Water Quantity
- Basement Flooding Assessment
- Salinity
- Nitrate
- Impervious Surface/Recharge Area.

The system also contains an on-line manual and tutorials, so that users can easily familiarize themselves with the various tools and thematic layers within the IWDSS.

OVERVIEW OF OTTAWA COUNTY

Location and Population

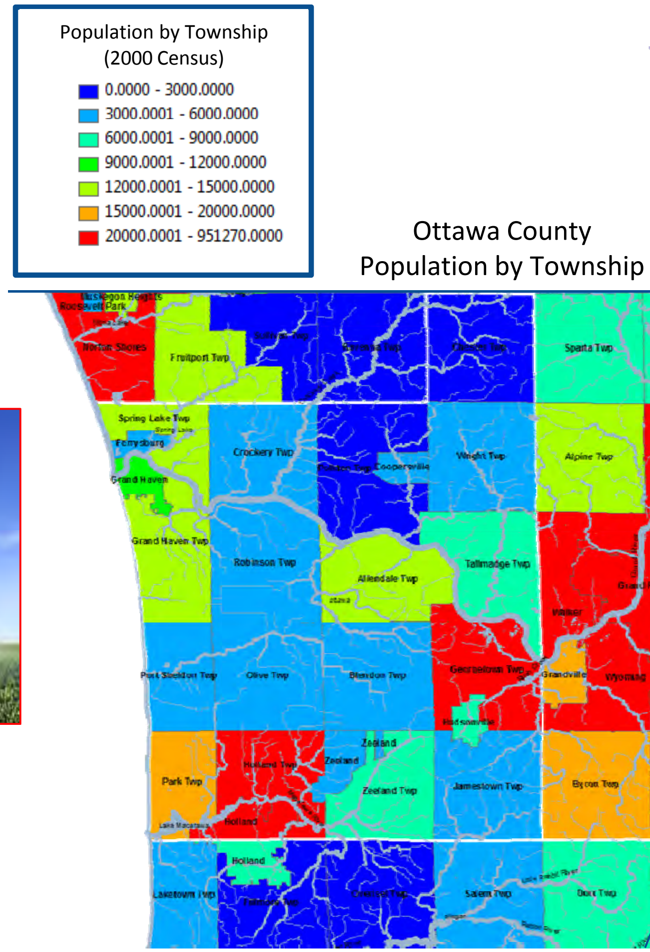
Ottawa County is located in the west-central portion of Michigan's lower peninsula. Its western boundary is formed by Lake Michigan and its eastern boundary is approximately 30 miles inland.

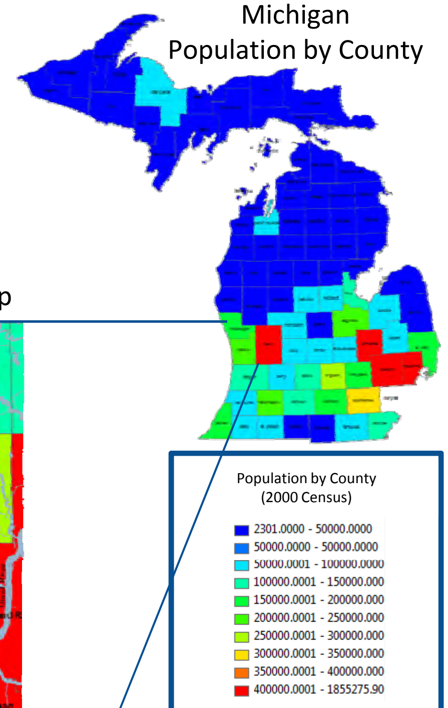
Ottawa County , has an area of 577 square miles and is composed of 17 townships, six cities and one village. The County has approximately 30 miles of frontage along Lake Michigan. Ottawa is bound by the counties of Allegan to the south, Muskegon to the north, and Kent to the east.

Economy:

Agriculture & Tourism

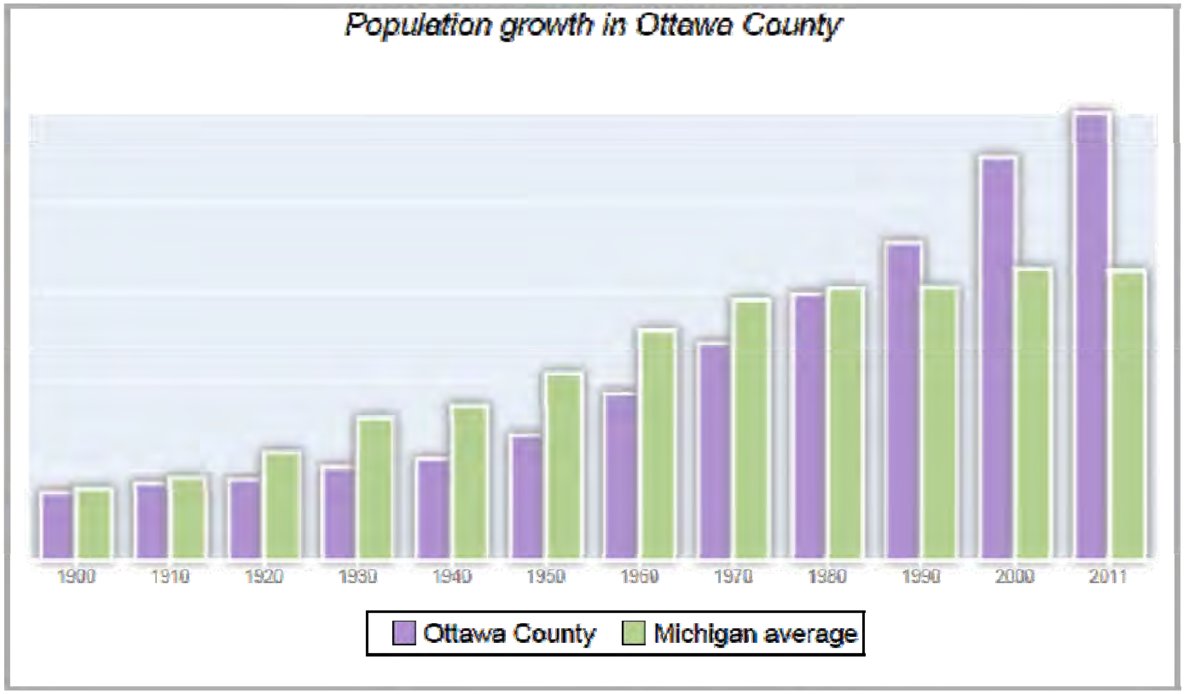
- ❑ County Population: 269,099 (2012)
- ❑ 8th most populous County in Michigan
- ❑ 2nd fastest population growth among Michigan counties





- ❑ Most populous township: Georgetown
- ❑ Fastest growing township: Allendale

Increased Demand for Water Resources

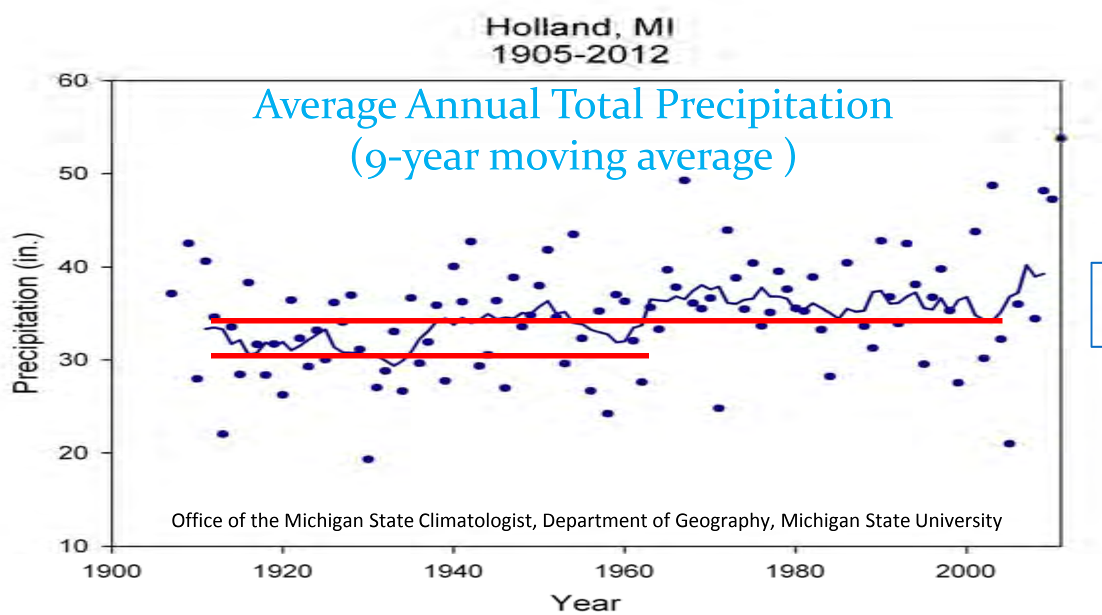


http://www.city-data.com/county/Ottawa_County-MI.html

Today , Ottawa County has a population of 269,099 inhabitants. It is the 8th most populous County in the state. In the last ten years, Ottawa County has experienced the second fastest population growth of the 83 counties in Michigan, and is the fastest growing of all Counties with a population over 200,000.

It seemed likely that rapid population growth and expanded agricultural uses may have led to increased demand for water resources. However, further data is needed to clarify the increasing demands.

Precipitation



~ 4" increase comparing 1962 – 2012 with pre-1962 era

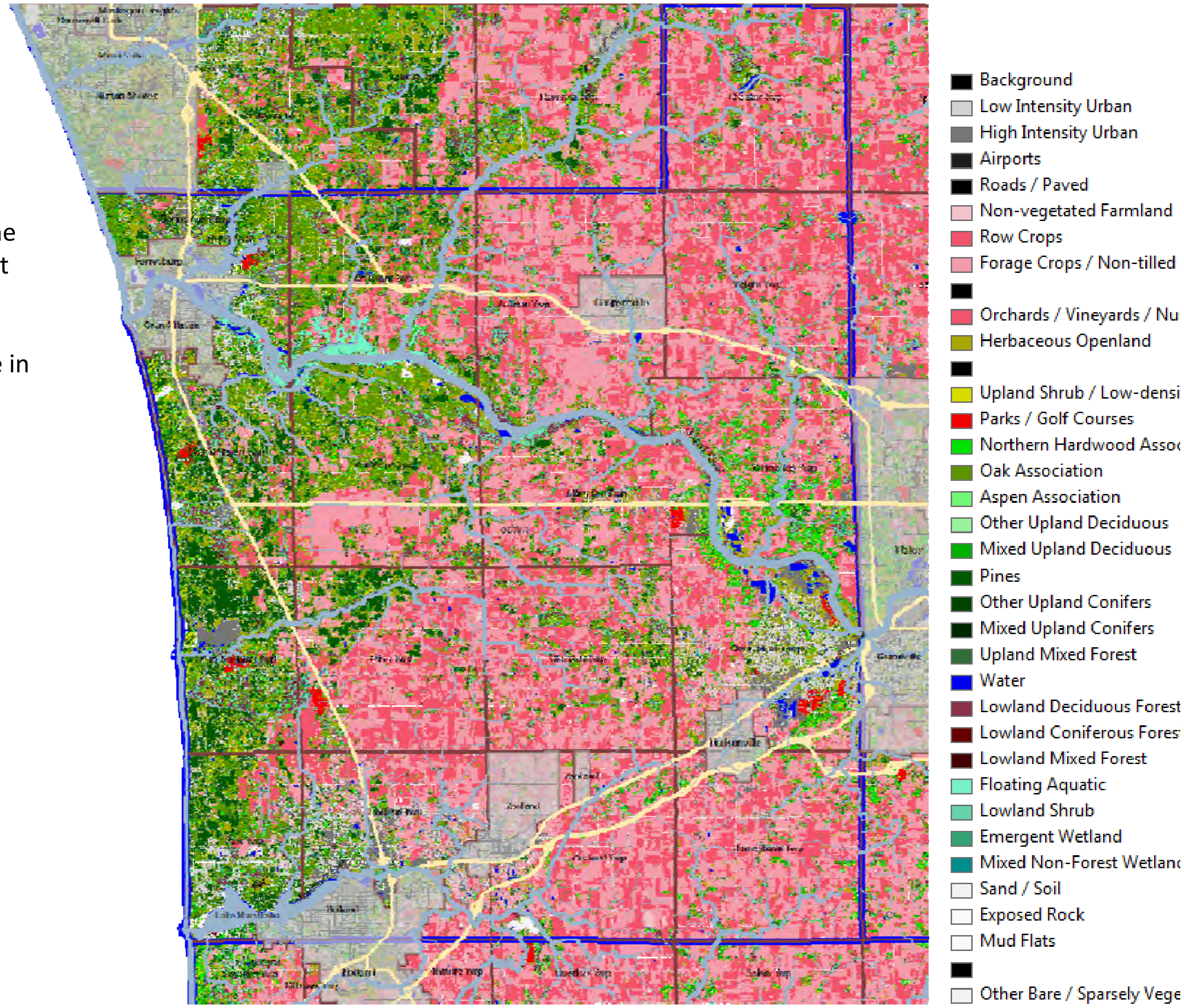
An average of 35 inches of total precipitation and 74 inches of snow fall on Ottawa County each year.

The graph above shows the average annual total precipitation in Holland, Michigan in the past 100 years. Note that the decadal mean precipitation in the past 30 years has been fairly constant, but the average annual precipitation since 1962 is about 4 inches greater than the long-term, pre-1962 annual average.

Land Use Patterns

The primary land use in Ottawa County is agriculture (shown by shades of pink on the map). Farmland comprises over 40 percent of the total land area in the County.

The second most extensive land cover/use in the County is forest (areas in green). The third most extensive land cover/use in the County is urban development (areas in grey).

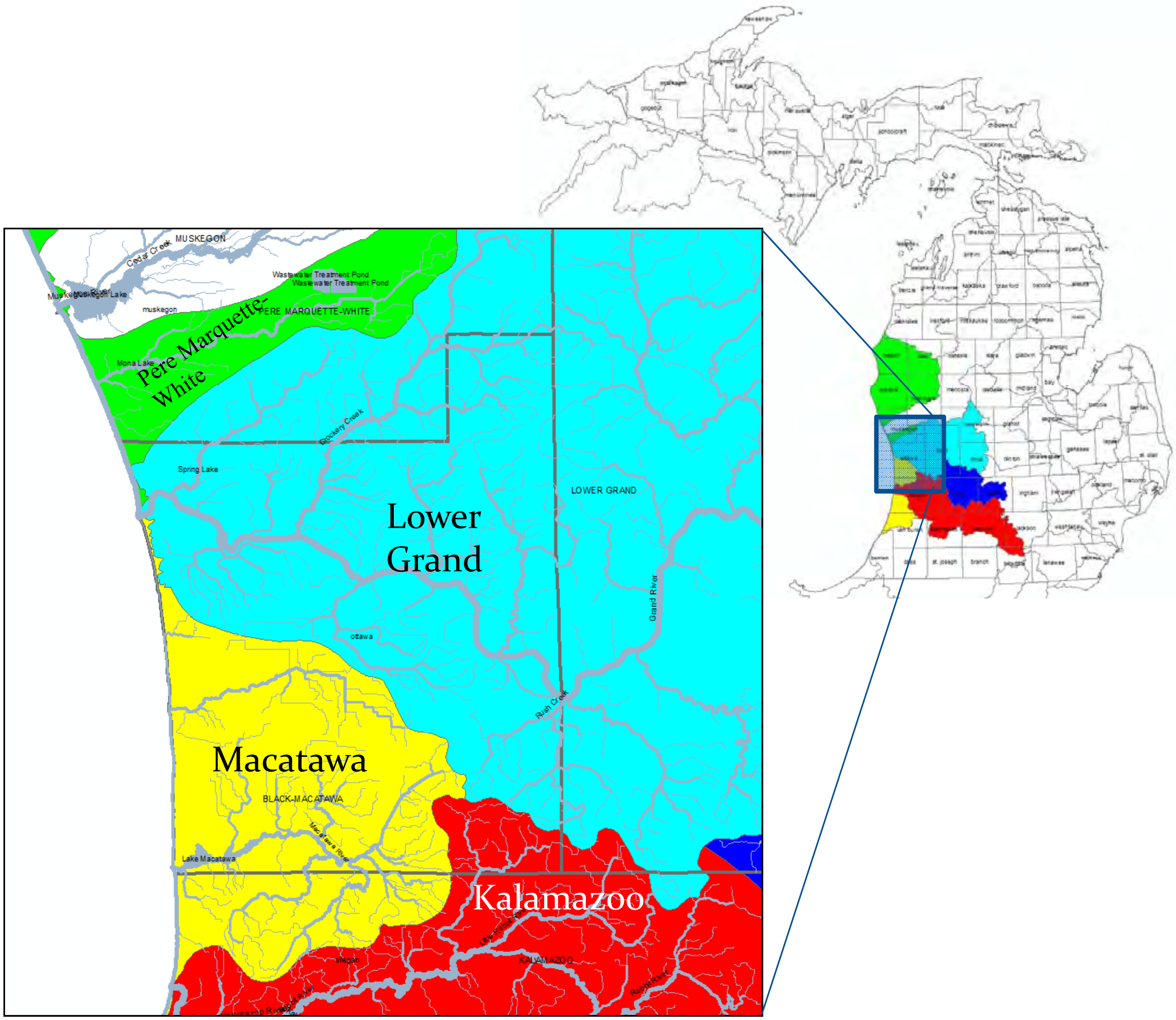


IFMAP/GAP Lower Peninsula Land Cover. 2003. Michigan Department of Natural Resources

Watersheds

Ottawa County is drained by several major watersheds:

- The Black-Macatawa
- Kalamazoo
- Lower Grand
- Pere Marquette-White

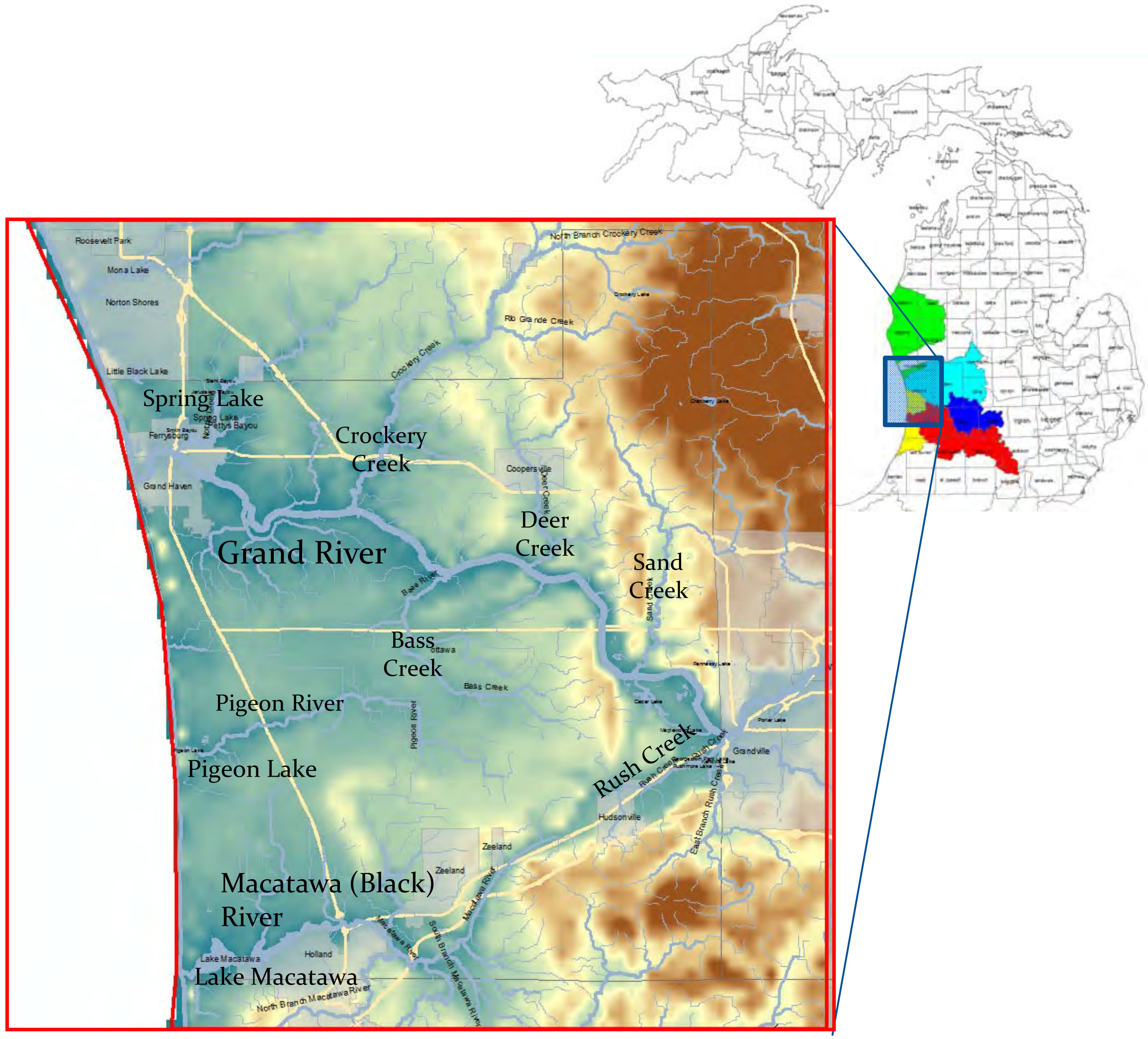


Rivers & Lakes

There are several inland lakes found throughout the County, ranging in size from 1,790 acres to less than 5 acres. Lake Macatawa (1790 acres), Spring Lake (803 acres), and Pigeon Lake (225 acres) are the largest of these lakes.

The primary water course in the County is the Grand River, which originates near the City of Jackson in eastern Michigan, and flows westward into Lake Michigan. The river extends 161 miles through Michigan, and drains the County's entire northern portion through several small tributaries including Sand, Rush, Deer, and Crockery Creeks.

The remaining portions of the County are drained by the Macatawa (Black River), which is 44 miles in length, and the Pigeon River, which is 12 miles in length.



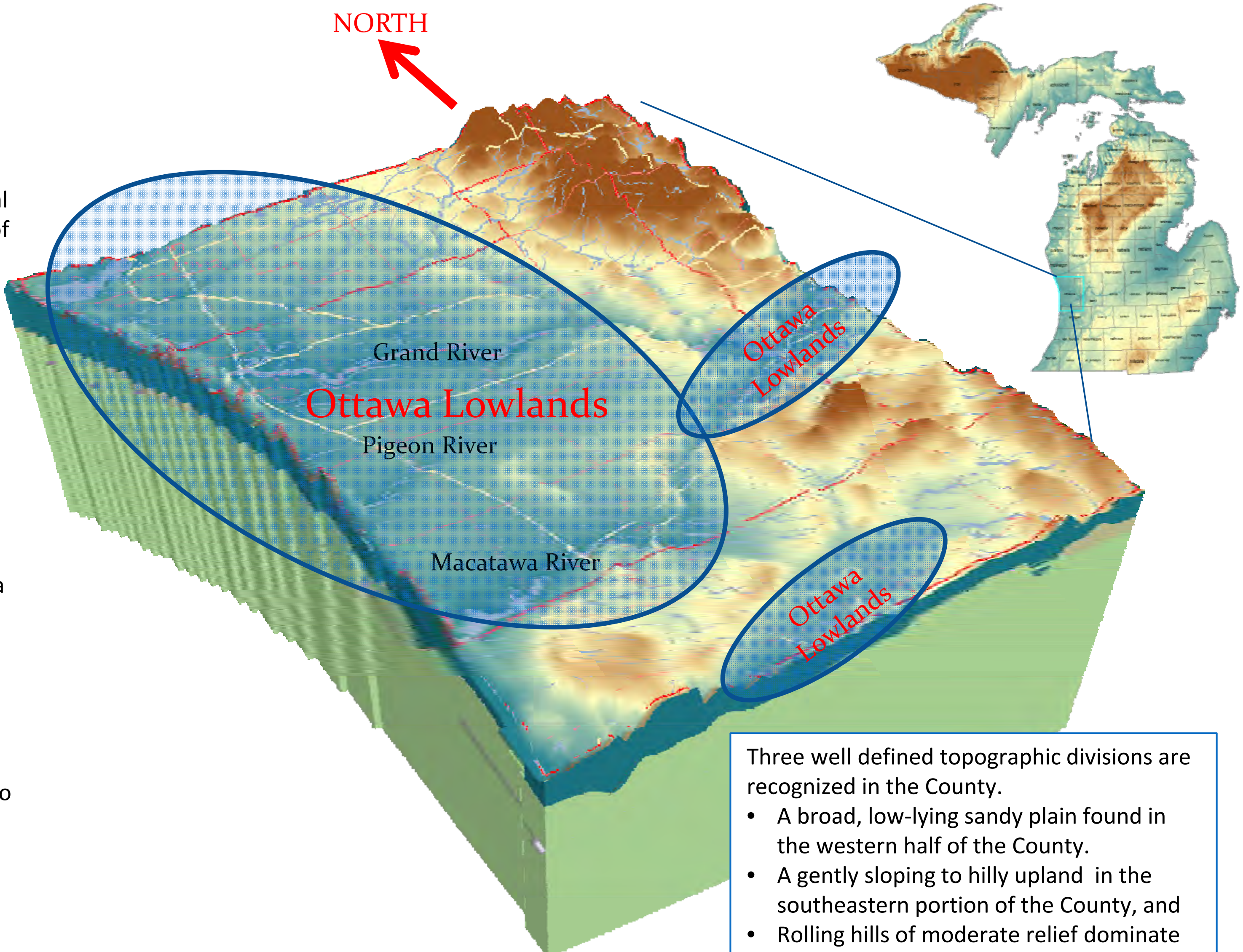
Topography

The topography within the County reflects it origin by both subaerial glacial and wind deposits coupled with sediments deposited in glacial lakes , as well as the effects of water erosion over time.

The land surface toward the eastern and southern end of the County is fairly rugged, undulating, and dissected by water courses.

The lower reaches of the Grand River toward Grand Haven and much of the central part of the County is a low, flat plains area.

The elevations in the County range from more than 850 feet above mean sea level (amsl), at the northeastern corner in Chester township, to 571 feet at the confluence of the Grand River with Lake Michigan at the City of Grand Haven.



Three well defined topographic divisions are recognized in the County.

- A broad, low-lying sandy plain found in the western half of the County.
- A gently sloping to hilly upland in the southeastern portion of the County, and
- Rolling hills of moderate relief dominate the northeastern corner.

REGIONAL GEOLOGY AND HYDROGEOLOGY

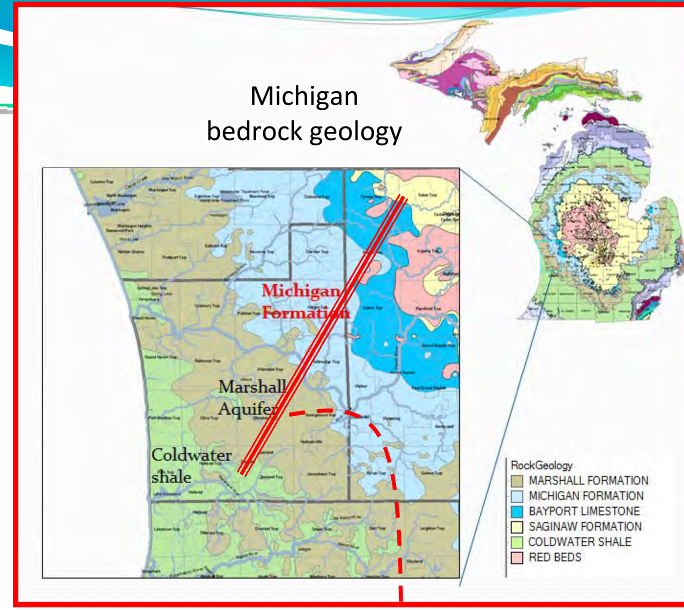
Aquifers

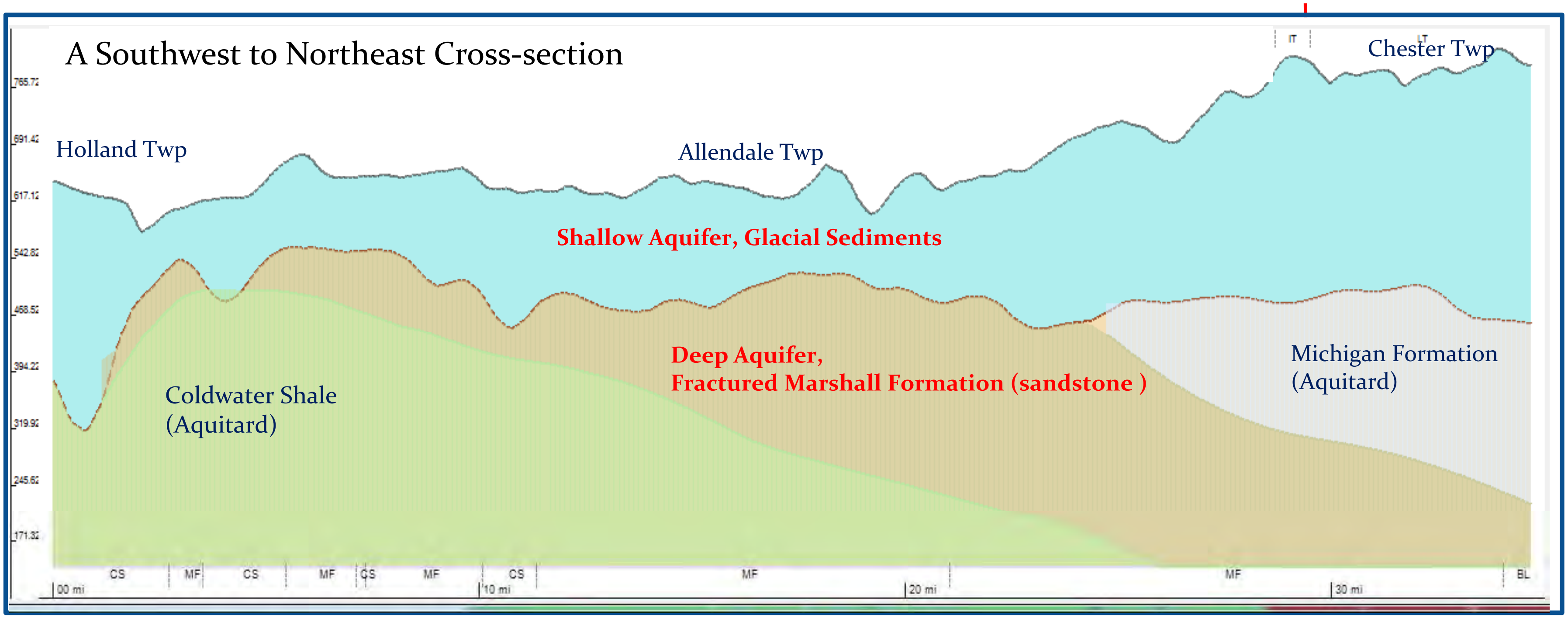
The County is underlain by multiple geological units, including a shallow, glacial aquifer and a deep, fractured, bedrock aquifer.

The glacial aquifer layer is composed of lacustrine (lake) deposits, outwash, and dune sand.

The thickness of glacial deposits in Ottawa County ranges from less than 30 ft to greater than 400 ft thick (Vanlier, 1968).

The bedrock units under the glacial deposits include, from northeast to southwest, the Michigan Formation, Marshall Formation, and Coldwater Shale.





Lacustrine (lake) Sand

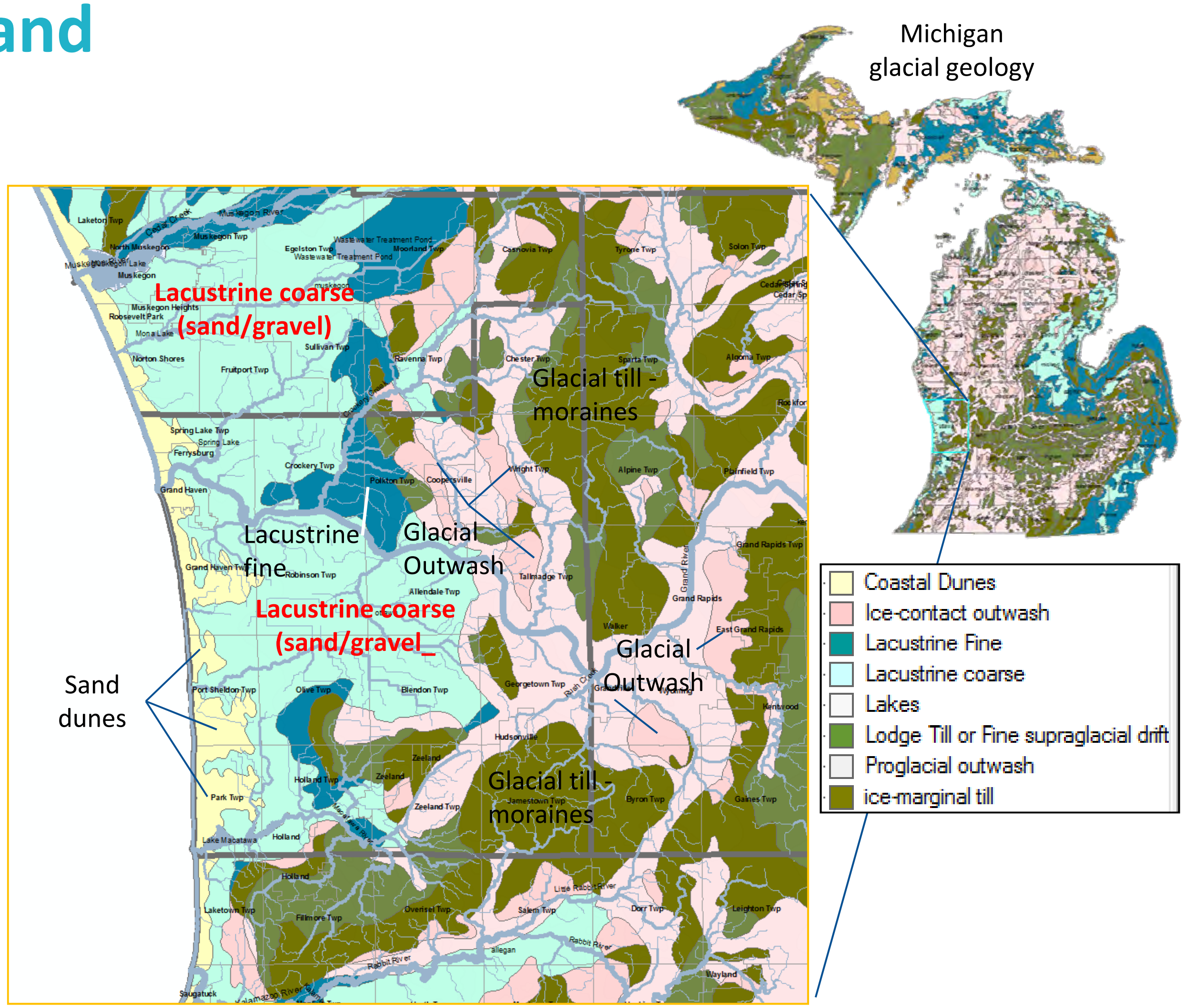
Lacustrine deposits are concentrated in the western and central portions of the County, and consist primarily of lacustrine sand and gravel (Farrand and Bell, 1982).

In the Holland area, lacustrine deposits are either clay-rich or sand-rich deposits. The clay lacustrine deposits may act as a confining layer which impedes surface recharge to lower aquifers.

The sandy lacustrine deposits and shallow outwash are considered one aquifer in the Holland area, because these deposits are interbedded and hard to distinguish from each other (Deutsch and others, 1958).

Sand dunes are present along the western portion of the County, bordering Lake Michigan (Deutsch and others, 1958; Farrand and Bell, 1982). Sand dunes usually lie above the water table and may provide areas of recharge (Deutsch and others, 1958).

Most wells in west part of Ottawa County obtain water from the shallow lacustrine sand.

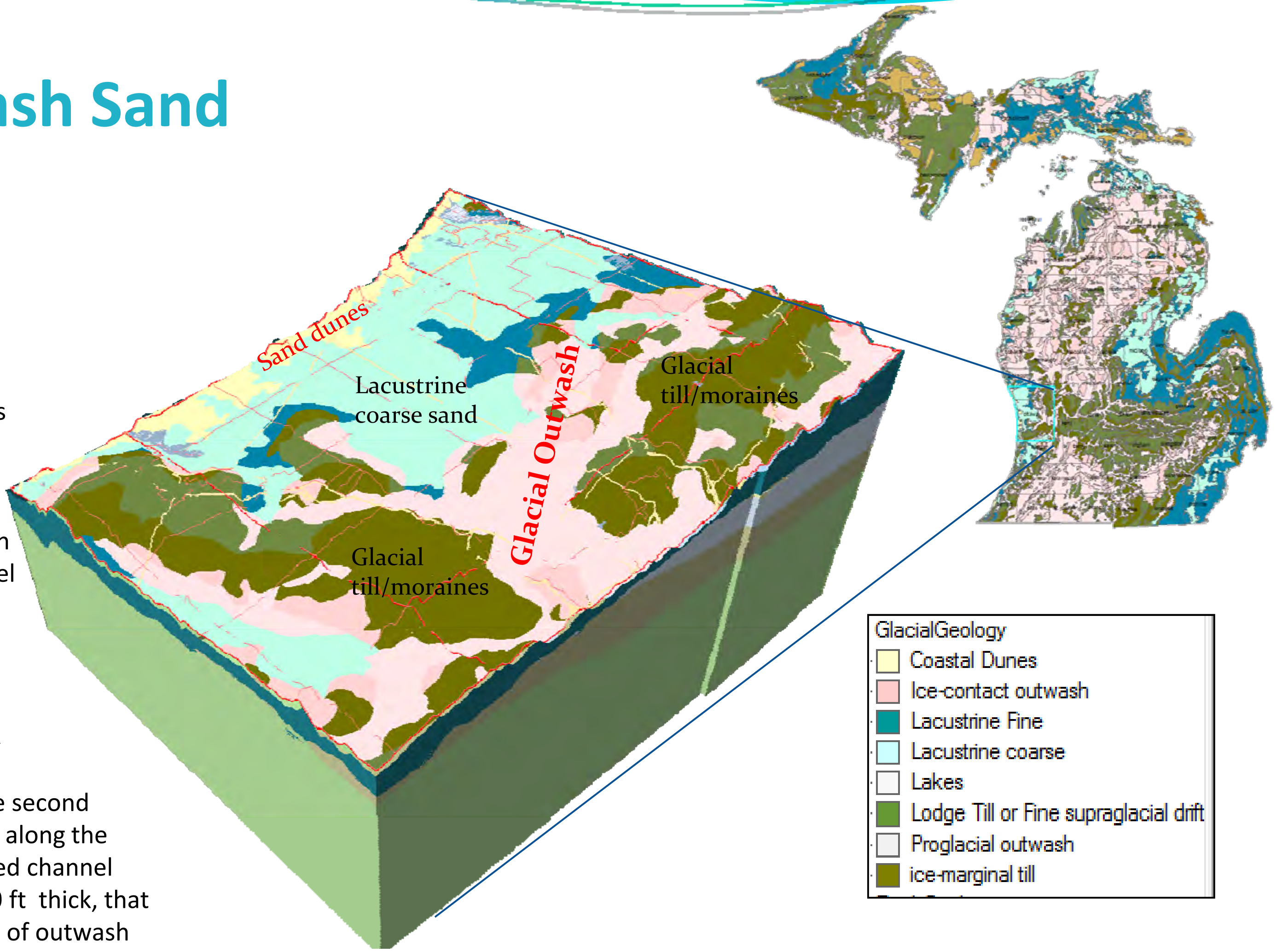


Ottawa County glacial geology

Glacial Outwash Sand

The sand and gravel outwash is an important water-yielding deposit. Glacial outwash occurs primarily in the eastern portion of the County.

However, shallow and buried outwash is present in the Holland area. The shallow outwash deposits contain some gravel, but are primarily fine to coarse sand.



In the Holland area, buried outwash occurs in two channels. One channel occurs northeast of Holland, and continues westward along the Ottawa - Allegan County line. The buried outwash in this channel is a confined aquifer nearly 400 ft thick that varies in permeability, and yields highly mineralized water. The second channel trends SE – NW and occurs along the eastern Holland city limit. This buried channel is also a confined aquifer, up to 100 ft thick, that supplies good quality water. Lenses of outwash also occur interbedded within the till deposits (Deutsch and others, 1958).

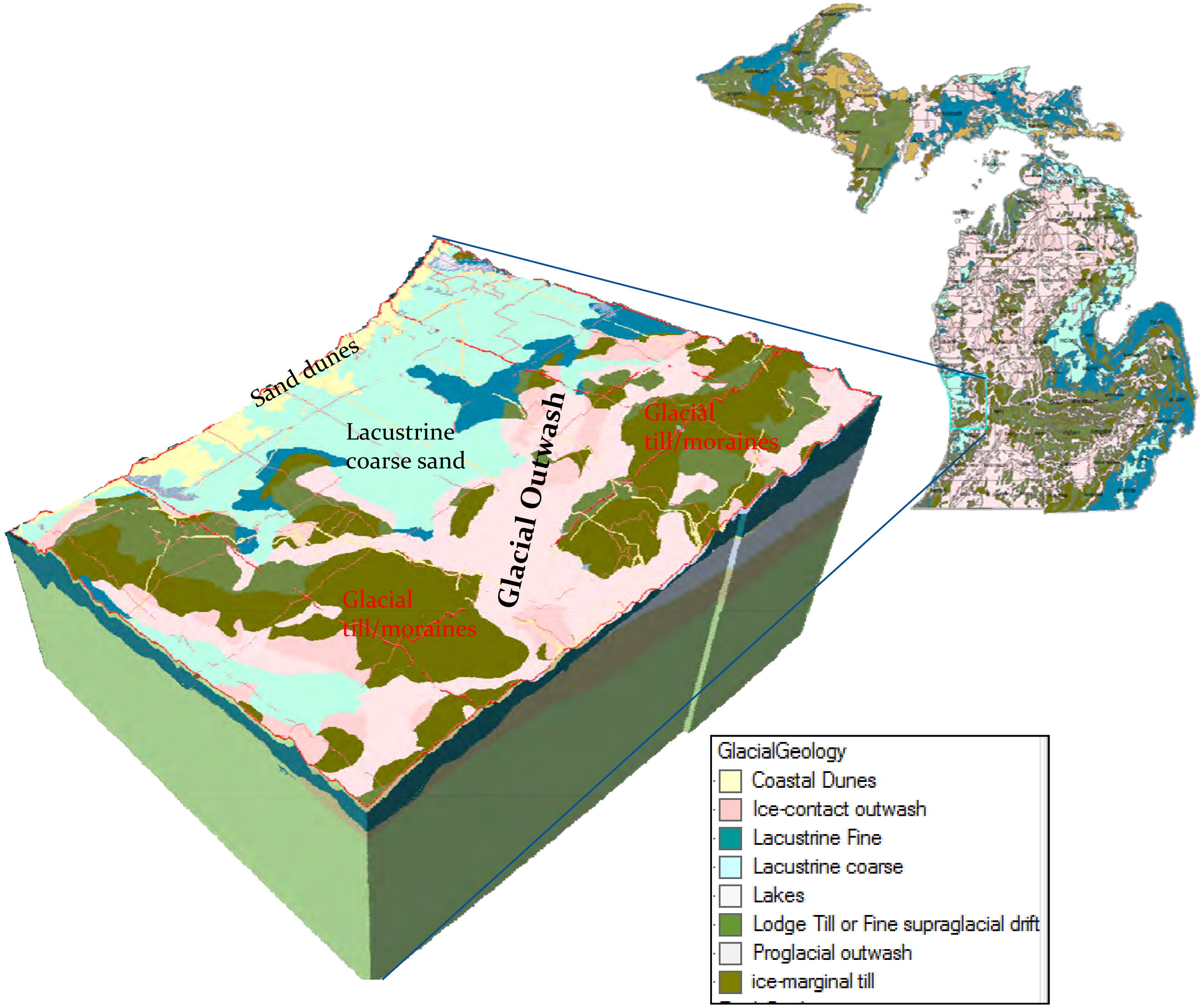
Most wells in the NE and SW of the County obtain water from the near-surface or buried outwash sands.

Glacial Till

Till occurs throughout the County, but is only visible from the surface in the southern and eastern portions of the County (Vanlier, 1968; Farrand and Bell, 1982). In general, the morainal deposits and till plains consist of sediments that has a high porosity, but low permeability.

Till generally contains boulders, gravel, and sand in a strongly heterogeneous clay and silt matrix.

In the central part of the County, till is buried underneath a thin layer of lacustrine sand. The till in this region, is particularly rich in clay and silt and extends vertically across almost the entire glacial layer.

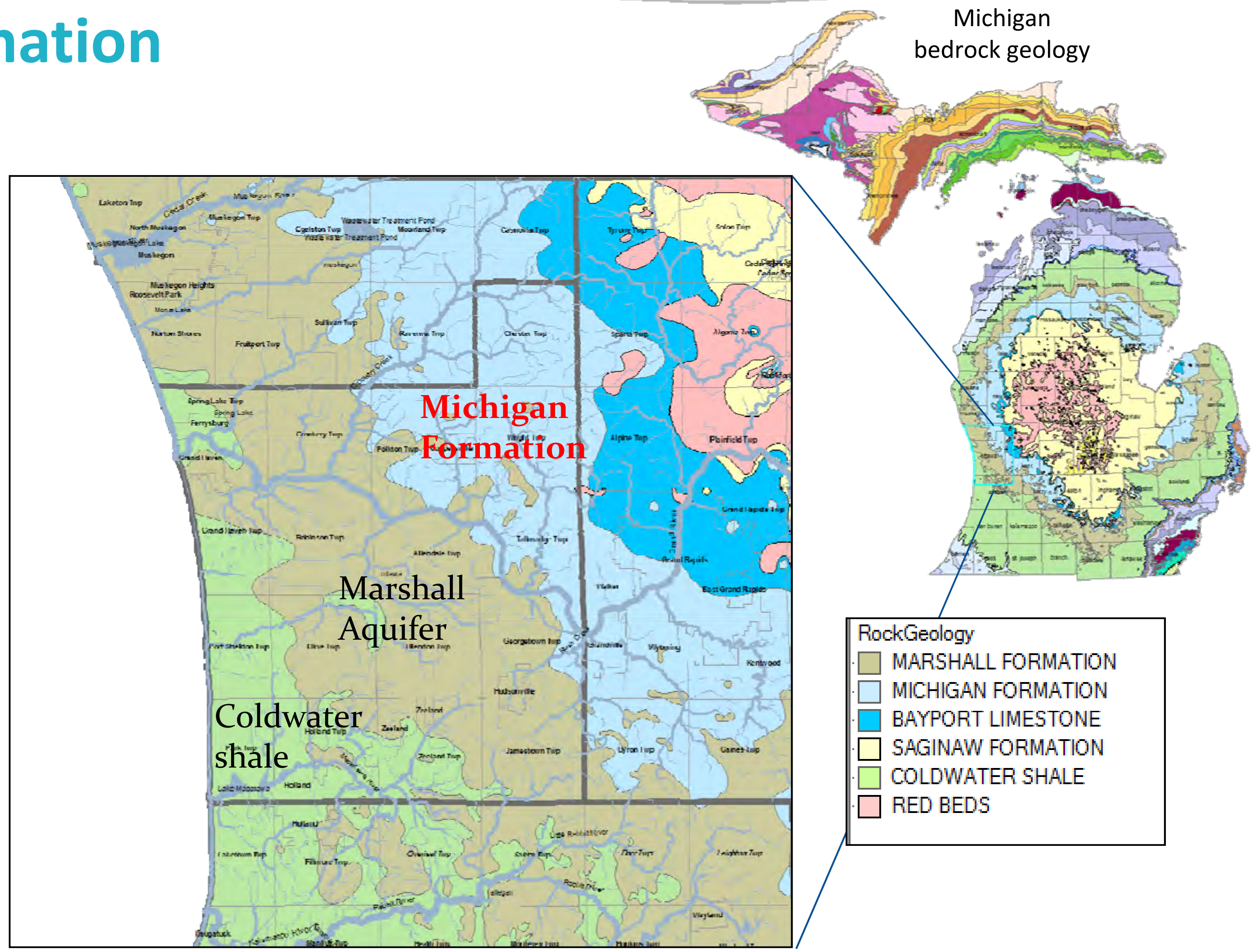


Michigan Formation

The Michigan Formation is dominantly shale, but also includes discontinuous beds of sandstone, limestone, dolostone, gypsum, and anhydrite.

In some places, the Michigan Formation is a marginal aquifer, but generally serves as a partially confining layer.

The thickness of the Michigan confining unit ranges from less than 50 to 400 ft within the County (Westjohn and Weaver, 1998).



Marshall Formation

Stratigraphically, the Marshall Formation overlies the Coldwater Shale and is overlain by the Michigan Formation.

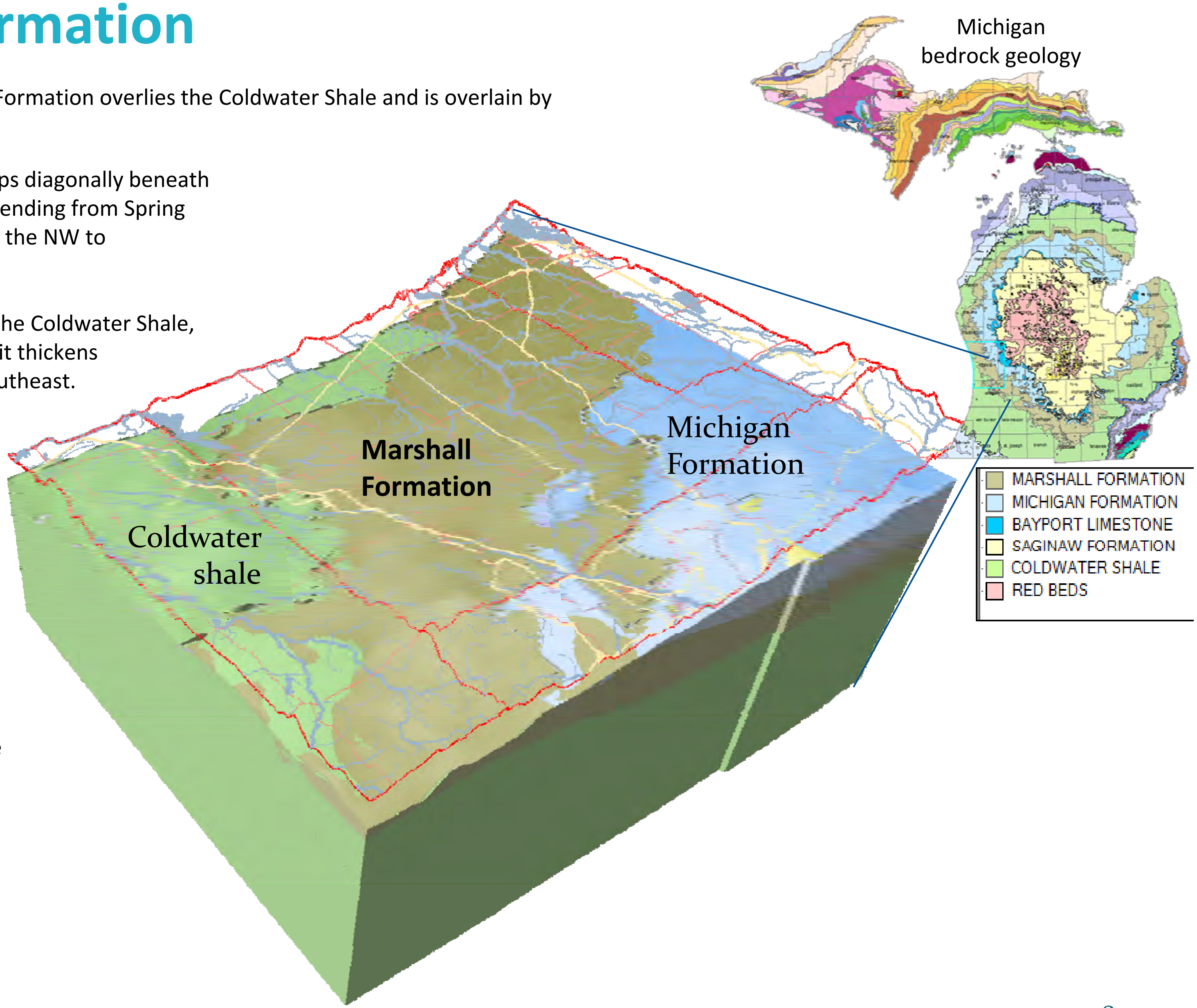
The Marshall Formation subcrops diagonally beneath the center of Ottawa County, trending from Spring Lake and Crockery townships in the NW to Jamestown Township in the SE.

Along its subcrop contact with the Coldwater Shale, the Marshall Formation is thin; it thickens considerably to the east and southeast.

The top portion of the Marshall Formation is composed of fractured sandstone which is fairly permeable and comprises the Marshall Aquifer.

The Marshall Aquifer ranges in thickness from 75 to more than 200 ft within the state (Westjohn and Weaver, 1998).

Most wells in central part of the County obtain water from the Marshall Aquifer.



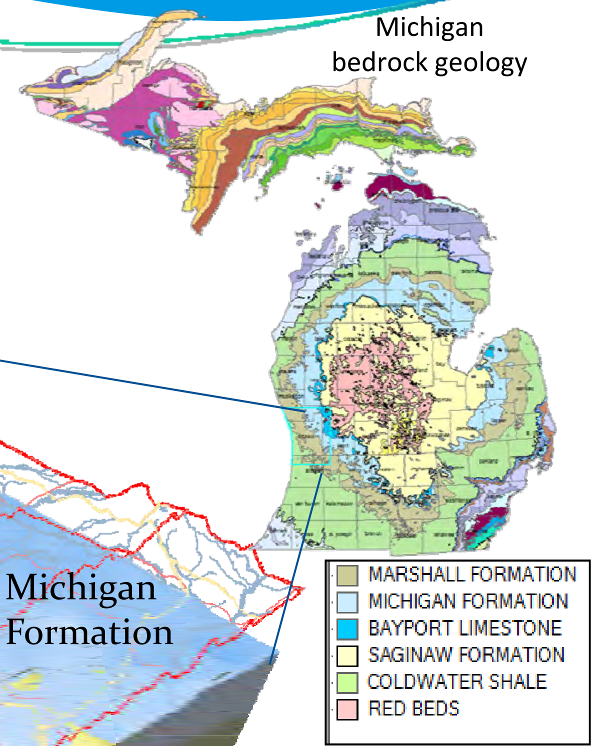
Coldwater Shale

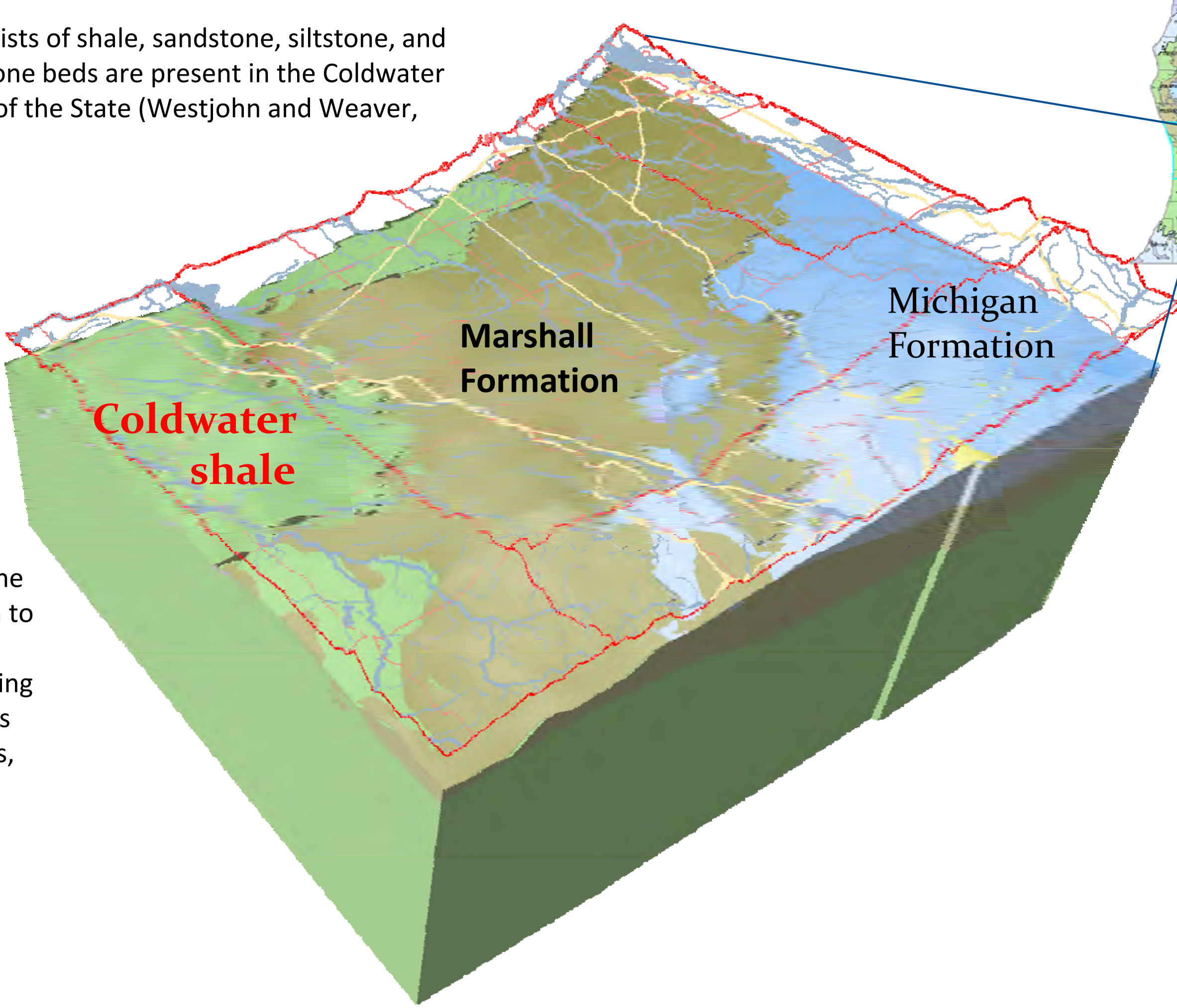
The Coldwater Shale is a master confining unit within the Michigan Basin, and ranges in thickness from 500 to 1,300 ft thick.

The Coldwater Shale consists of shale, sandstone, siltstone, and carbonates. More sandstone beds are present in the Coldwater Shale in the eastern part of the State (Westjohn and Weaver, 1998).

In Ottawa County, fractured portions of the carbonates in the Coldwater Shale may yield water. However, the water is so highly mineralized that it is not suitable for most uses.

In the Holland area, the mineralized water from the Coldwater Shale is known to have migrated upward in areas where heavy pumping of overlying aquifers takes place (Deutsch and others, 1958).





METHODS

This section of the report documents the tool, data, and methods used for the Water Resources Study.

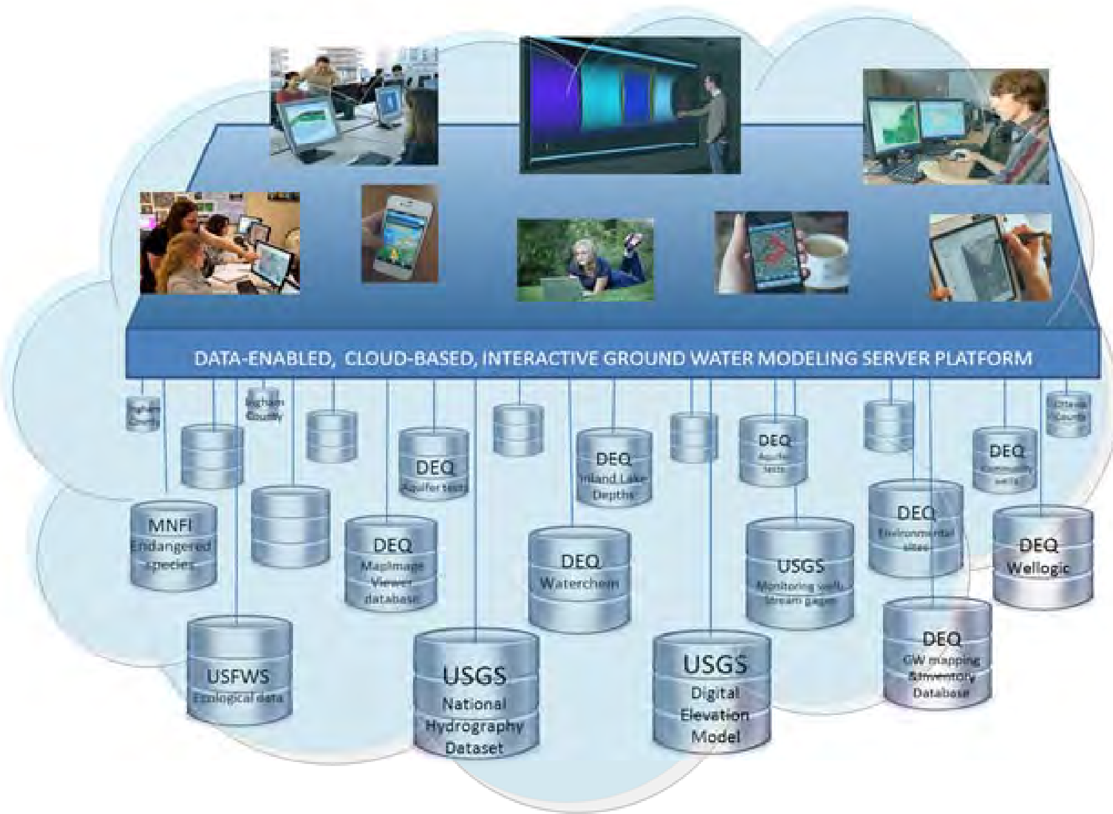
The Study capitalizes on recent advances in geospatial data integration, including integration of data that directly benefits groundwater protection (*e.g.*, State of Michigan, 2006), and on data intensive groundwater modeling [Li and Liu, 2006; Li et al., 2009, 2012].

We employed the data-enabled, Michigan groundwater modeling platform to visualize, analyze, and understand the subsurface environment and groundwater system and to address key water resources questions facing Ottawa County.

The ***Michigan Interactive Ground Water Modeling Program*** was developed by the MSU Department of Civil and Environmental Engineering in collaboration with the Michigan Department of Environmental Quality.

The software has been utilized by MDEQ to develop cost effective, science-based management solutions, including protection of drinking source water, site-specific assessment of adverse resource impacts of large-scale water withdrawals, prediction of contaminant transport, and optimization of groundwater remediation systems. The platform has also been applied to characterize, model, and understand groundwater –dependent ecosystems and to inform endangered species recovery (Li et al., 2013; Abbas, 2010; Sampath et al., 2013).

Michigan Interactive Groundwater Modeling System



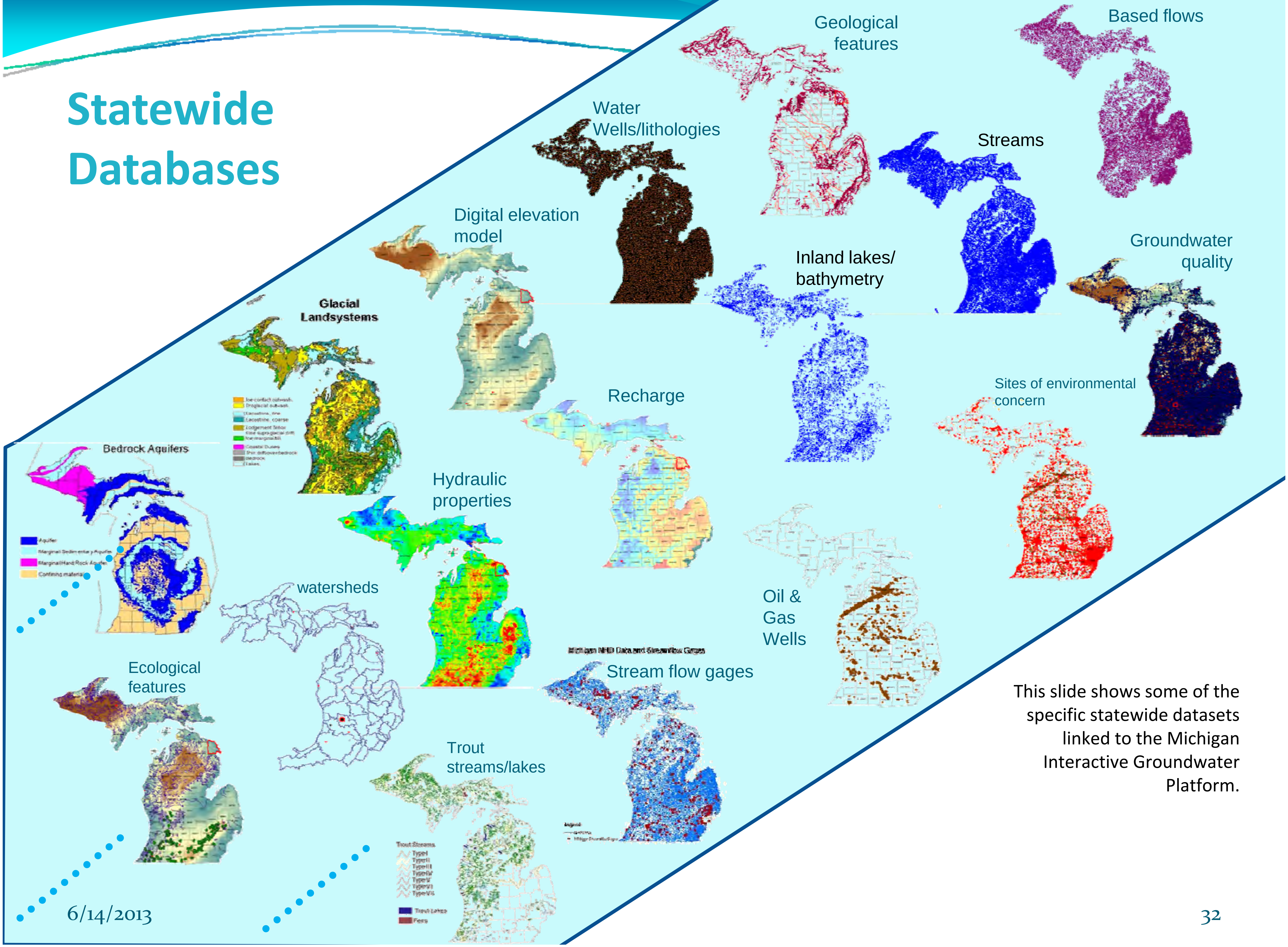
The Michigan Groundwater Modeling System is being converted to a cloud-based platform

The integrated modeling platform consists of two key sub-platforms;

- Data driven modeling platform - analysis, interpolation, query, mining, and visualization of present and historical data
- Process-based simulation platform – use water/mass balance and fundamental laws for porous media to simulate groundwater flow and contaminant transport under different stresses scenarios.

The integrated modeling system is live linked to a network of databases containing a vast amount of information on Michigan's groundwater. The System enables users to "see into the earth" - visualizing subsurface, modeling groundwater flow and contaminant fate and transport, mapping recharge/discharge areas, evaluating threats and vulnerability, and performing management analyses.

Statewide Databases



This slide shows some of the specific statewide datasets linked to the Michigan Interactive Groundwater Platform.

Awards for Interactive Groundwater Modeling Program

The interactive groundwater modeling system was recently recognized by the national ASCE Civil Engineering magazine (2009) and was the winner of several local, regional, and national awards.

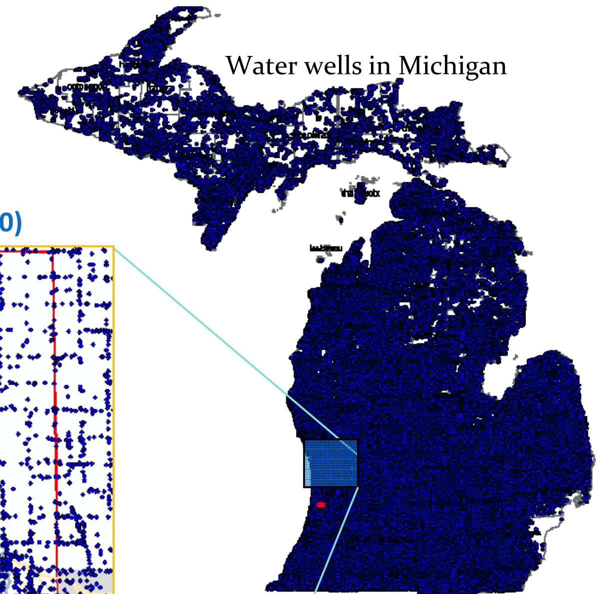
- MDEQ Director’s Project Team Award, Michigan Interactive Groundwater for Wellhead Protection, 2009.
- Michigan AWWA “Fresh Idea Competition” First place. 2009
- National AWWA “Fresh Idea Competition” Third Place. 2009
- Editor’s Choice by National Science Foundation Digital Library *Eng Pathway Project,* 2007
- The Premier Award, The National Engineering Education and Delivery Systems, 2002
- National Science Foundation Showcase, ASEE, 2002.

Wellogic Database

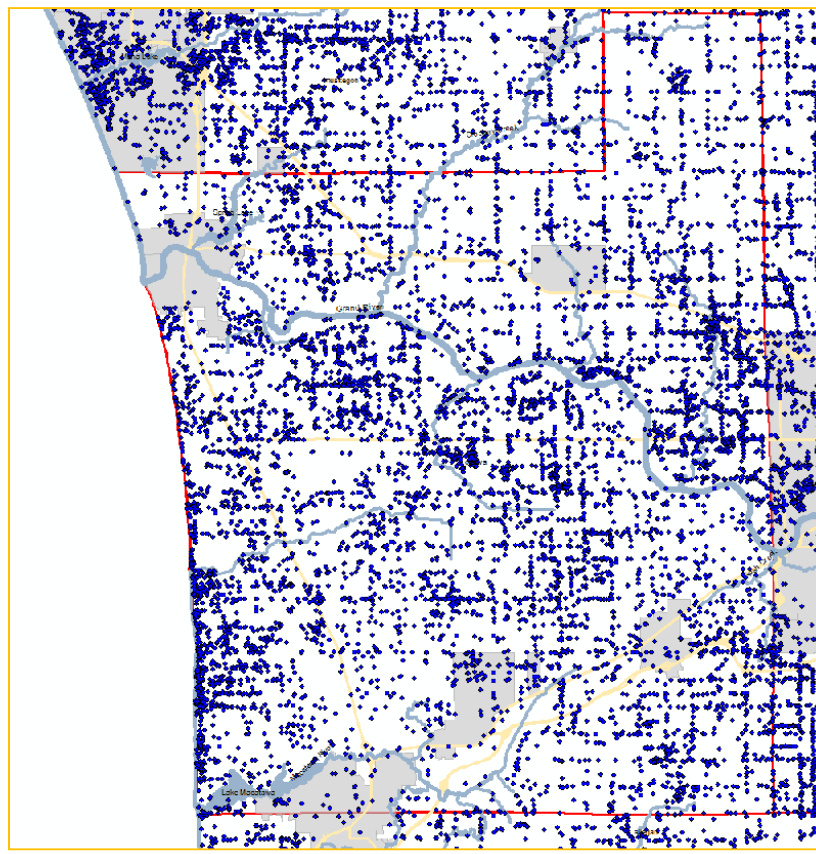
The statewide Wellogic database plays a particularly important role in the modeling system.

Wellogic is the internet-based data entry program developed by the state of Michigan to provide an easy method for water well drilling and pump installation contractors to submit water well records. Electronic well record submittal satisfies state and county well record submittal requirements.

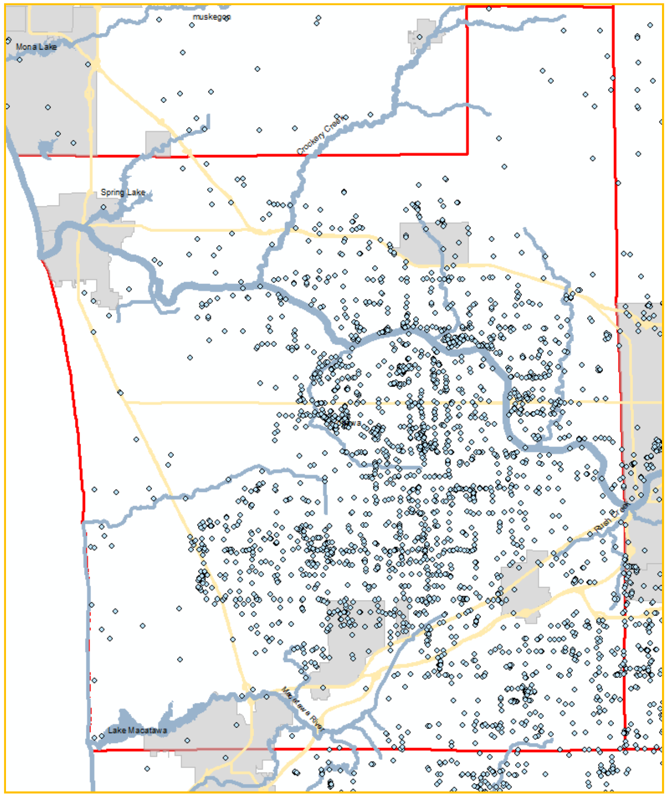
The Wellogic database contains information such as static water level (SWL), depth of the well, screened interval, pumping capacity, aquifer type, and a vertical description of the sediments (*e.g.*, sand or clay) that were encountered in the drilling of the well.



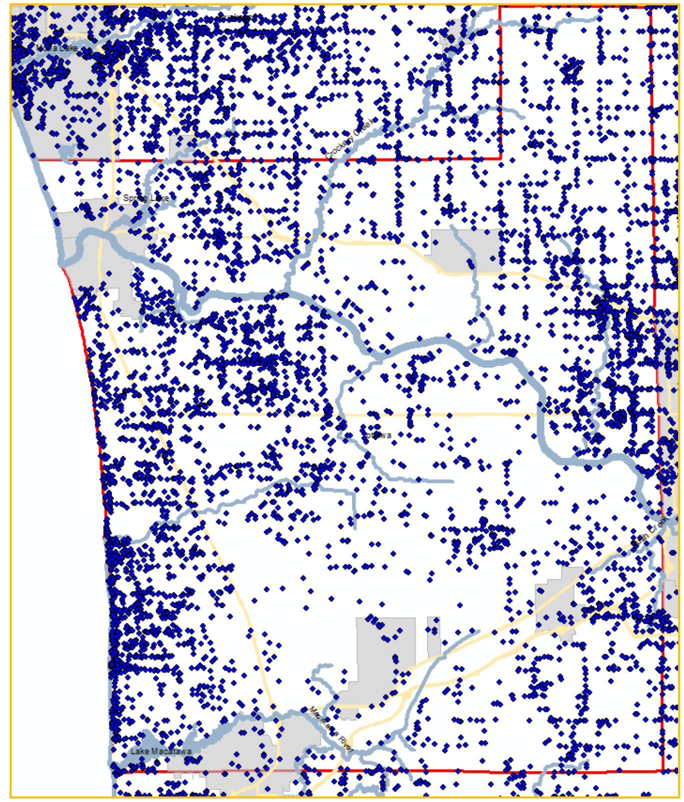
Water wells in Ottawa County (more than 8000)



Bedrock wells in Ottawa County



Glacial wells in Ottawa County



Although many groundwater specialists hold the opinion that water well records from drillers lack quality control and are often too crude, noisy, and inconsistent for meaningful groundwater flow analysis**, our recent systematic analysis shows that, when properly processed, this dataset can be very effective** (Li *et al*., 2008; Simard, 2006). In fact, our extensive comparative analyses show that many noisy measurements are actually much more useful than only a handful of precise measurements for delineating large, complex groundwater patterns.

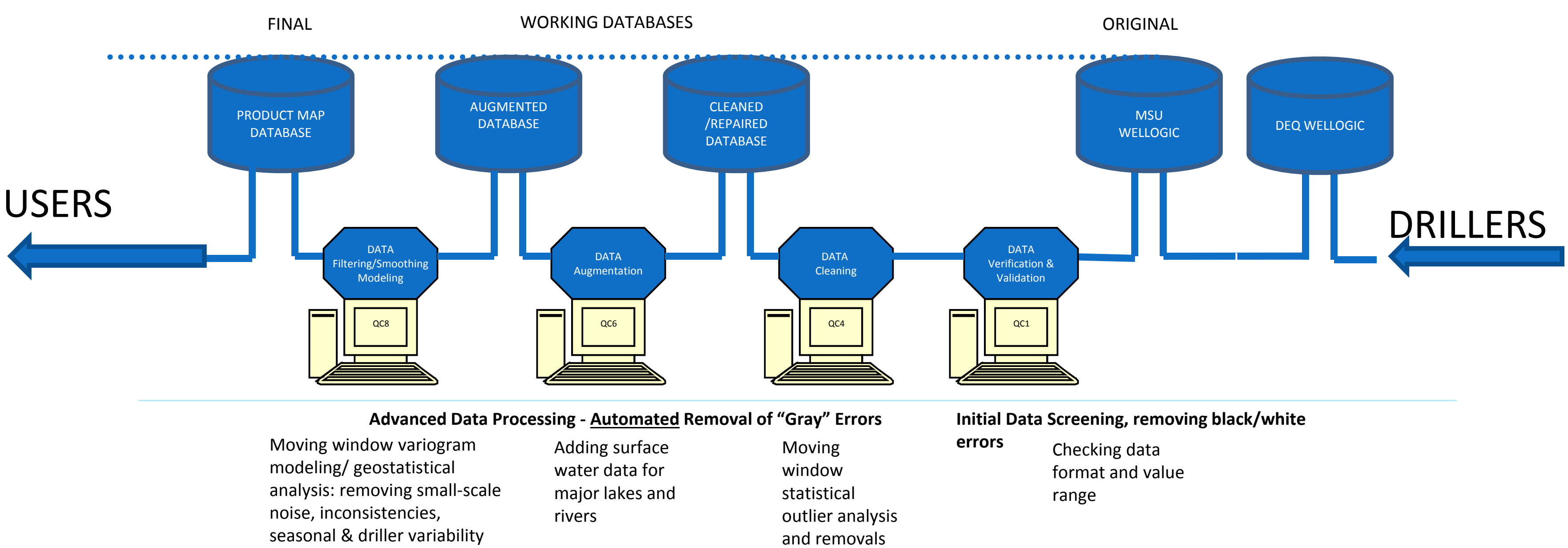
Data Filtering and Analysis

Our approach to using water well records, specifically static water levels, follows a three-step procedure:

1. Remove "black/white" errors. This step removes data values that are clearly wrong through a systematic process.

2. Remove statistical outliers. This step performs a moving window statistical data analysis and identifies and removes data values that deviate significantly from local trends based on a predefined criterion (*e.g.*, outside three standard deviations).

3. Remove "gray" errors. This step attempts to remove "randomly" distributed data noises representing errors caused by inaccurate well location, seasonal variability, inconsistencies, measurement uncertainty, and "driller variability". We achieve this using an advanced "moving window, non-stationary, multiscale Kriging technique". This filtering technique, using a location dependent variogram, enables removing noise in complex datasets in the presence of strongly non-stationary spatial trends.



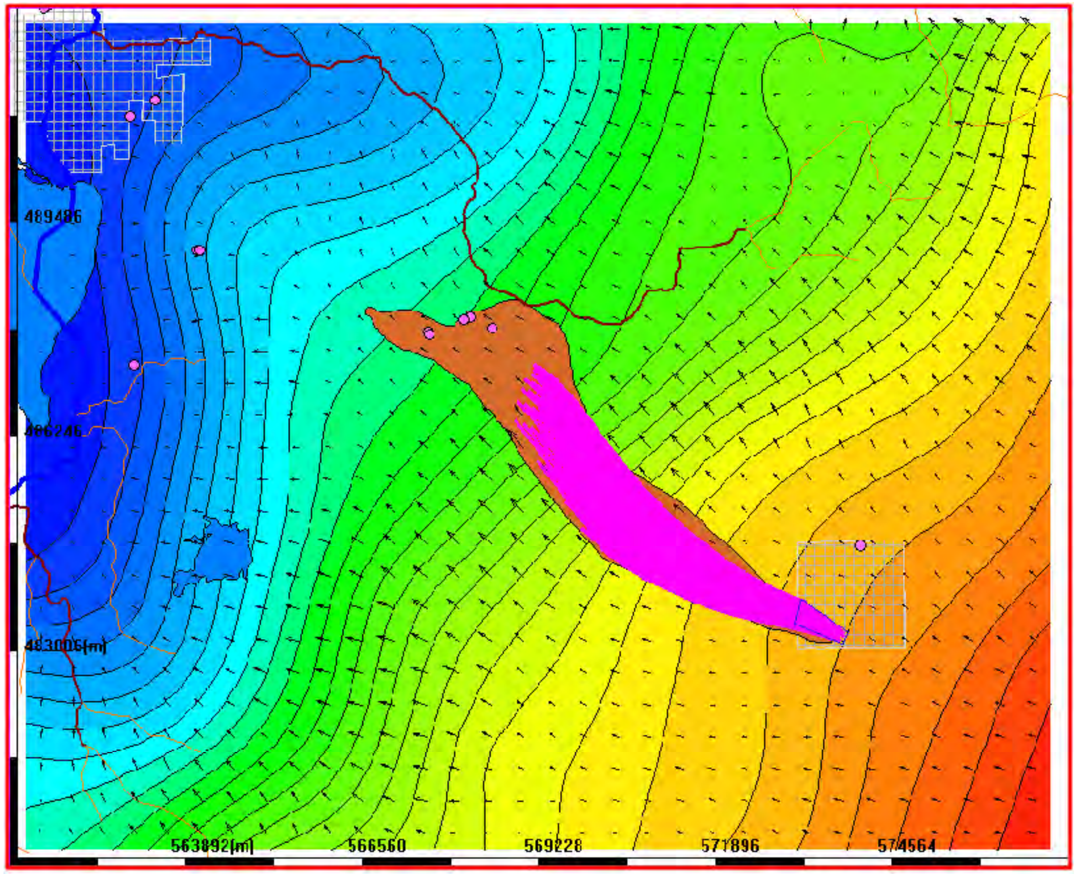
Static water level analysis and processing

Illustrative Examples

This slide illustrates how the advanced filter we recently developed enables accurate simulation of regional groundwater flow and transport.

The static groundwater levels based on the preprocessed Wellogic data are shown by contours with velocity illustrated by the magnitude and direction of arrows.

It can be seen that groundwater velocity field and the simulated particle plume (magenta flowlines) follow the traditionally delineated plume (in brown) that was based on data collected on-site.



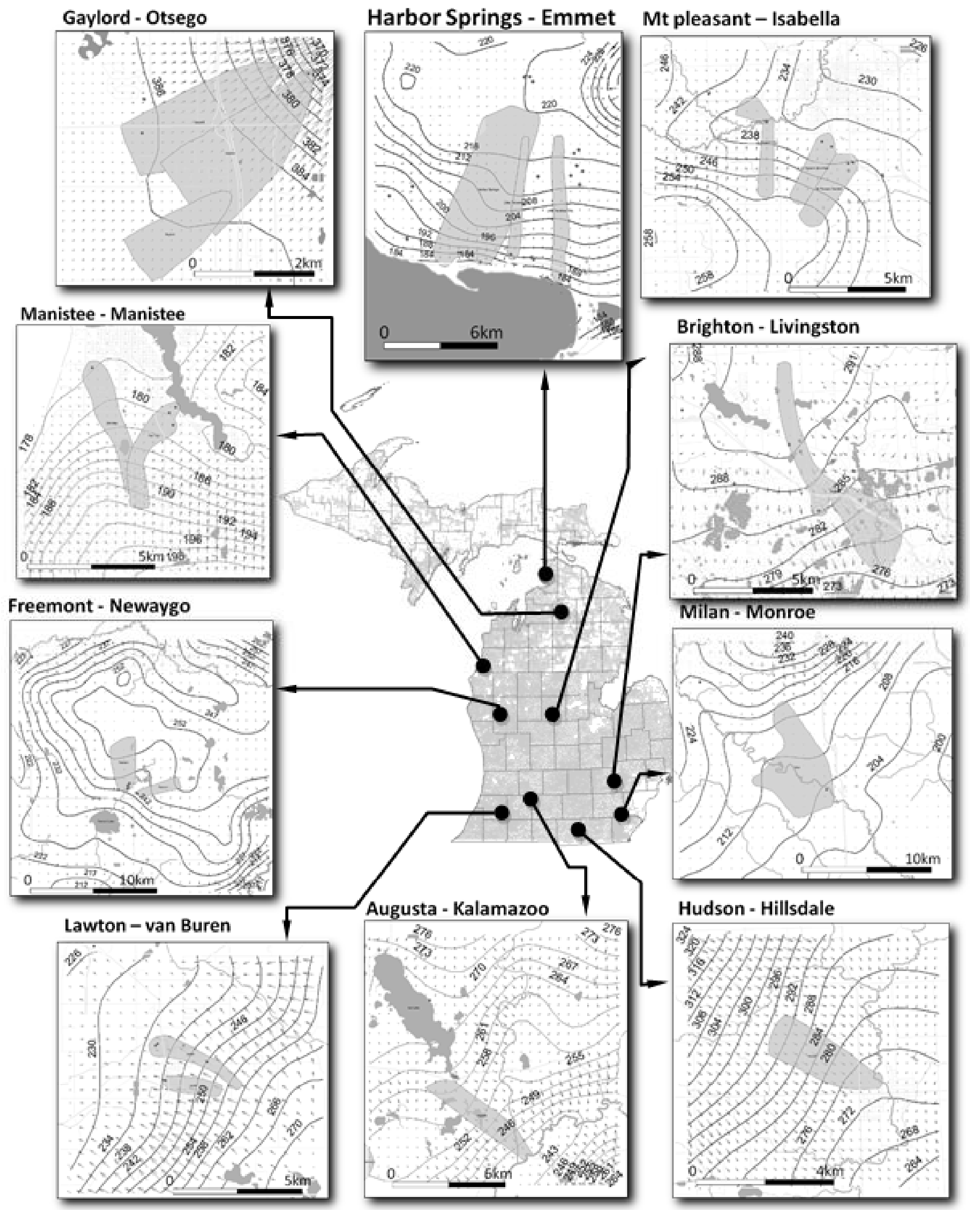
The area in brown is the Wickes Manufacturing TCE Plume near Mancelona, Michigan delineated based on data from on-site monitoring wells. The plume boundary is a 5 ppb concentration contour. The pink particle plume was delineated by the Michigan groundwater modeling system using the preprocessed Wellogic data.

Illustrative Examples

This slide illustrates the unique advantage of water well data in that it allows mapping flow patterns and directions virtually anywhere within Michigan (in areas covered by the database).

Groundwater levels are shown by contours with velocity illustrated by the magnitude and direction of arrows.

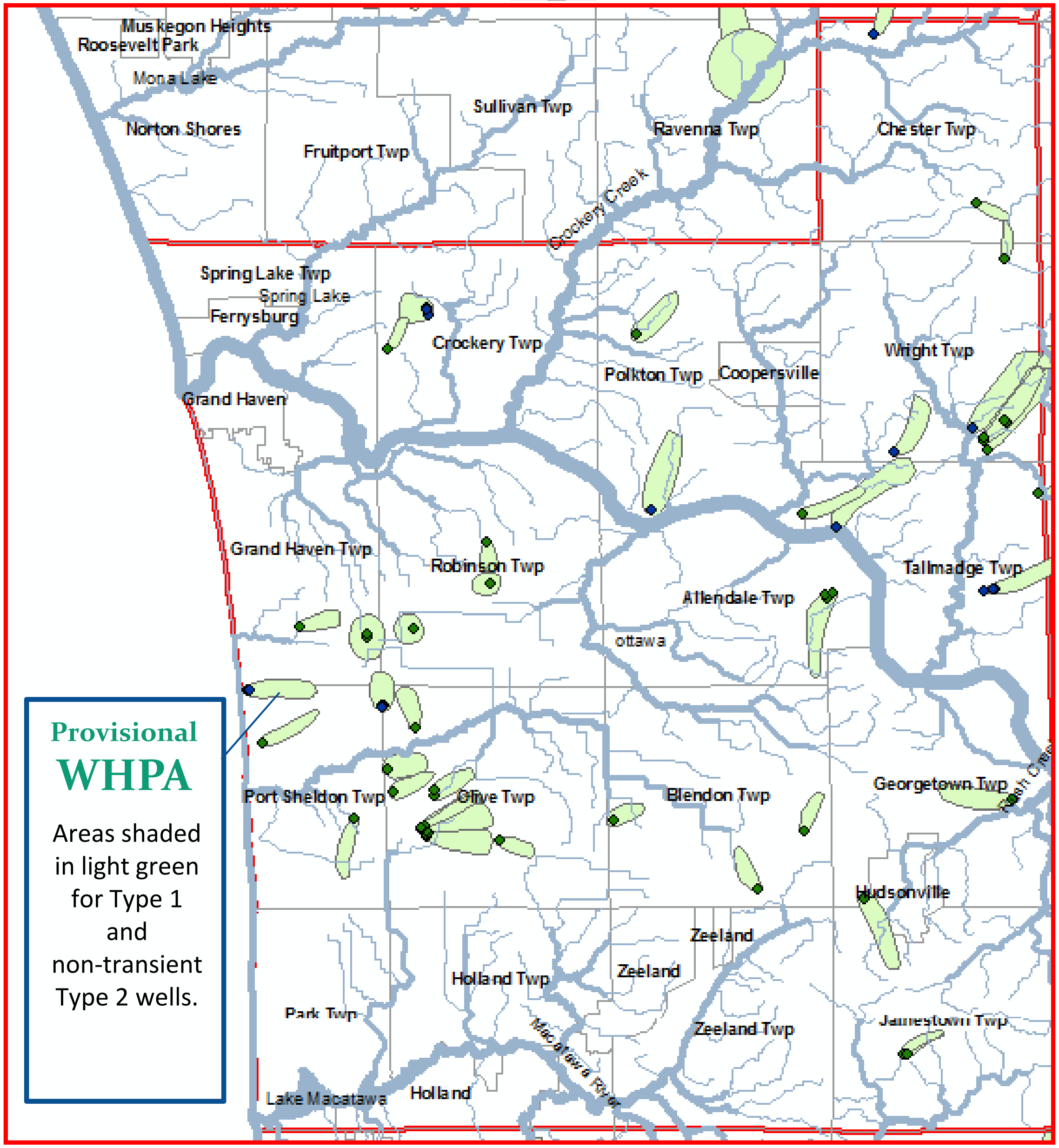
It can be seen that groundwater velocity based on Wellogic follows the traditionally delineated directions of wellhead protection areas. The state map in the middle shows data density of water well records.



Groundwater flow directions and patterns mapped using preprocessed Wellogic data match the traditionally delineated flow directions for wellhead protection areas (WHPAs) virtually anywhere in the state (the WHPA s are shown as light grey polygons).

Provisional Wellhead Protection Areas in Ottawa County Delineated Using Wellogic Data

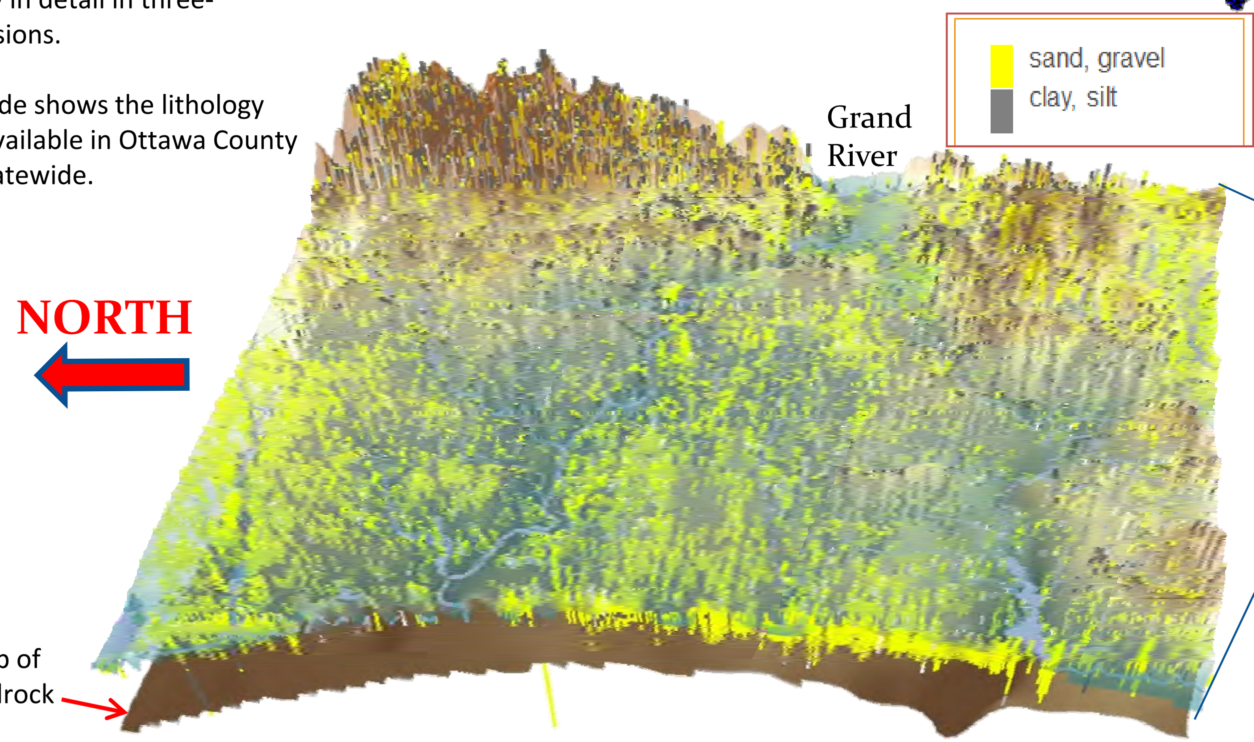
This slide shows active Type 1 and non-transient Type 2 wells in Ottawa County with their provisional wellhead protection areas newly delineated by MDEQ **using the Michigan groundwater modeling system**



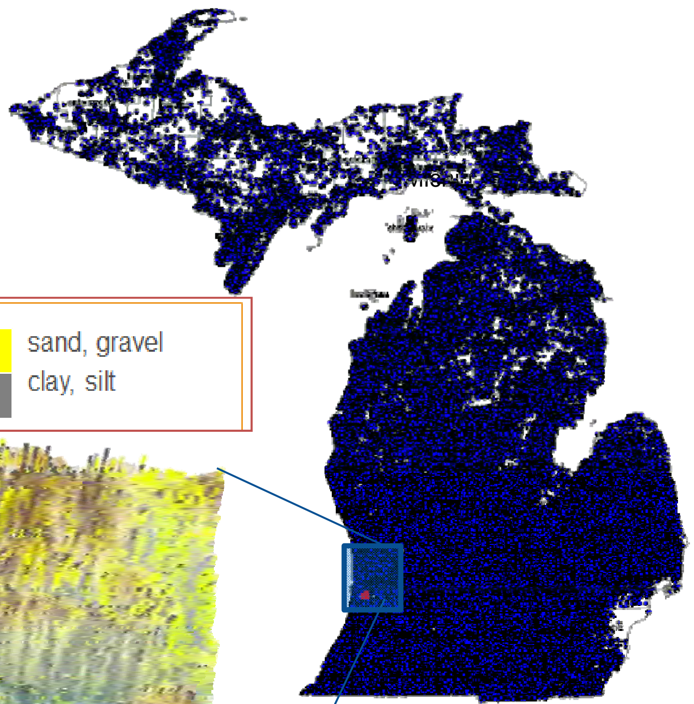
Lithologic Database

The lithologic information in Wellogic is also a significant component in the modeling system and can be used to map the glacial sediments in Ottawa County in detail in three-dimensions.

This slide shows the lithology data available in Ottawa County and statewide.



The database contains more than 8,000 lithologic records in Ottawa County.



The Lithologic database containing nearly 500,000 usable well records statewide.

The Michigan groundwater modeling system allows accessing and mapping well lithology anywhere in the state in both 3D and as cross-section.

3-D Glacial Aquifer Mapping

Despite their critical importance to environmental issues and water resources, near-surface sediments are largely unmapped at depth in Michigan. Full three-dimensional (3-D) models of these materials are needed to support groundwater modeling, water use management, aquifer protection, and groundwater remediation activities.

The ***Michigan Interactive Ground Water Modeling Program*** facilitates 3-D mapping of glacial aquifers using the lithological information contained in the Wellogic database.

The system applies a new, advanced, geological simulation technology – ***hierarchical transitional probability geostatistics*** - to statistically interpolate/simulate the water well lithologic records in Ottawa County.

The approach allows incorporating geologic interpretations into the development of cross-correlated spatial variability. The model links fundamental observable attributes –material proportions, anisotropy, mean lengths, and juxtapositioning – with probabilistic “Markov chain model” parameters.

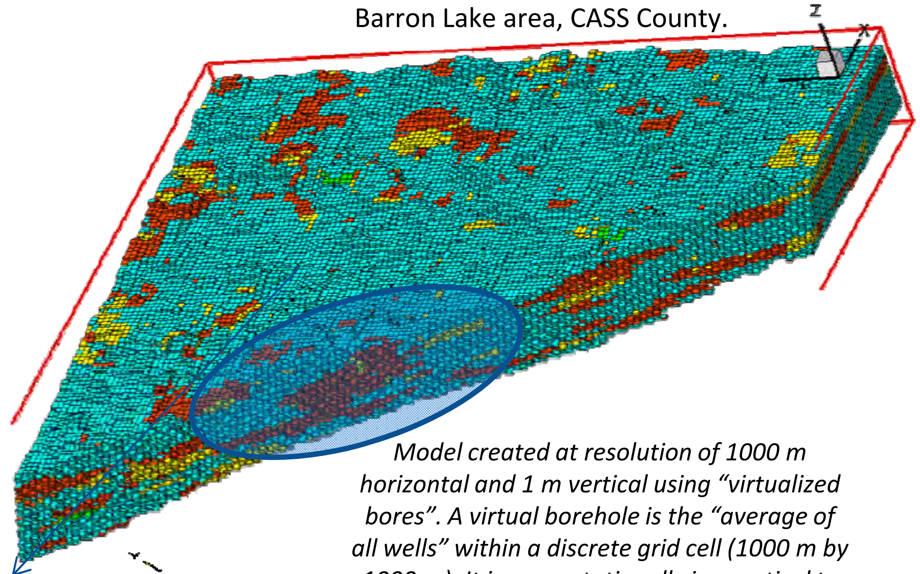
The output of this geostatisatical simulation approach is an interpolated volume of material sets [*e.g.*, AQ (aquifer), MAQ (marginal aquifer), PCM (partially confining material), and CM (confining material)] and a visual representation on a 3-D grid. Each of the material sets is conditioned to the borehole data (or virtualized/aggregated borehole data for a regional model) and the material proportions and transitions between the boreholes follows the trends observed in the borehole data.

3-D Glacial Aquifer Mapping

This slide presents an illustrative example of simulated, 3-D geological models we recently developed in an integrated groundwater/surface water modeling study in the Barra Lake area.

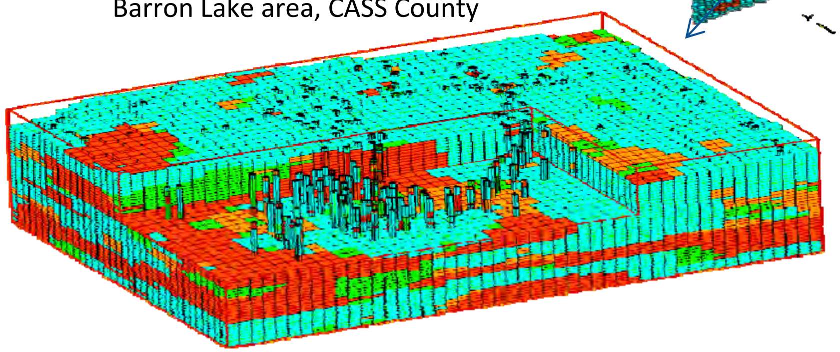
The capability to map detailed, 3-D heterogeneity in the glacial layer allows high-fidelity groundwater modeling and will significantly enhance our understanding of complex glacial aquifer dynamics and aquifer-lake interaction.

A **regional-scale**, 3-D glacial geological model – Barron Lake area, CASS County.



Model created at resolution of 1000 m horizontal and 1 m vertical using "virtualized bores". A virtual borehole is the "average of all wells" within a discrete grid cell (1000 m by 1000 m). It is computationally impractical to simulate the geology using actual borehole data on a regional scale

A **site-scale**, 3-D glacial geological model – Barron Lake area, CASS County



Model built using actual borehole data, recovering more detailed heterogeneity important for site specific studies; Model resolution: 100 m horizontal and 1m vertical.

RED = Confining Material

BROWN = Partially Confining Material

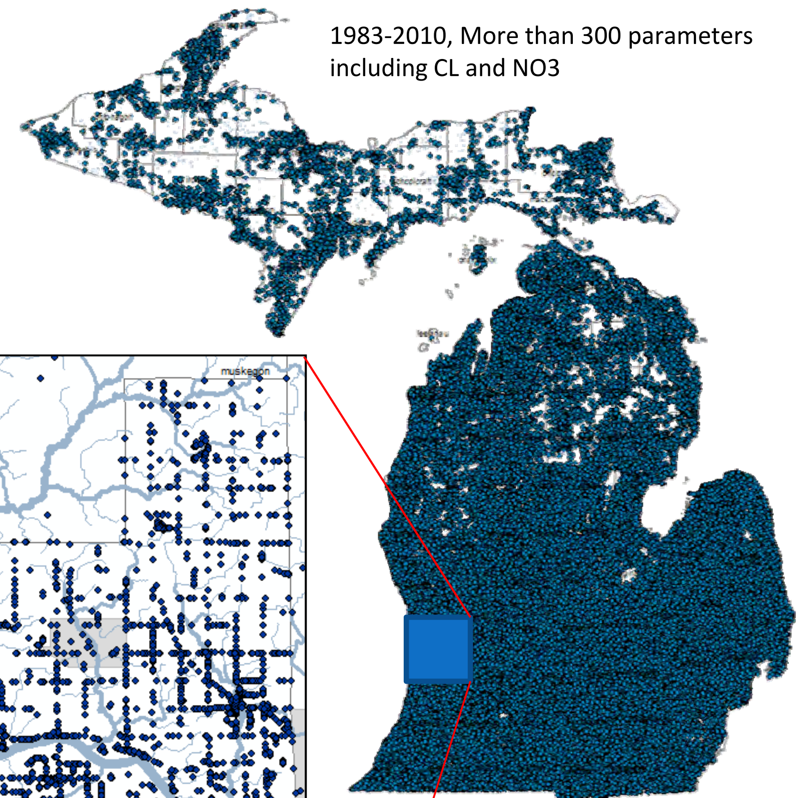
LIGHT BLUE = Aquifer

GREEN = Marginal Aquifer

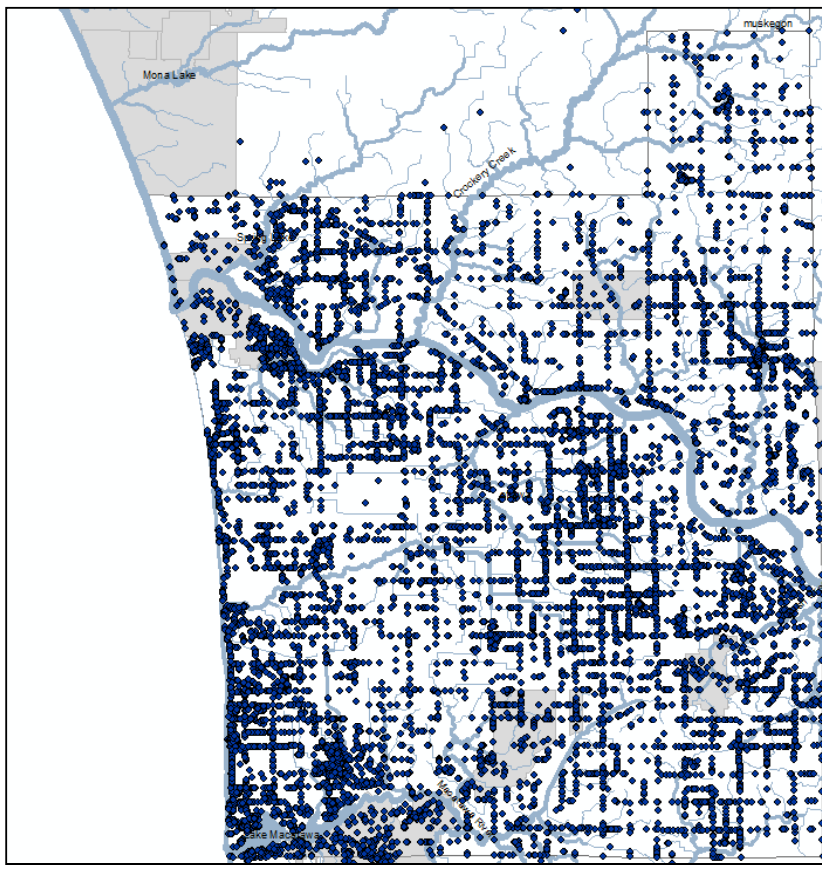
WaterChem Database

To characterize groundwater quality, we utilized the statewide WaterChem database.

The MDEQ recently assembled a statewide water quality database that integrates and digitizes, on a continuing basis, historical and new water quality data collected from Michigan's water wells and analyzed at the State of Michigan's *Drinking Water Analysis Laboratory*.



1983-2010, More than 300 parameters including CL and NO3



WaterChem Database

DEQ's Drinking Water Analysis Laboratory was established under the authorization of the Michigan Safe Drinking Water Act, 1976 PA 399, as amended (Act 399), and the United States Environmental Protection Agency (USEPA) and is certified by "The Laboratory Certification Program" which certifies laboratories to ensure that proper methods and quality control are used in the testing of drinking water samples. The certification process includes an extensive review of the applicant laboratory's Quality Assurance Program Plan, Standard Operating Procedures, as well as an on-site audit of the facility and their analytical data.

The water samples that were collected for various purposes since 1983 have been analyzed at the DEQ's Drinking Water Analysis Laboratory and the test results are stored in the WaterChem database. Owners test their well water when they are selling or buying a home, when a new well is installed or an old well or pump is maintained, when they are having water quality problems (unusual color or odor), or when they wish to evaluate their drinking water source if posed with health-related problems.

WATERCHEM DATABASE
1983 - present

Michigan Drinking Water Analysis Laboratory

Areas of certification:

- Bacteriology
- Wet Chemistry
- Organic Chemistry, and
- Inorganic Chemistry.

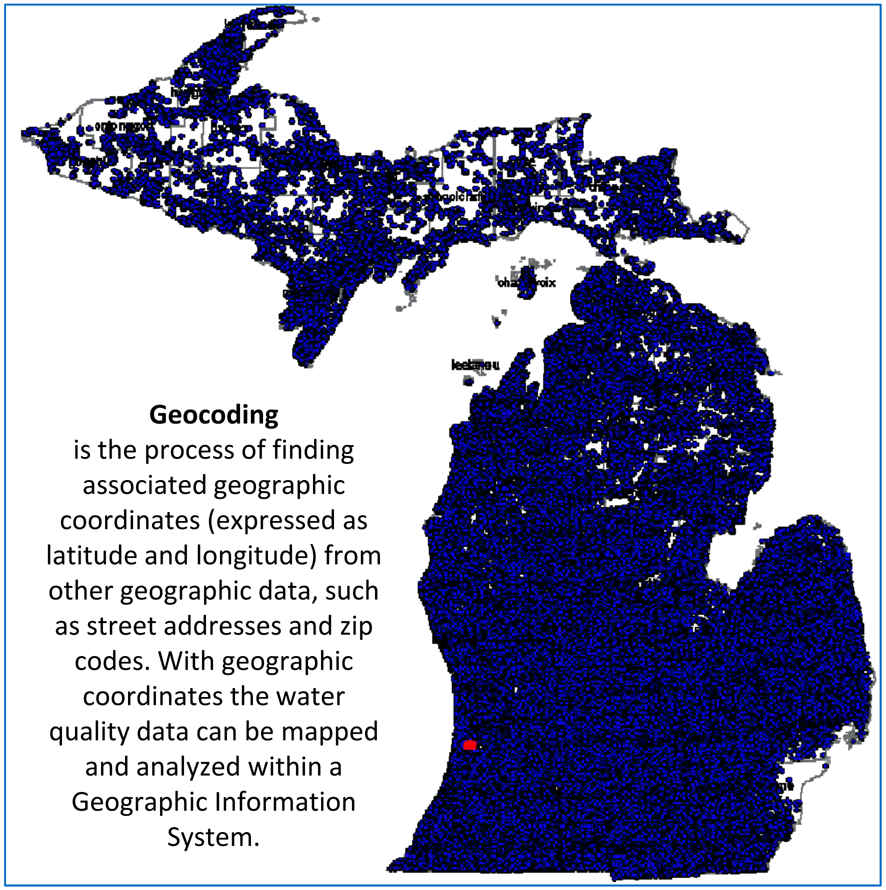
Geocoding WaterChem

One limitation of the current WaterChem database is that it contains no geographic coordinates, aquifer types or well depth. There are no common identifiers between the WaterChem and Wellogic databases.

The MSU CEE team recently geocoded the statewide WaterChem database in a separate project.

This newly geocoded database, now containing 30 years of analytical data from more than 1 million well samples, offers a unique opportunity to significantly improve the understanding of the spatial (geographic) and statistical patterns of water quality in Michigan's groundwater.

WATERCHEM DATABASE
1983 - present

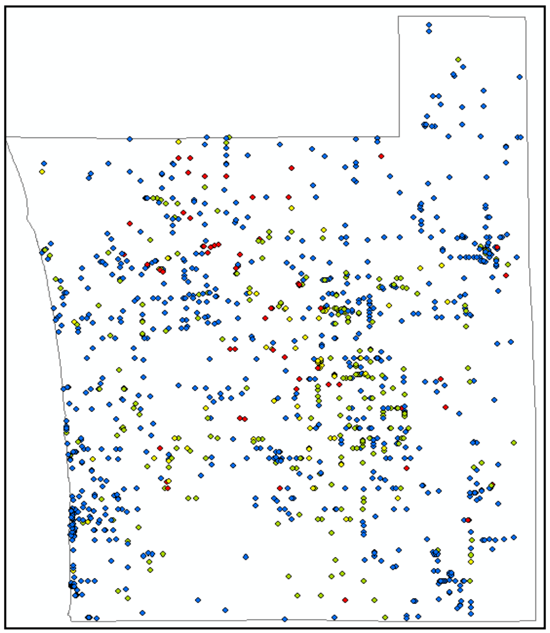


Geocoding
is the process of finding associated geographic coordinates (expressed as latitude and longitude) from other geographic data, such as street addresses and zip codes. With geographic coordinates the water quality data can be mapped and analyzed within a Geographic Information System.

Geocoding WaterChem

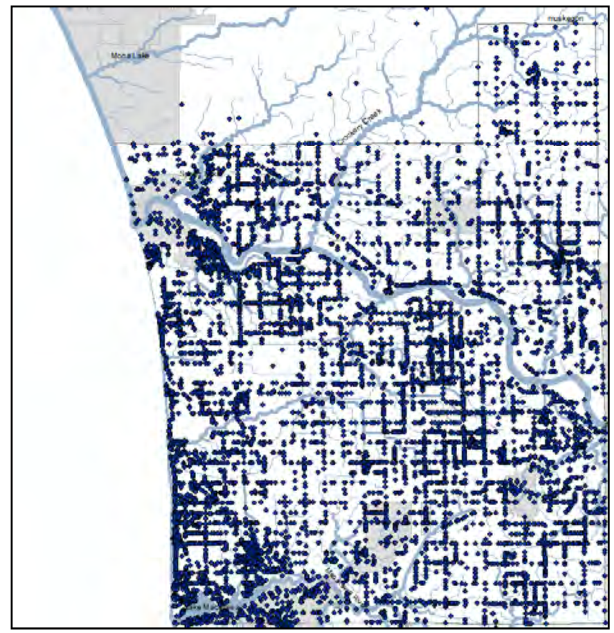
In this study, we co-geocoded the Wellogic and WaterChem data for Ottawa County. This co-geocoding process allows us to create a link between Wellogic and WaterChem for approximately 1,500 wells. For these linked WaterChem wells, we assigned a common Wellogic ID, an aquifer type, and a depth, enabling 3-D water quality mapping.

WaterChem wells linked with Wellogic



These wells in WaterChem were assigned a well depth and aquifer type

WaterChem samples



Phase-1 Study Limitations – Geocoding Uncertainty

The spatial uncertainty induced in the WaterChem data by the address matching methodology is relatively inconsequential for the broad-scale investigation that Phase-1 represented. However, these spatial uncertainties become more important at the local scale or hotspot scale. In Phase-2, actual well location coordinates will be collected using GPS for all of the wells to be sampled in the County-wide synoptic sampling effort. This Phase-2 effort will constrain and partially control the spatial uncertainty associated with the current WaterChem data for Ottawa County.

The Ottawa County Health Department has a large number of paper copies of groundwater chemical analyses that are not replicated in the WaterChem database. The Phase-2 project will evaluate the utility of adding some of these records to the WaterChem database in order to improve the overall coverage of the County in both space and time. Although these paper records will undoubtedly be very useful, it is not anticipated that they will alter the Phase-1 conclusions about water quality .

MODELING ANALYSES AND RESULTS

The integrated, data-enabled statewide modeling platform enables groundwater analysis and visualization in ways that were previously impractical.

We have applied this data-enabled platform to characterize and analyze Ottawa County's groundwater resources. In particular, we have characterized County-wide:

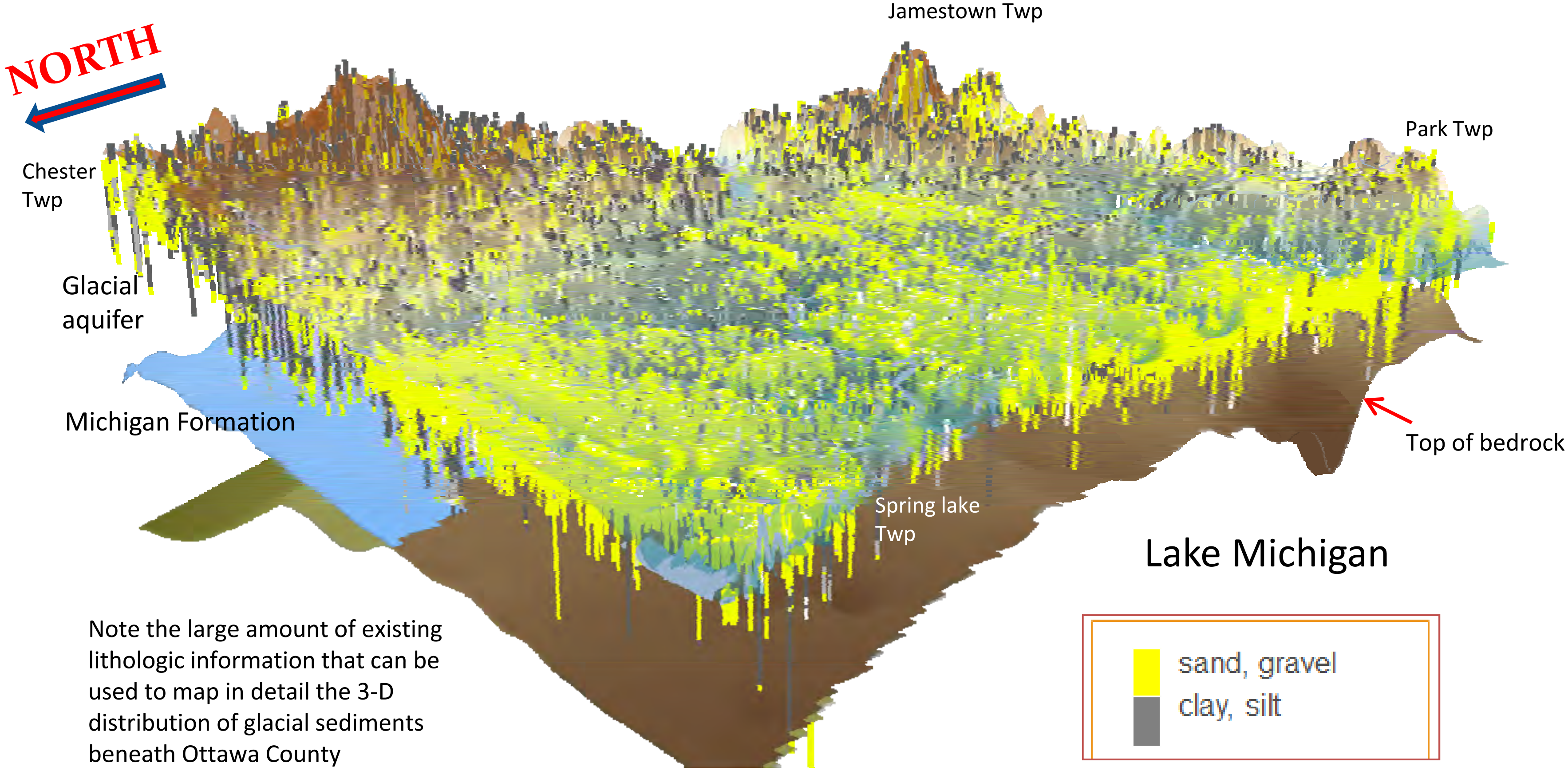
- Regional Geology (*e.g.*, local and regional aquifers; 3-D aquifer heterogeneity, aquifer connectivity; confining layers).
- Static Water Levels *(e.g.,* spatial patterns, recharge and discharge areas; temporal trends)
- Chloride Contamination (*e.g.*, 2-D and 3-D mapping, hotspots, temporal trends, sources of contamination)
- Nitrate Contamination (*e.g.*, 2-D mapping and temporal trends)
- Depth to Water (2-D mapping, long term average);

The results are presented and discussed next. We made a special effort to create a visual presentation of the data and analyses so that they are meaningful to audiences with or without a technical background in groundwater hydrogeology.

Lithology and Stratigraphy

In this section of the report we visualize aquifer lithology, in 3-D and from different angles, at more than 8,000 well locations in the County with a goal of understanding the complex material distribution, heterogeneity, material connectivity, and aquifer interactions that control aquifer yields and recharge, particularly recharge into the deep bedrock aquifer.

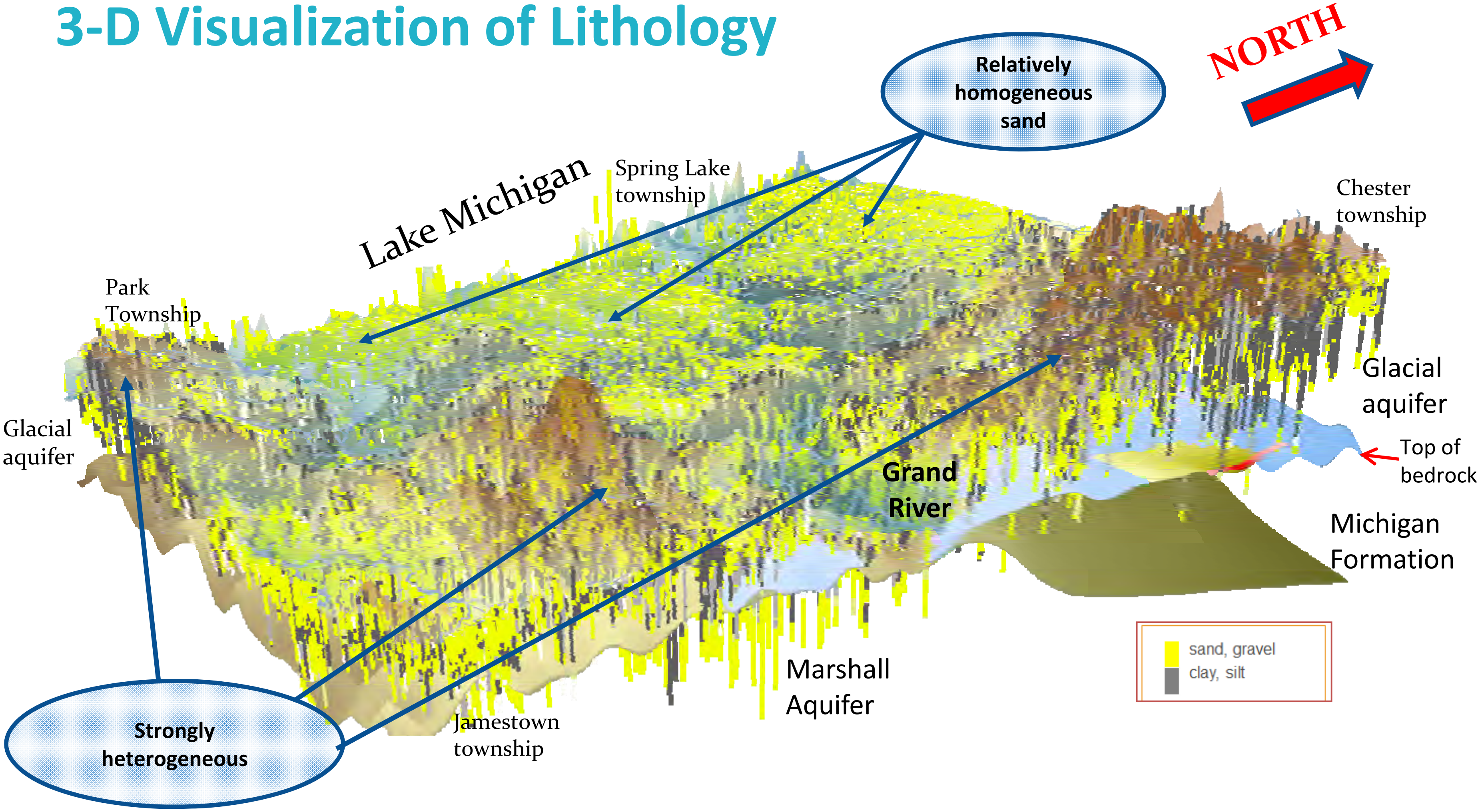
3-D Visualization of Lithology



Note the large amount of existing lithologic information that can be used to map in detail the 3-D distribution of glacial sediments beneath Ottawa County

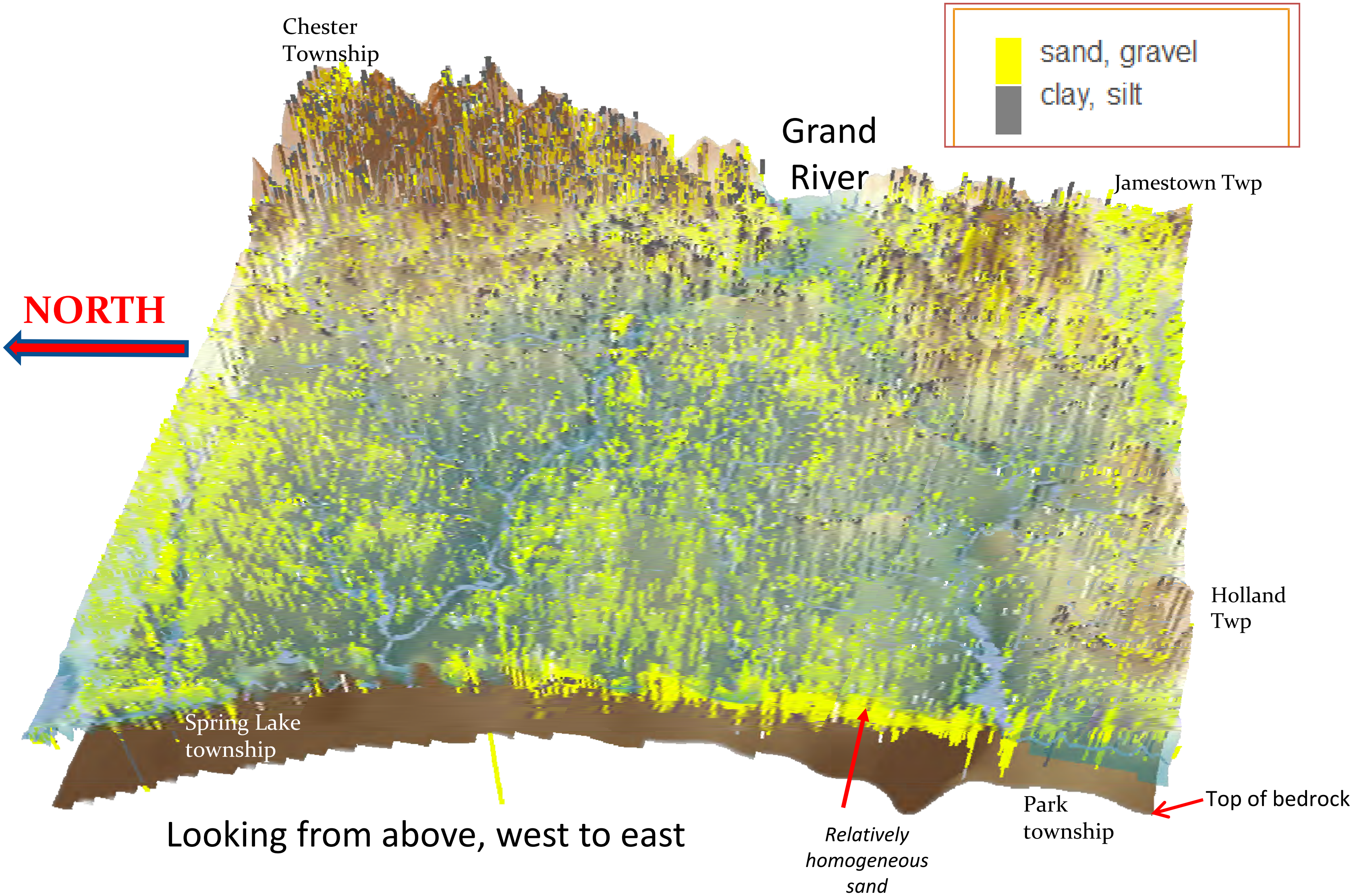
Viewing from above, northwest to southeast

3-D Visualization of Lithology



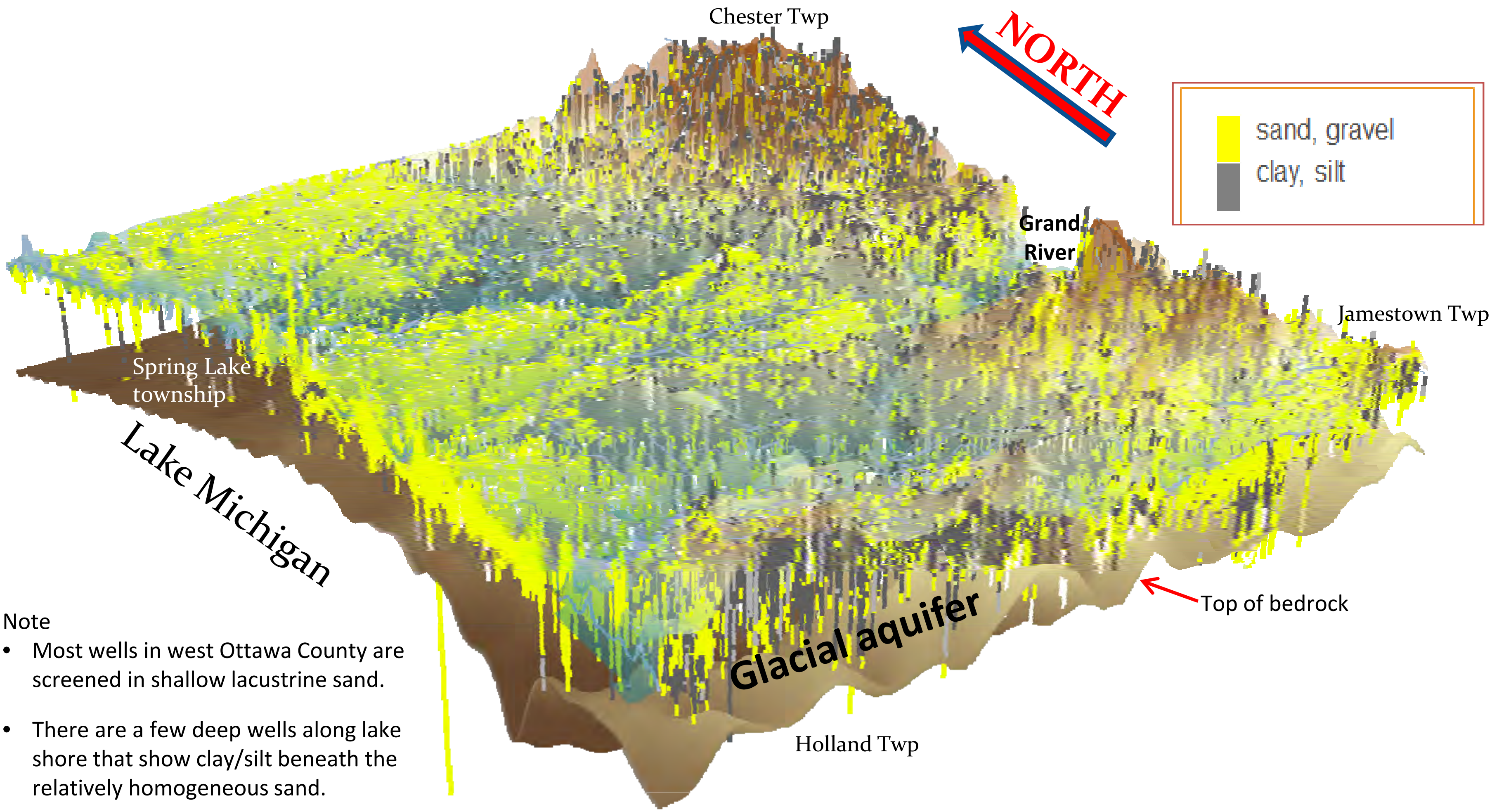
Looking from above, southeast to northwest

3-D Visualization of Lithology



Looking from above, west to east

3-D Visualization of Lithology

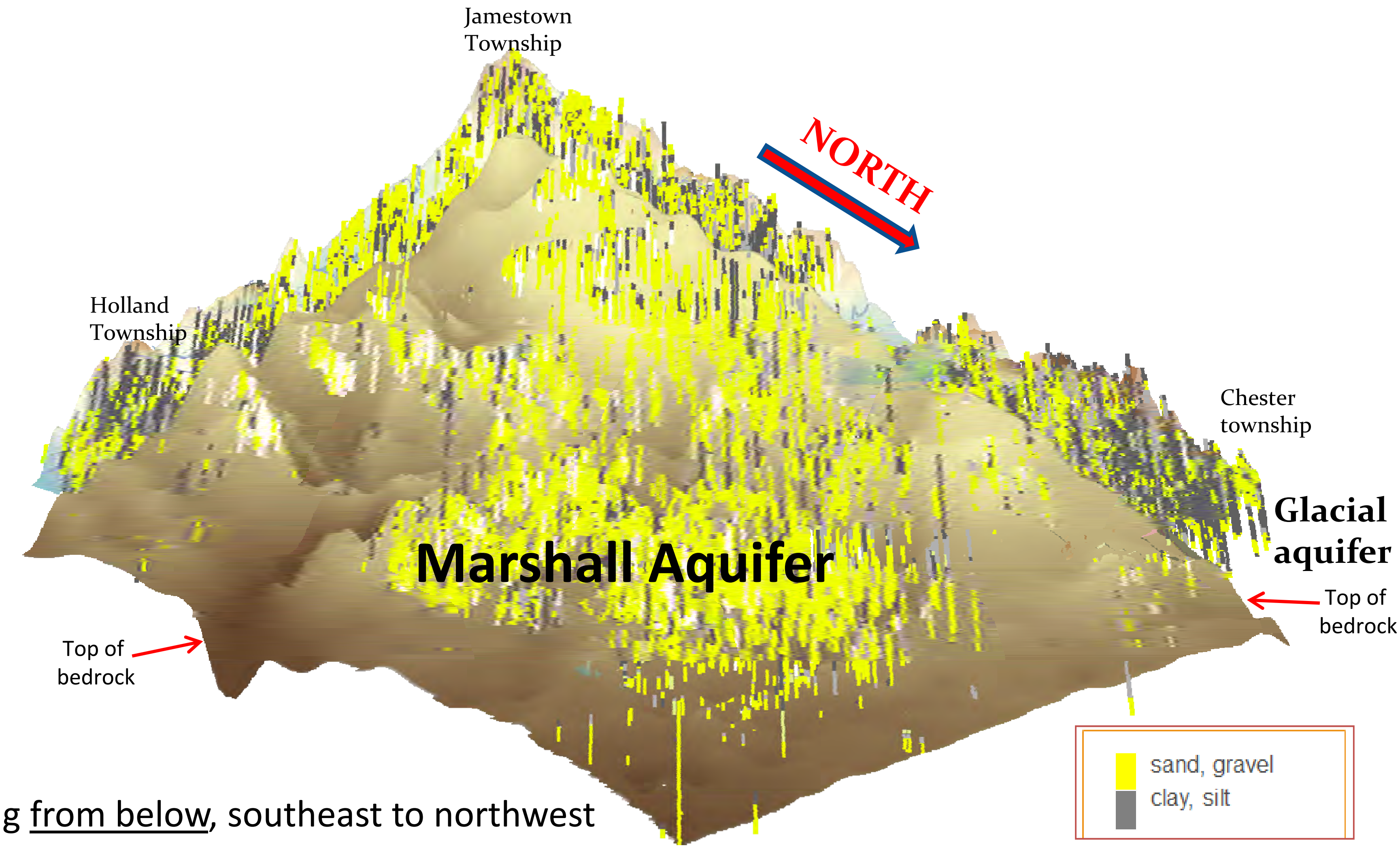


Note

- Most wells in west Ottawa County are screened in shallow lacustrine sand.
- There are a few deep wells along lake shore that show clay/silt beneath the relatively homogeneous sand.

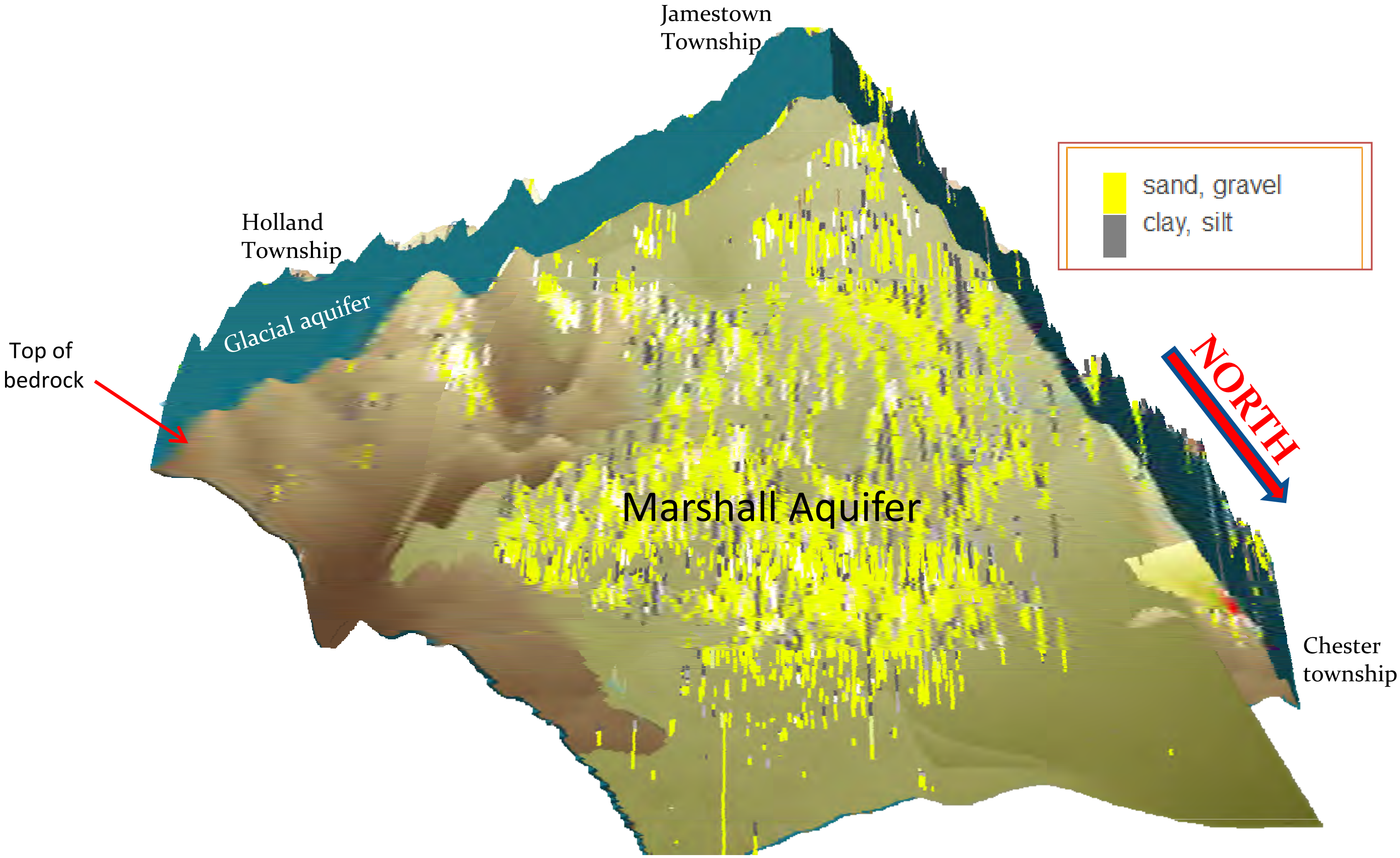
Looking from above, southwest to northeast

3-D Visualization of Lithology



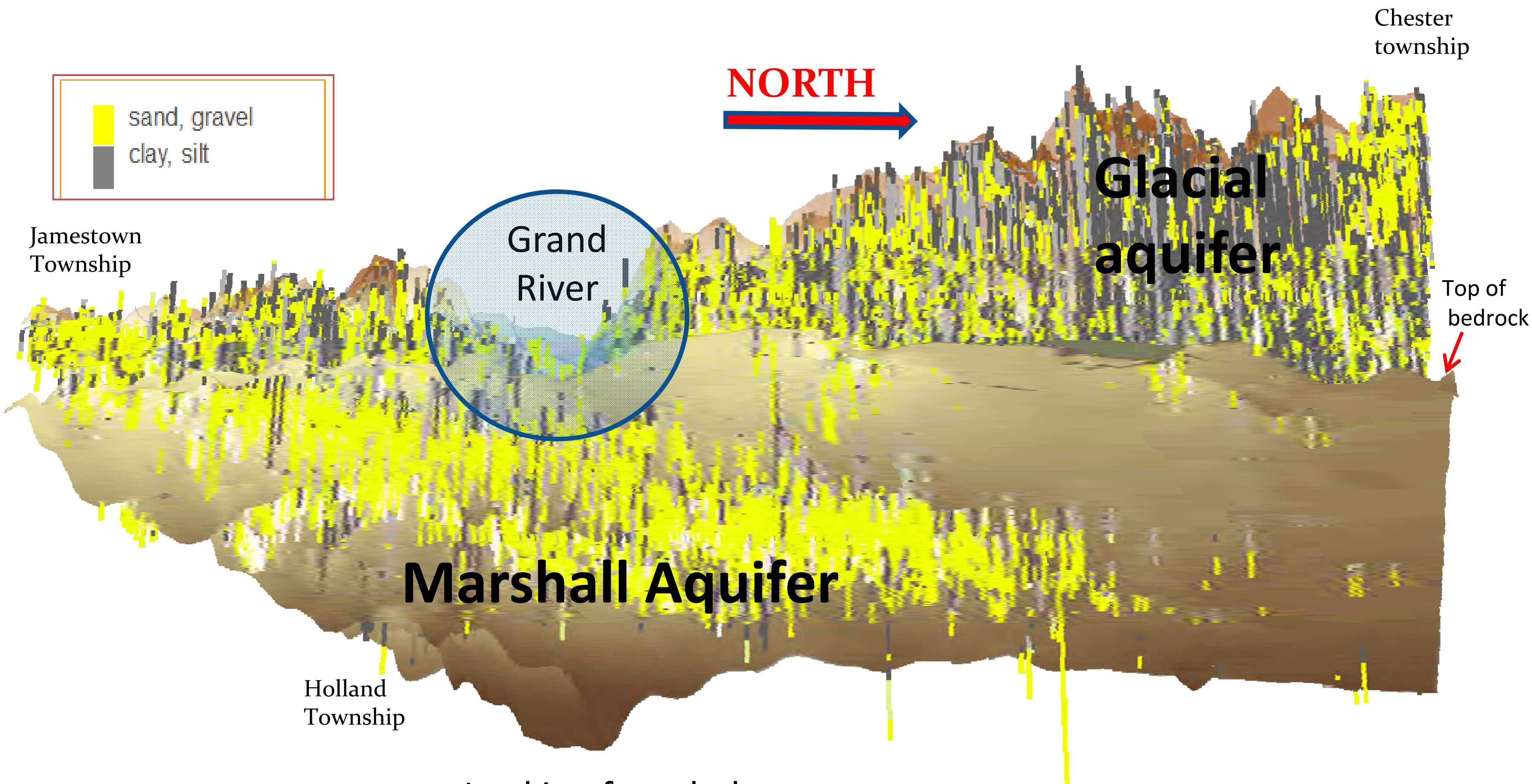
Looking from below, southeast to northwest

3-D Visualization of Lithology



Looking from below, southeast to northwest

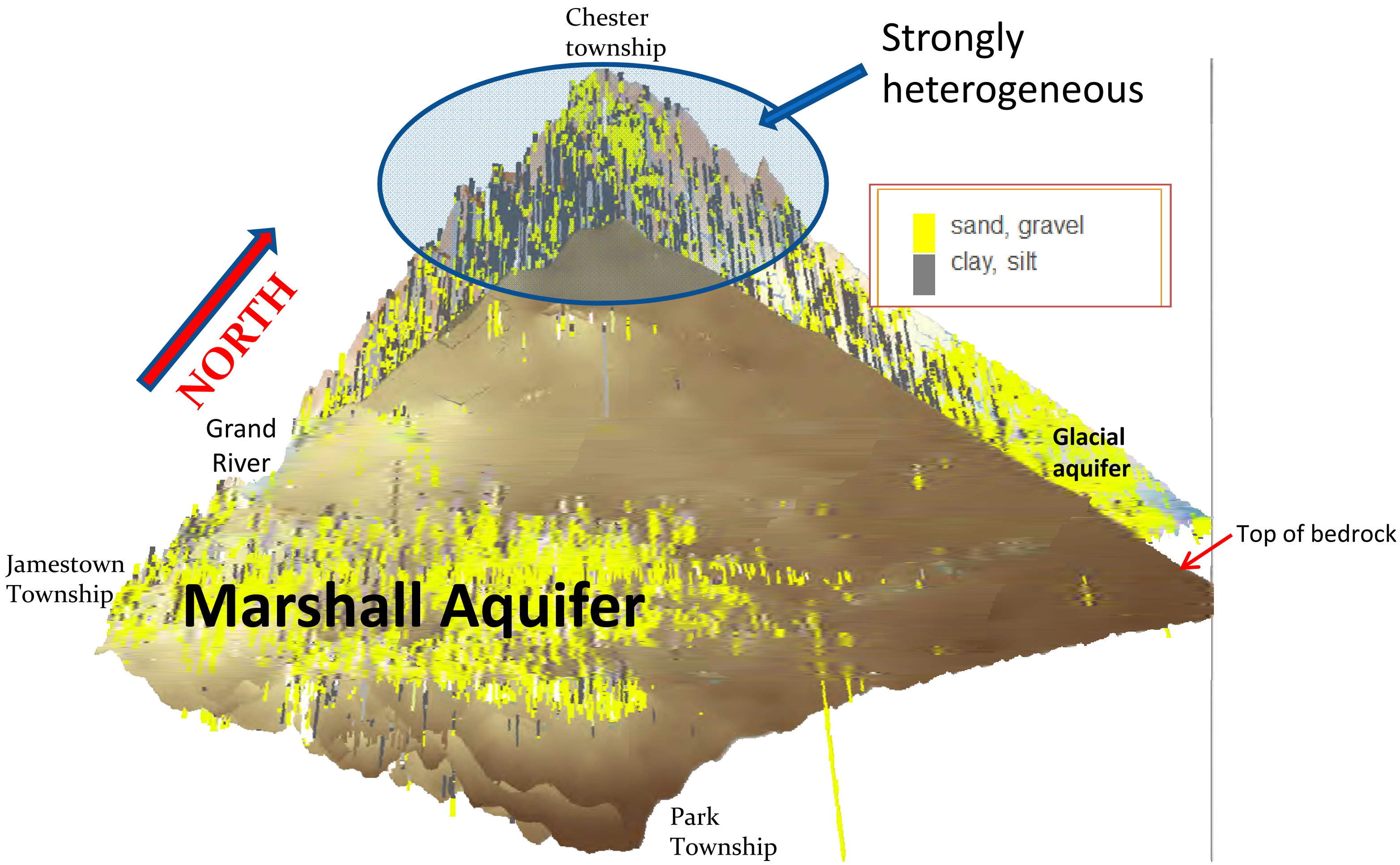
3-D Visualization of Lithology



Looking from below, east to west.

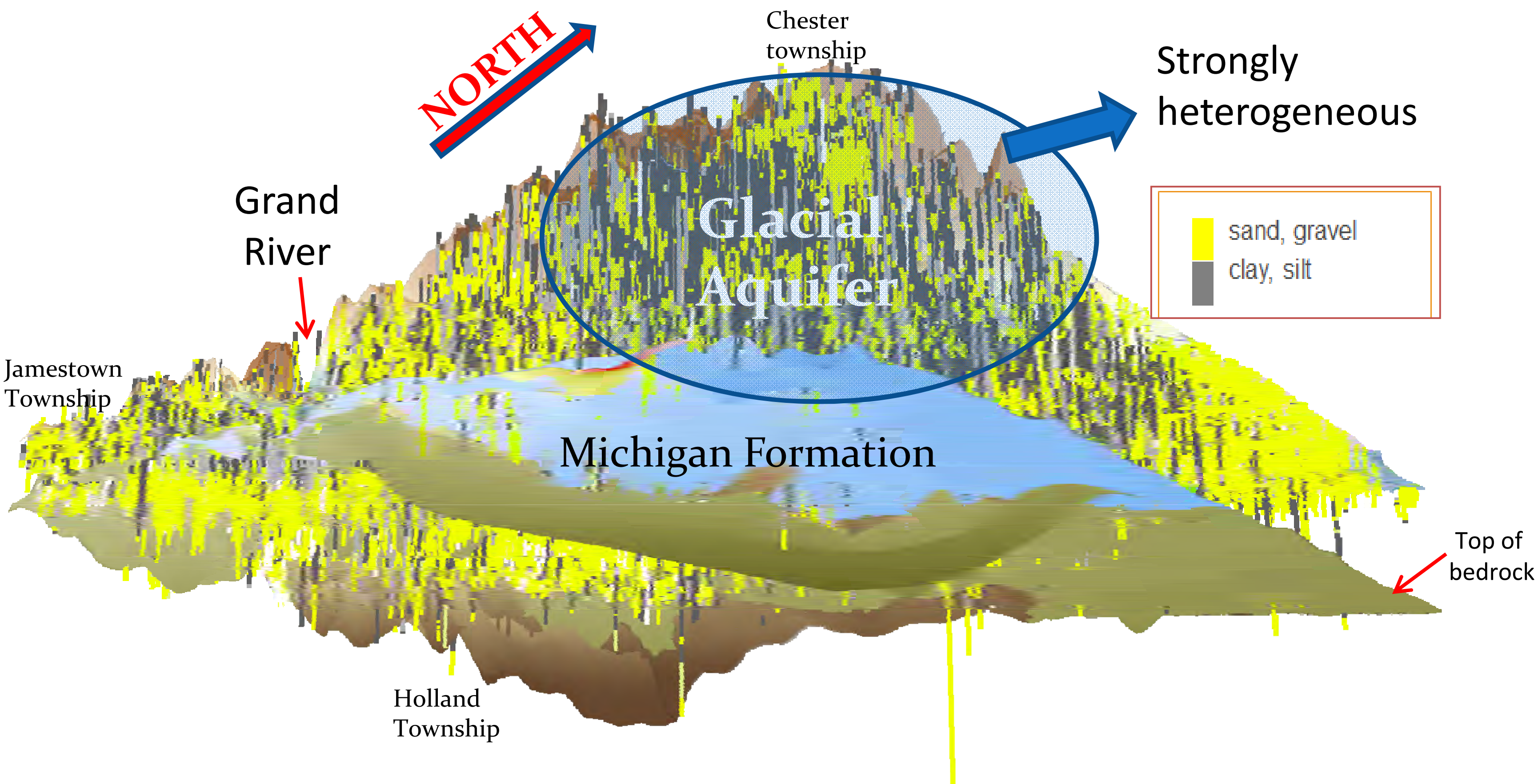
Note: the Grand River at the east end of the County is almost directly connected to the bedrock aquifer.

3-D Visualization of Lithology



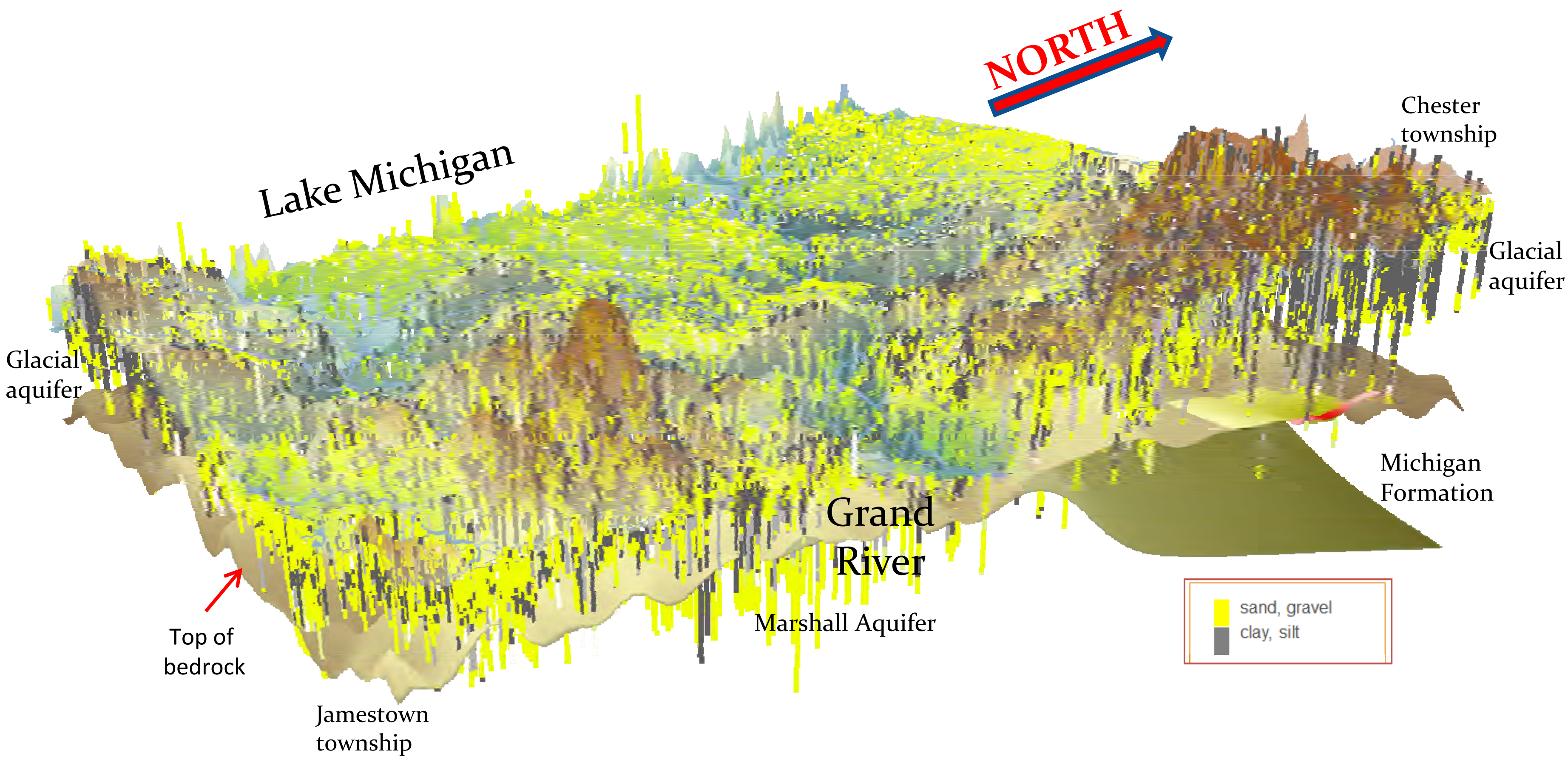
Looking from below, northeast to southwest

3-D Visualization of Lithology



Looking from below, northeast to southwest

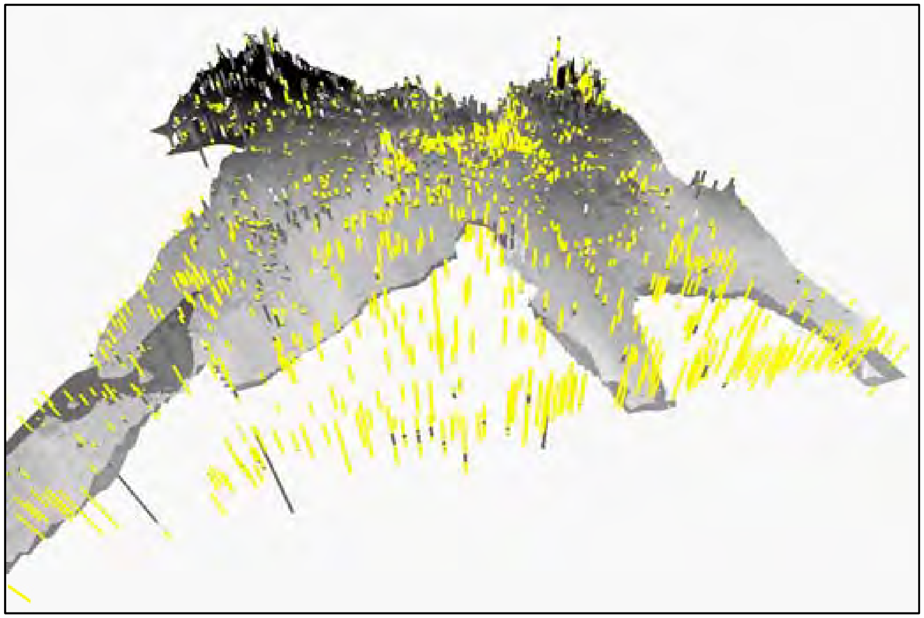
3-D Visualization of Lithology

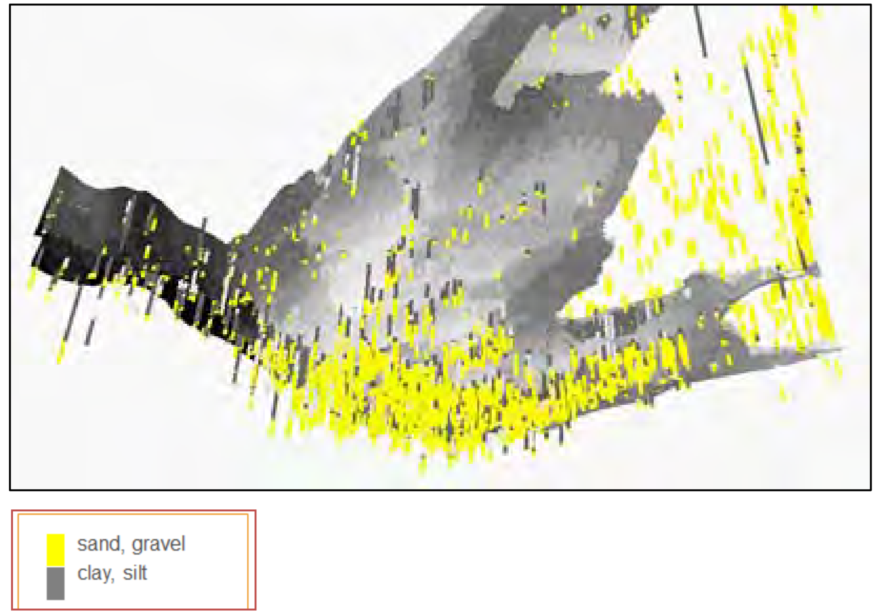


Looking from above, southeast to northwest

3-D Visualization of Lithology

This slide presents two 3-D visualizations of well lithology and the approximate top and bottom surface of the extensive clay body in Ottawa County. Note that the extensive clay deposit thickens eastward across the County and is thin to discontinuous along the western fringe of the County. The lacustrine sandy sediments on the west side of the County are relatively homogeneous and also thin eastward. In much of central Ottawa County, clay and silt occur below the lacustrine sand, as documented in deep wells.





3-D Glacial Aquifer Mapping

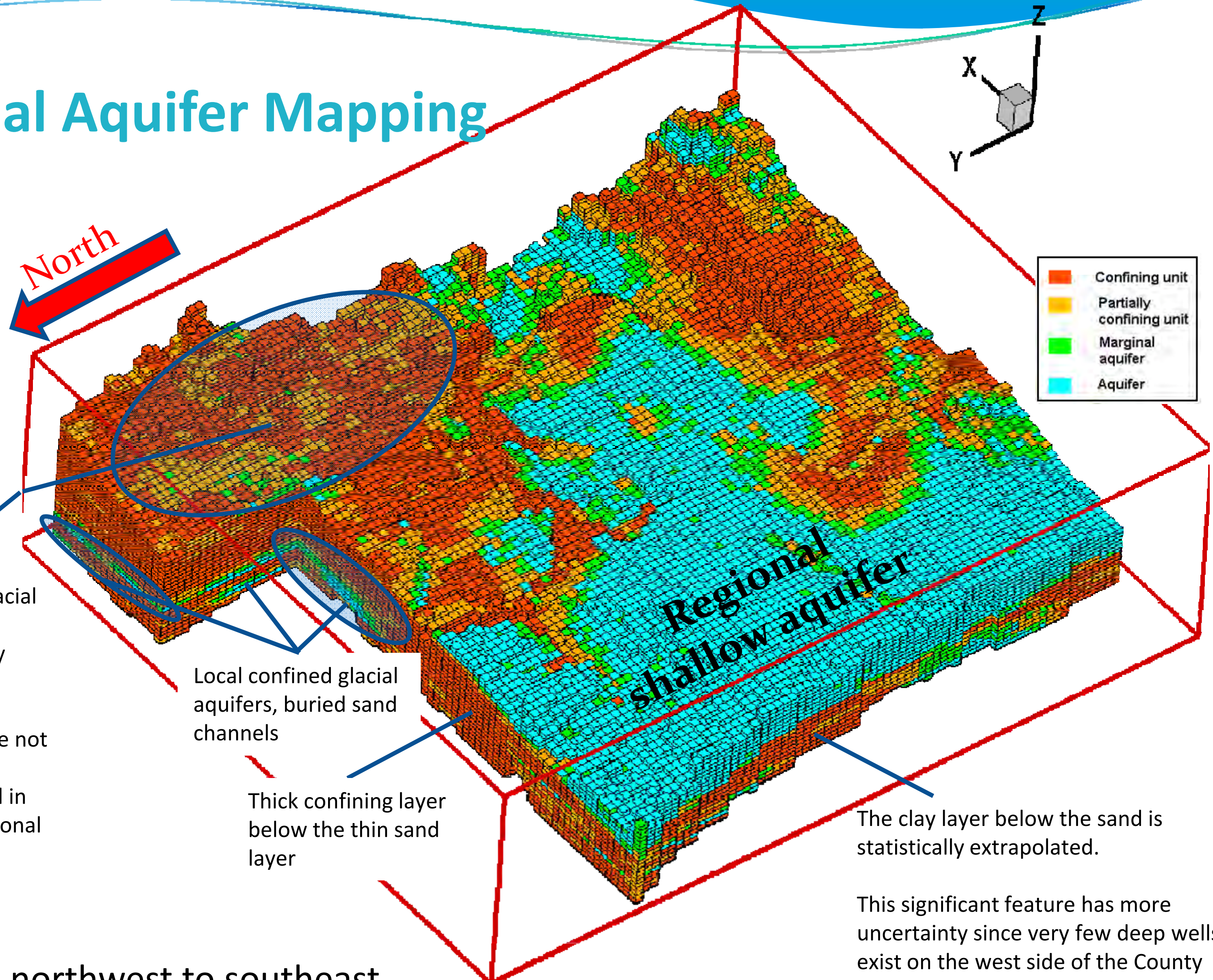
In this section, we present a regional glacial aquifer model for Ottawa County in both 3-D diagrams and as cross-sections.

The model was developed using the transition probability geostatistical simulation technique based on available well logs from more than 8,000 wells. The model was built at a resolution of 1,000 m horizontally and 1m vertically.

In many places in the County, water wells are within a few hundred meters of one another. Wherever multiple wells occurred in one model cell (1000 x 1000 m) they were virtualized or aggregated into a single well with effective lithologies interpolated to each 1-meter of depth, in order to reduce the number of wells. This aggregation method was necessary to enable the coarse scale geostatistical simulation for the entire County.

This 3-D model represents only the coarse-scale variability of glacial deposits across Ottawa County. The horizontal and vertical distribution of the major lithologies (aquifer, marginal aquifer, partially confining or confining materials) within the actual glacial deposits can be significantly more heterogeneous.

3-D Glacial Aquifer Mapping



This portion of the glacial deposits is strongly heterogeneous. Many sand pockets and localized outwash channels exist, but are not properly represented/resolved in this coarse-scale, regional model.

Local confined glacial aquifers, buried sand channels

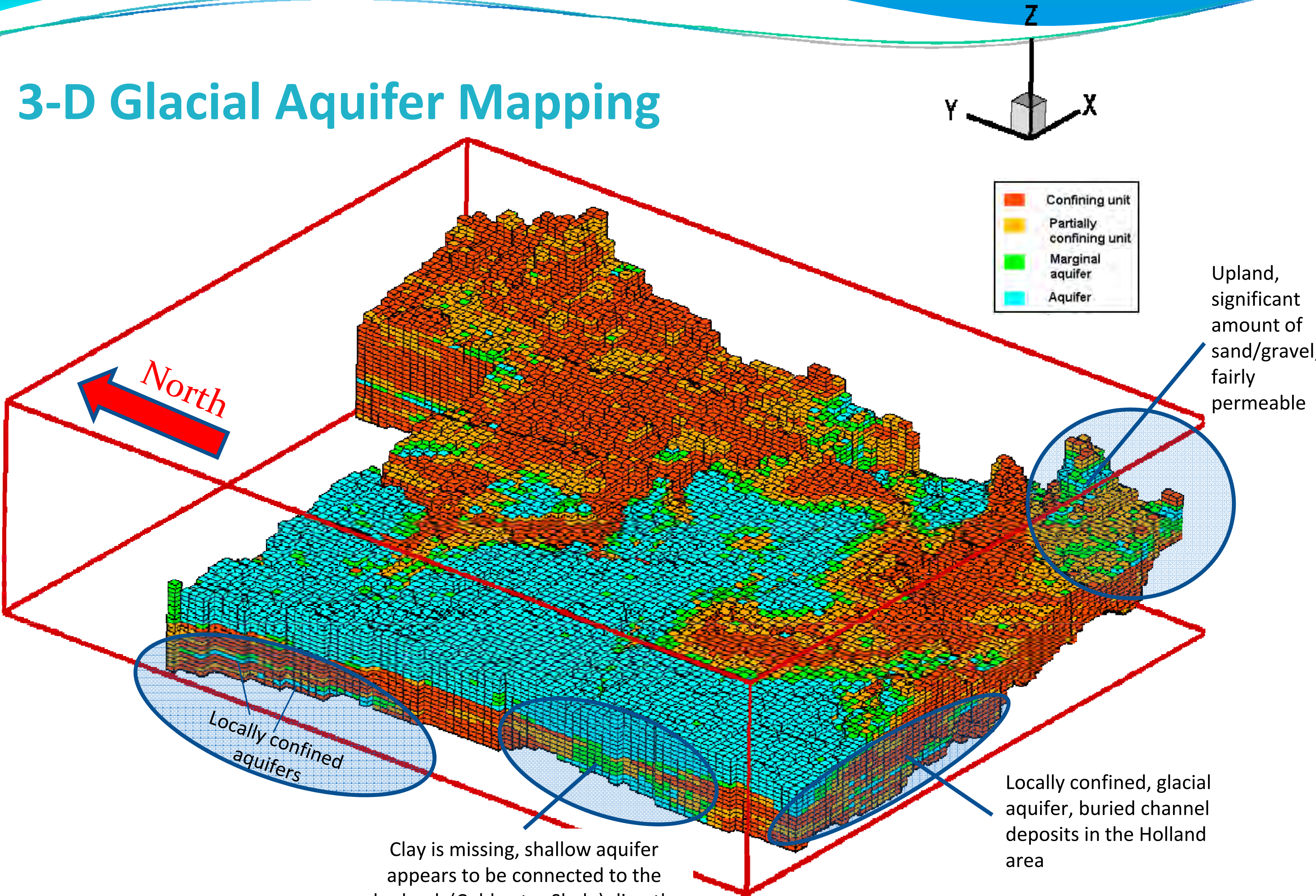
Thick confining layer below the thin sand layer

The clay layer below the sand is statistically extrapolated.

This significant feature has more uncertainty since very few deep wells exist on the west side of the County

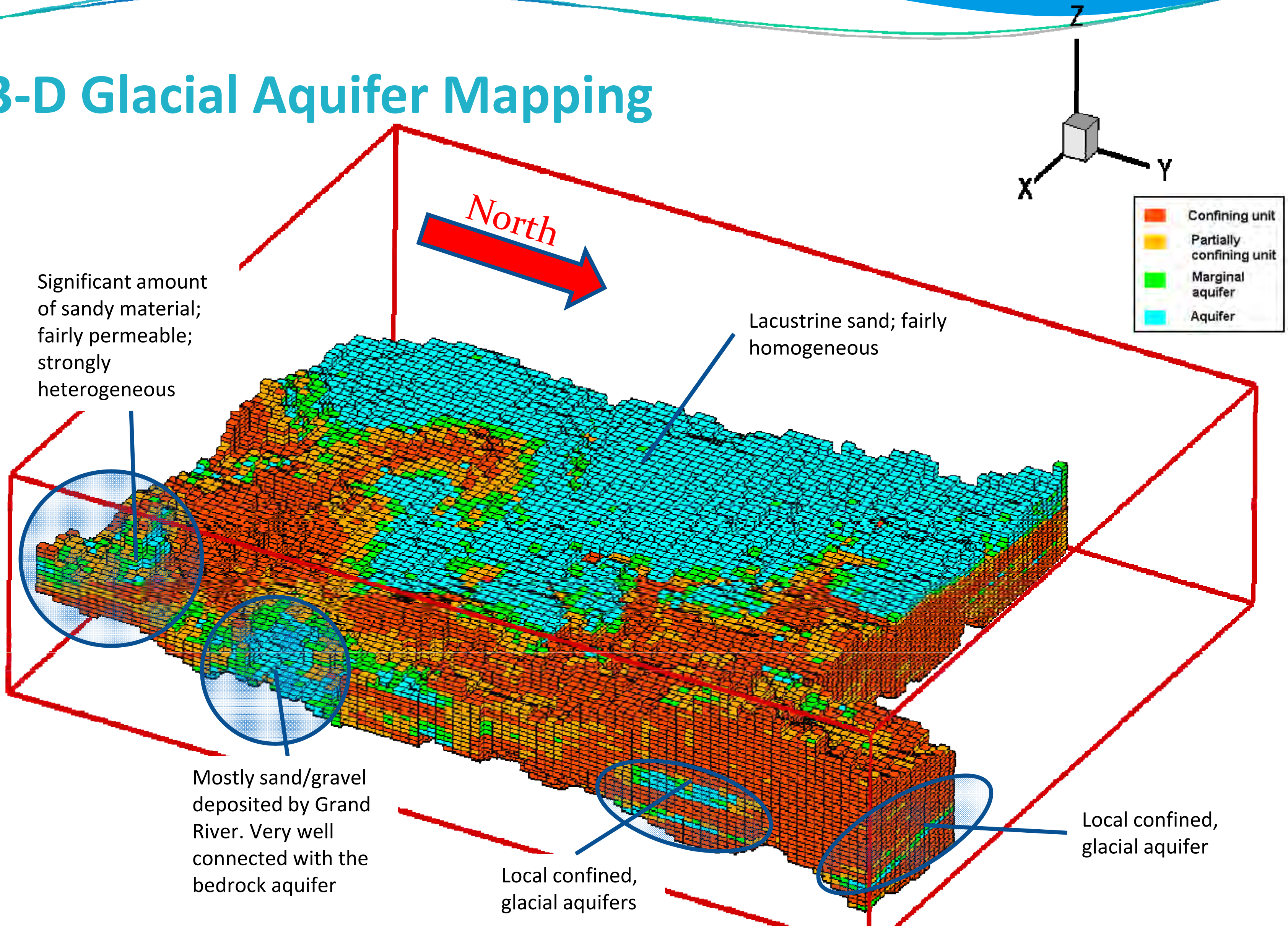
Looking from northwest to southeast

3-D Glacial Aquifer Mapping



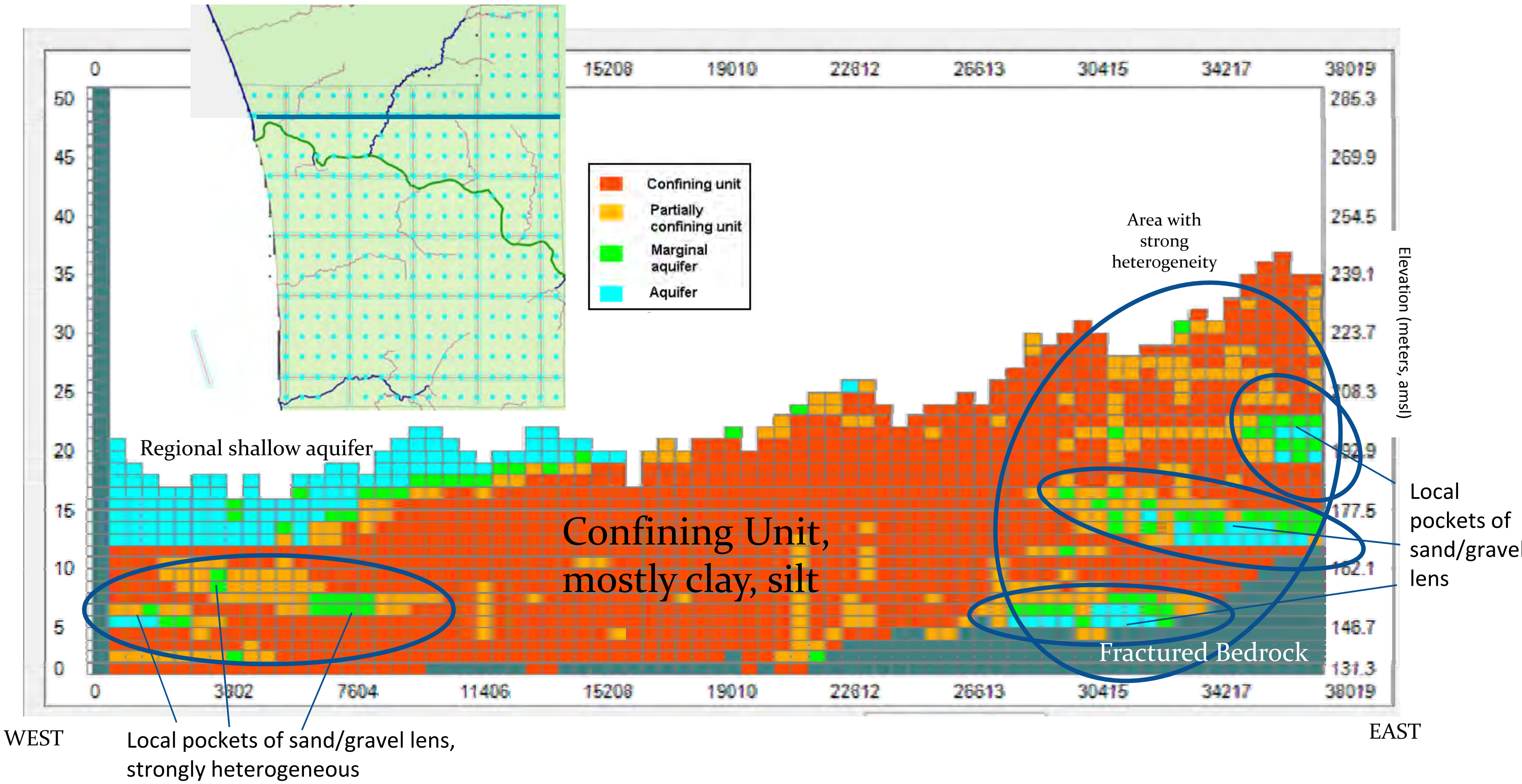
Looking from west-southwest to east-northeast

3-D Glacial Aquifer Mapping

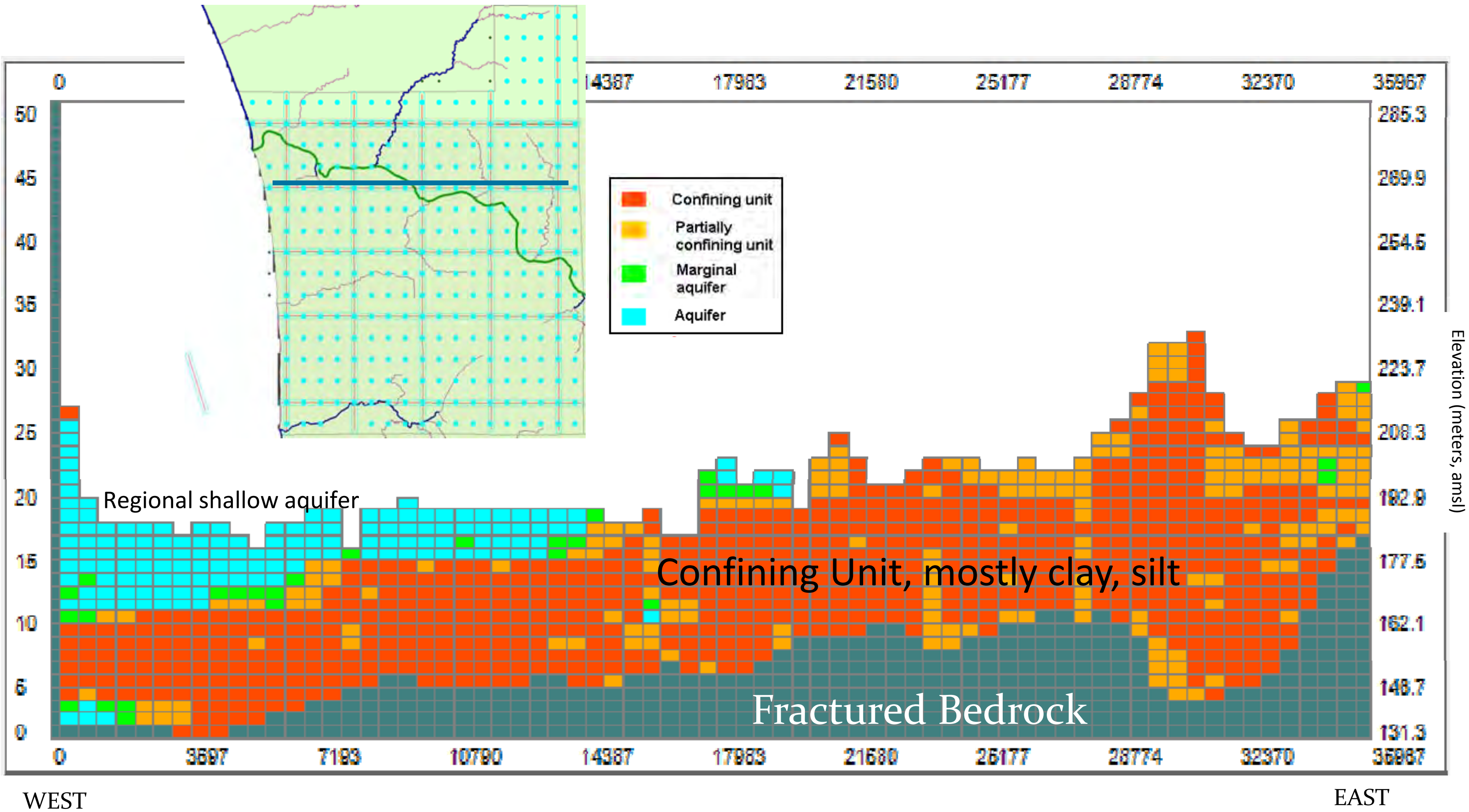


Looking from east-northeast to west-southwest

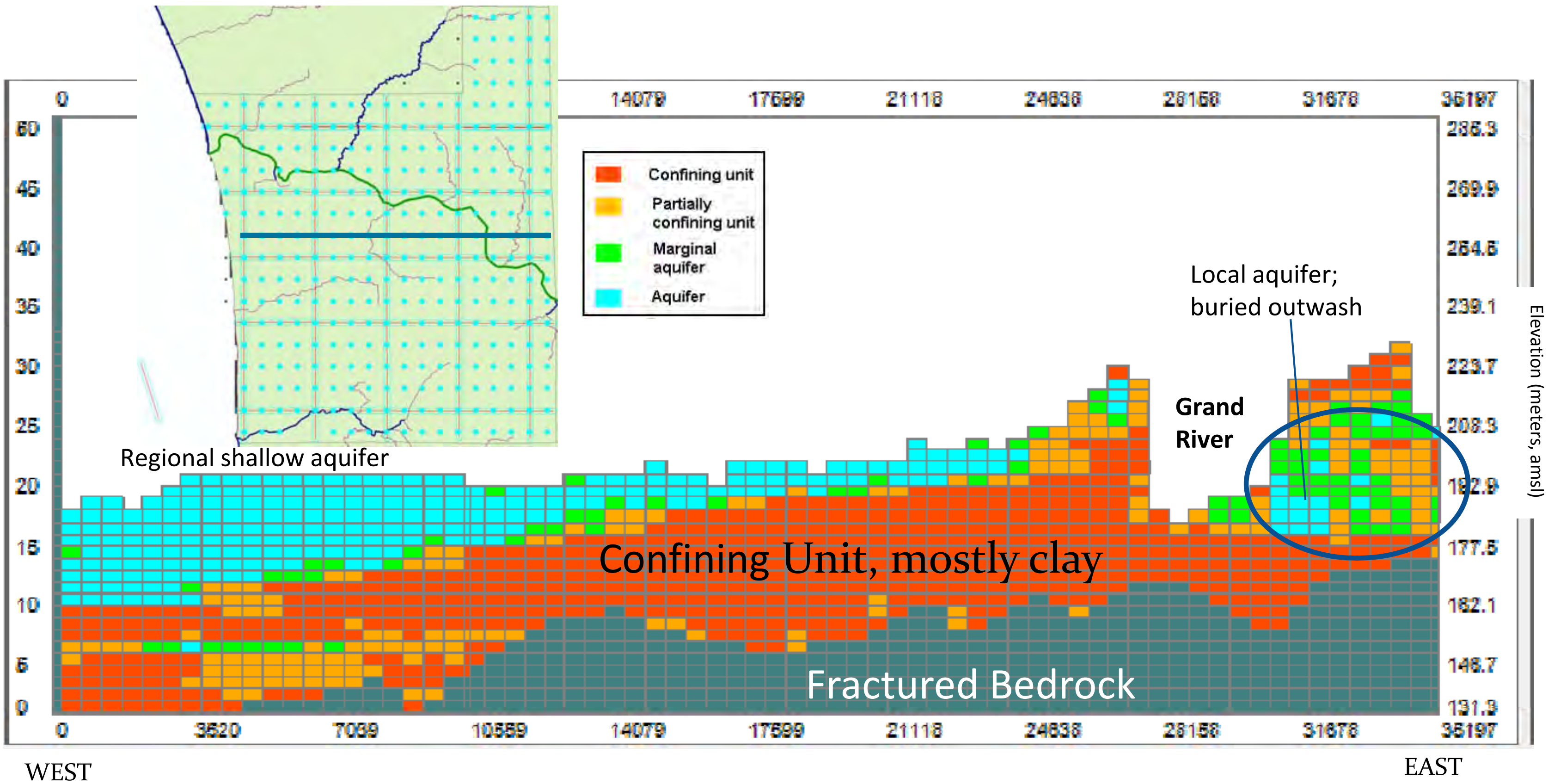
West-East Cross-section 1



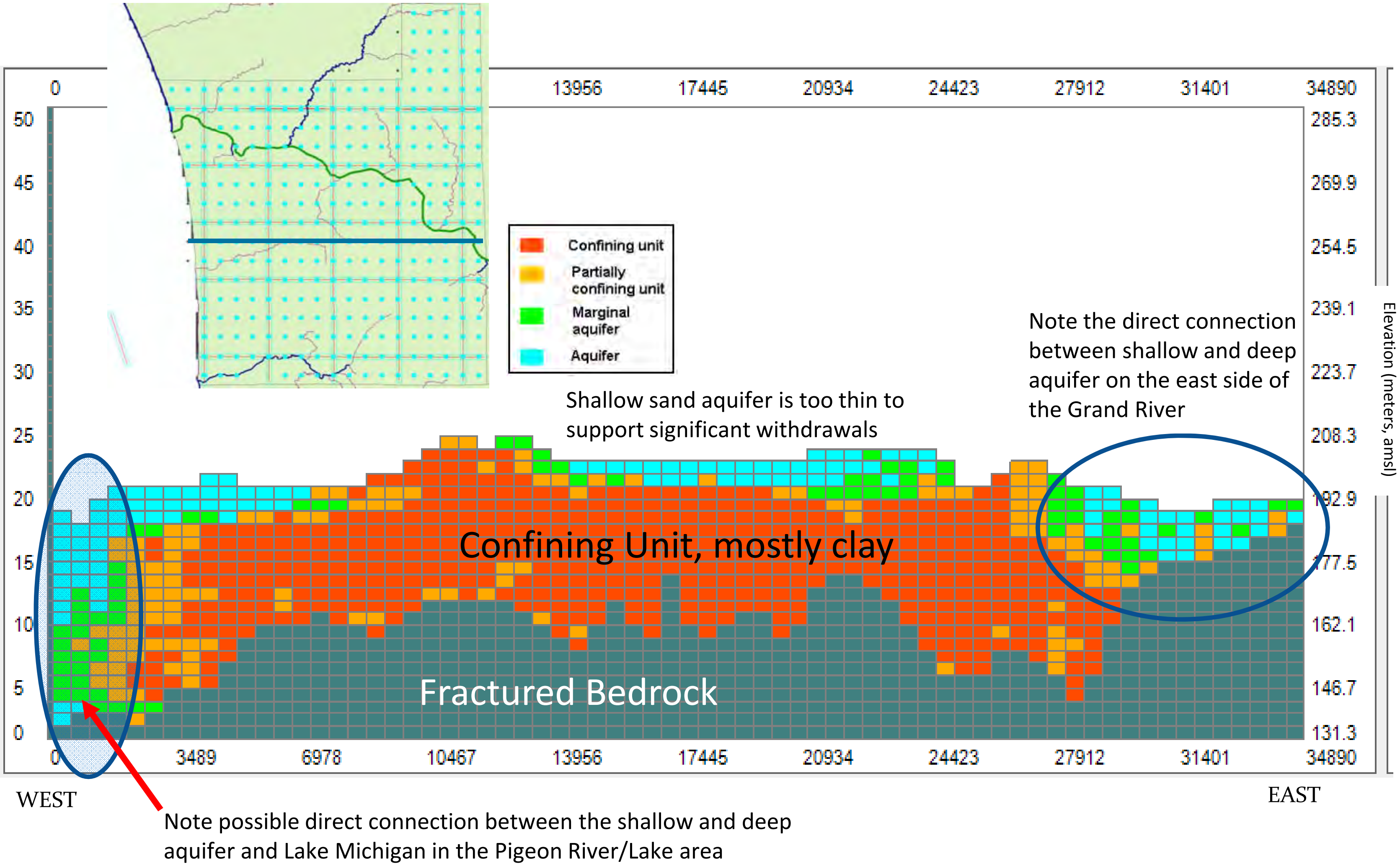
West-East Cross-section 2



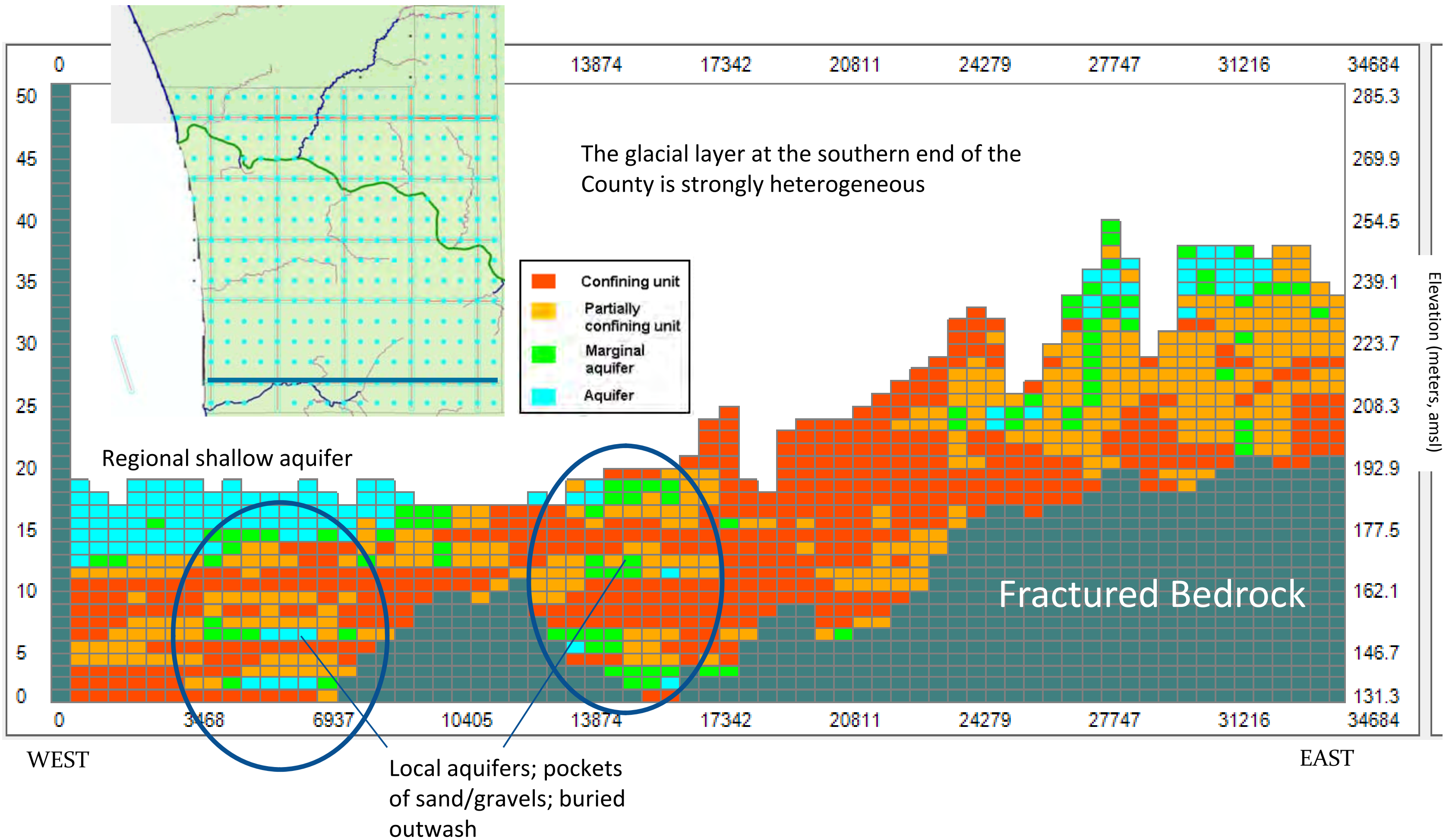
West-East Cross-section 3



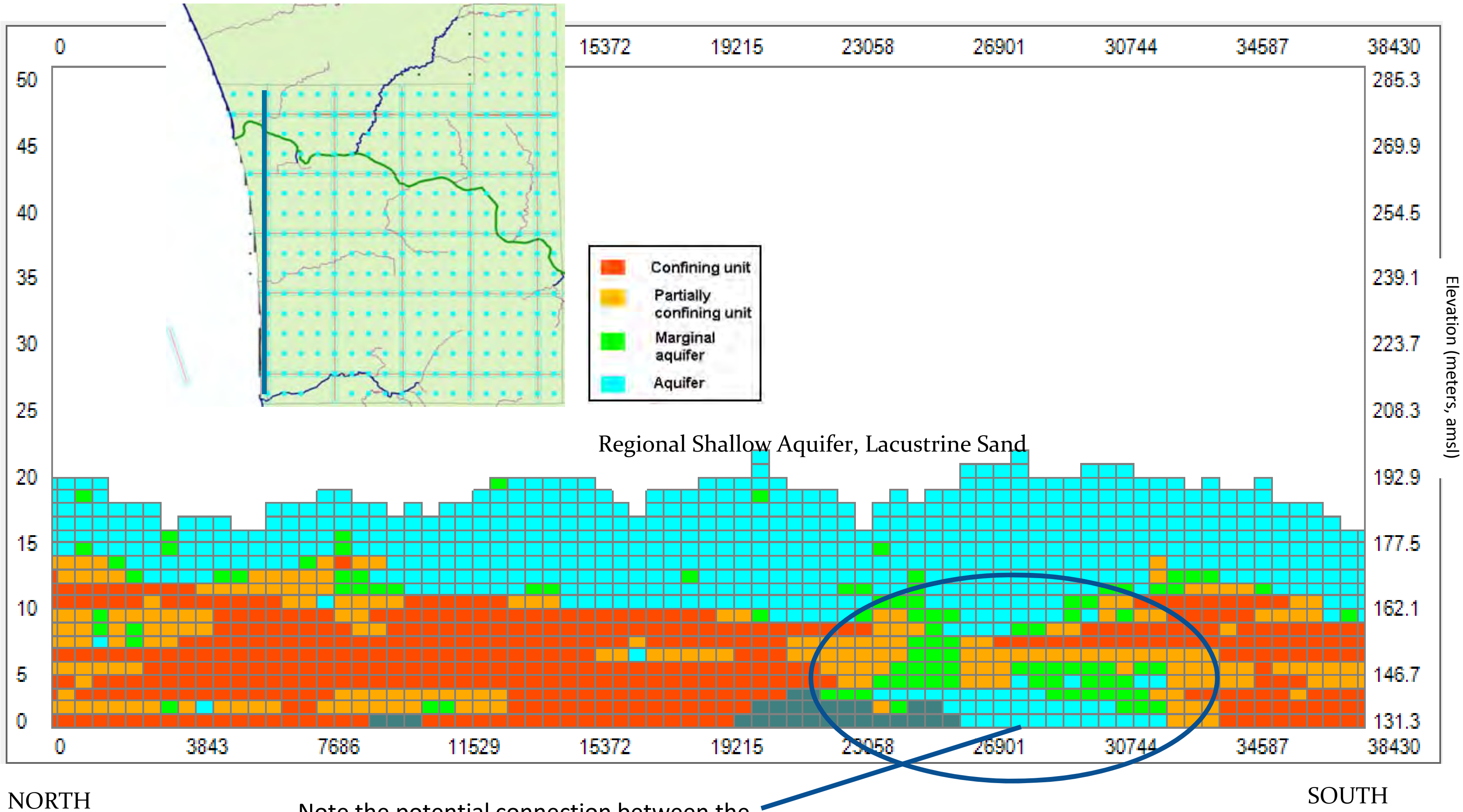
West-East Cross-section 4



West-East Cross-section 5

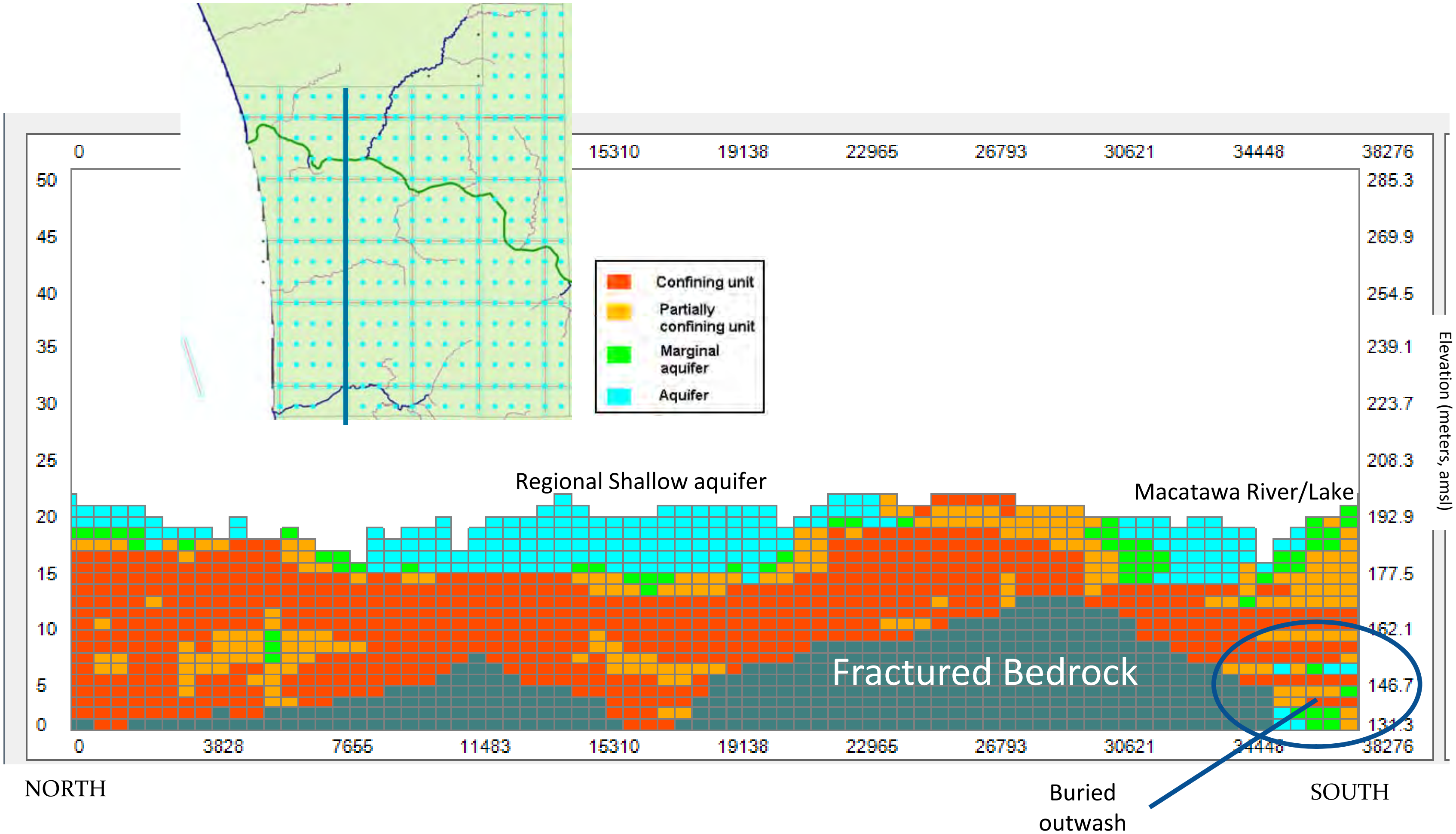


North-South Cross-section 1

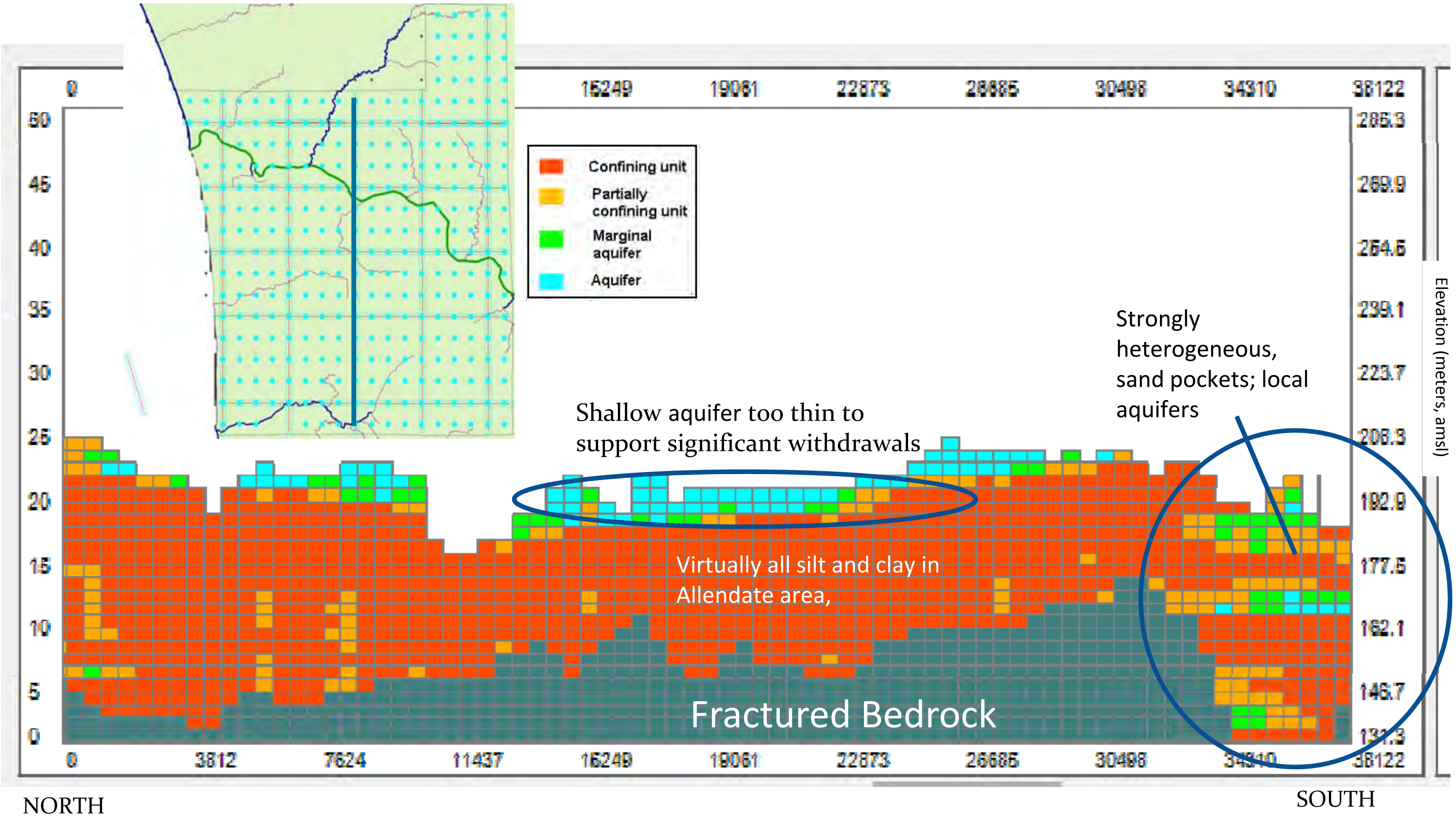


Note the potential connection between the shallow sand and deep bedrock in the Pigeon River/Lake area

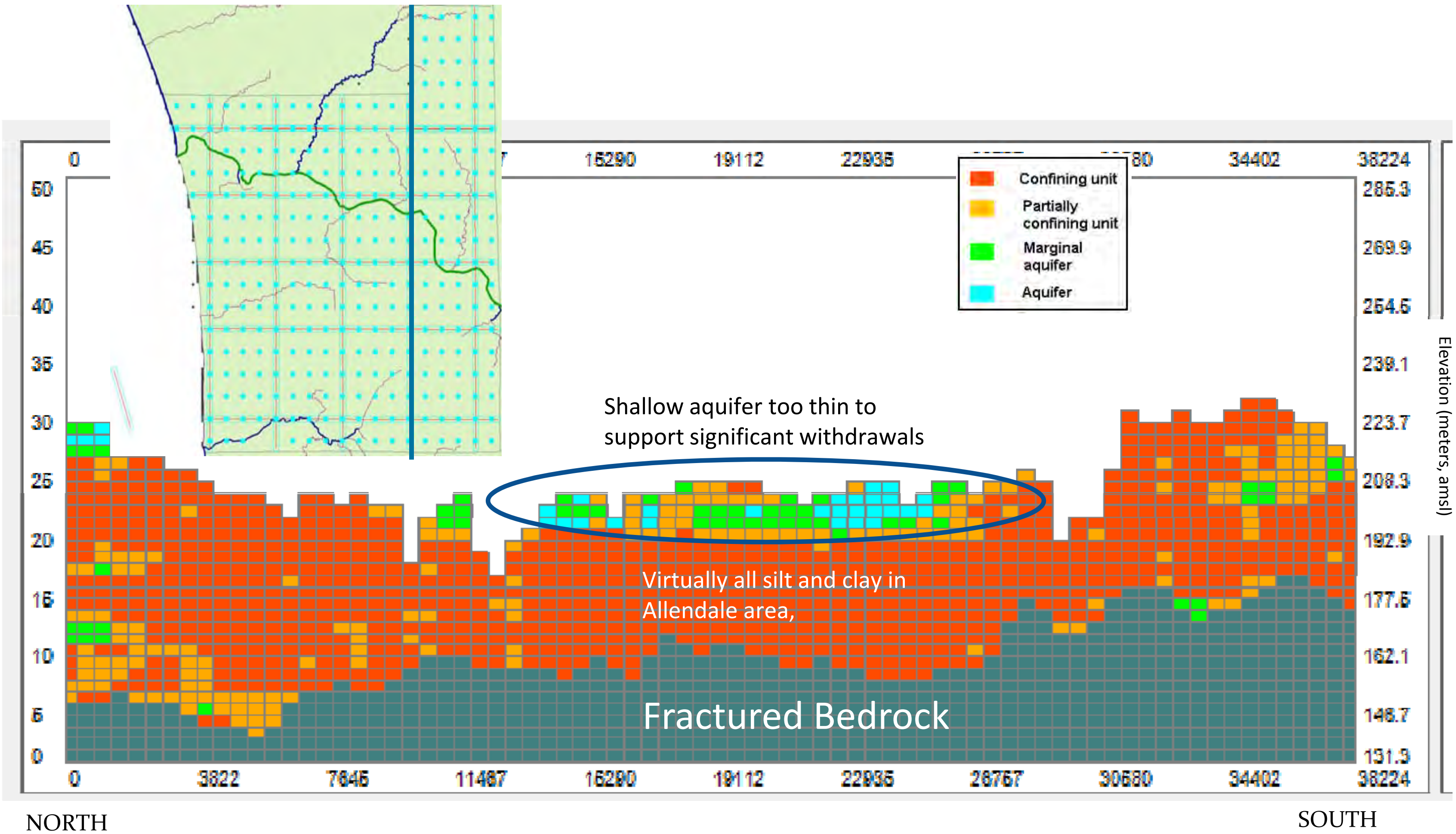
North-South Cross-section 2



North-South Cross-section - 3

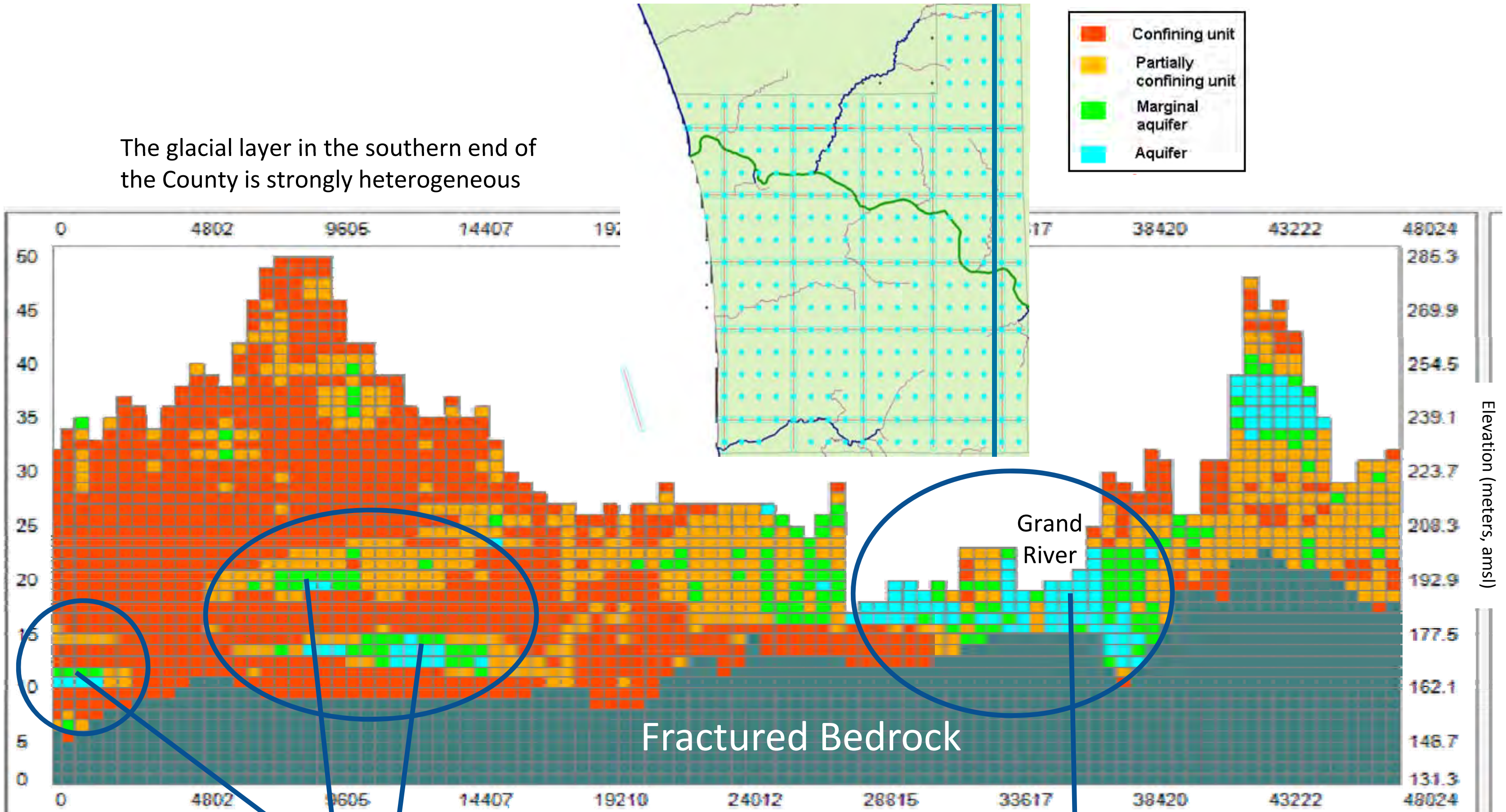


North-South Cross-section 4



North-South Cross-section 5

The glacial layer in the southern end of the County is strongly heterogeneous



Local confined aquifer; buried sand/gravel pockets

Coarse channel deposits; Grand River is well connected to the bedrock aquifer toward the eastern end of the County

Messages from the Geological Modeling

There are two, areally extensive aquifers in Ottawa County: a shallow, unconfined aquifer in the glacial deposits and a deep, confined aquifer in one of the bedrock formations beneath the County. In most places within Ottawa County, these two aquifer systems are separated by an extensive, thick clay layer. The upper, glacial aquifer is thickest and most areally extensive along the coastal margin of the County. It thins and becomes less extensive inland, essentially pinching out on the west side of the Grand River valley near the common borders of Allendale, Tallmadge and Georgetown townships.

This thick clay layer has the impact of magnifying and regionalizing the effects of pumping in the bedrock aquifer.

Local sand and gravel lenses in the glacial sediments, some isolated, others interconnected to varying degrees, regulate the degree of local connection between the shallow, glacial aquifer and the deep, bedrock aquifer. In general, however, the hydraulic connection between the upper and lower aquifers in Ottawa County is weak and spatially limited.

Phase-1 Study Limitations - Glacial Aquifer

As emphasized in the previous analyses, many of the glacial deposits in Ottawa County exhibit extreme heterogeneity laterally and vertically. As illustrated on page 41, site-scale heterogeneity and connectivity are not well represented in this Phase-1 study. Yet, it is likely that local heterogeneity and local subsurface features may be what dictates water use sustainability in the long run.

Local complexity and patterns of connectivity vary from site to site. Simulating site-scale heterogeneity is important, but much more difficult, due to data limitations and inherent data resolution issues. Data noise also becomes more limiting at the site scale. The challenge is to simulate site-scale heterogeneity in order to be able to address local groundwater quantity and quality issues.

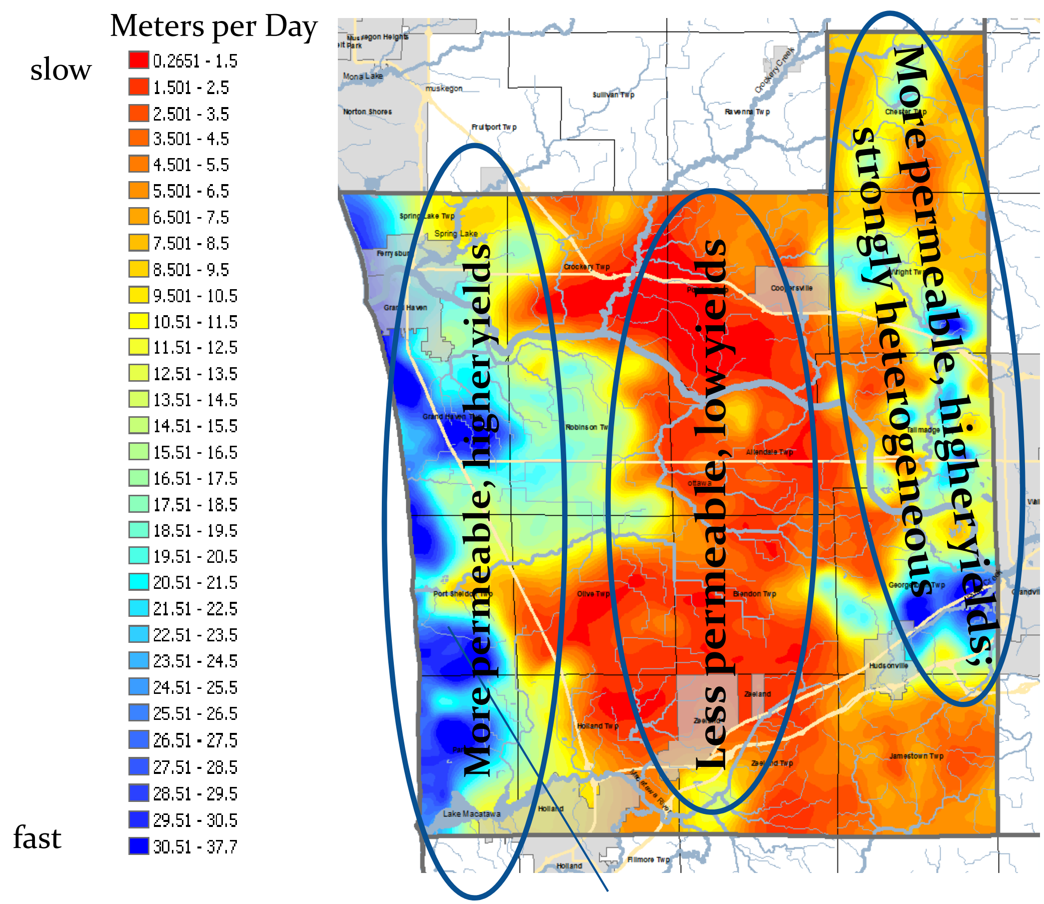
The results of this Phase-1 study have provided an excellent initial conceptual framework for the Phase-2 modeling effort. Much of the science in the Phase-2 effort will deal with appropriately simulating site-scale heterogeneity in the presence of noise from the unequal distribution of data points (Wellogic and observation wells).

Hydraulic Conductivity for the Glacial Aquifer

This slide shows a 2D map of interpolated hydraulic conductivity distribution of the glacial layer. The conductivity was estimated based on well lithology (State of Michigan, 2006) from the bottom of the wells to the static water levels or the land surface.

Note

- the low hydraulic conductivity in the central part of the County due to the presence of a thick confining layer containing mostly clay and silt;
- the higher conductivity along the west coast due to the presence of relatively homogeneous, lacustrine coarse sand;
- the higher hydraulic conductivity toward the east end of the County due to the presence of significant outwash material (shallow and/or buried) that exists along the river valley.



GROUNDWATER QUANTITY

In this section, we analyze the static water levels in both the glacial and bedrock aquifers and map groundwater recharge and discharge areas.

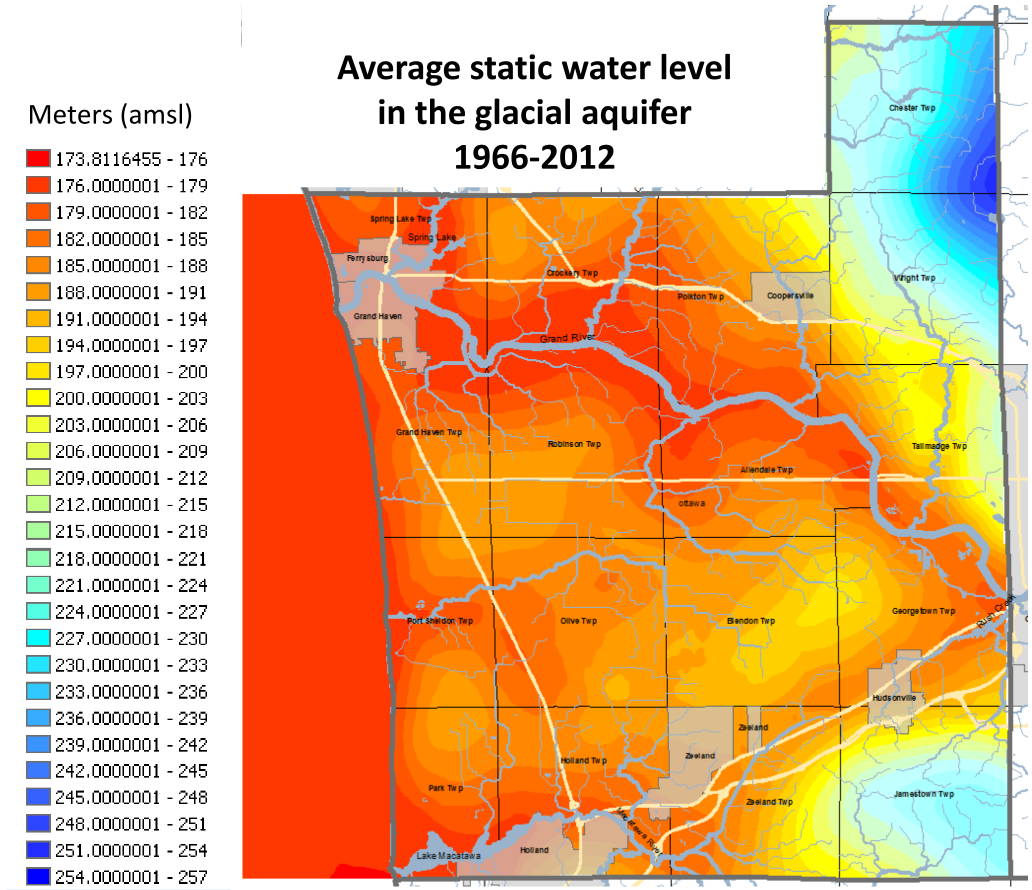
Static Water Levels – Glacial Aquifer

This slide shows a map of the long term average static water level in the glacial aquifer (1966-2012).

The blue areas are the high-elevation water table regions and the red areas are where the water table is at low elevations. The maximum water level difference is approximately 80 ft.

Note that the footprint of the rivers and creeks is clearly seen in the "valleys" of aquifer static water level surface.

The rivers and streams create not only a topographic lowland, but also a water depression – this is typical of master discharge areas.

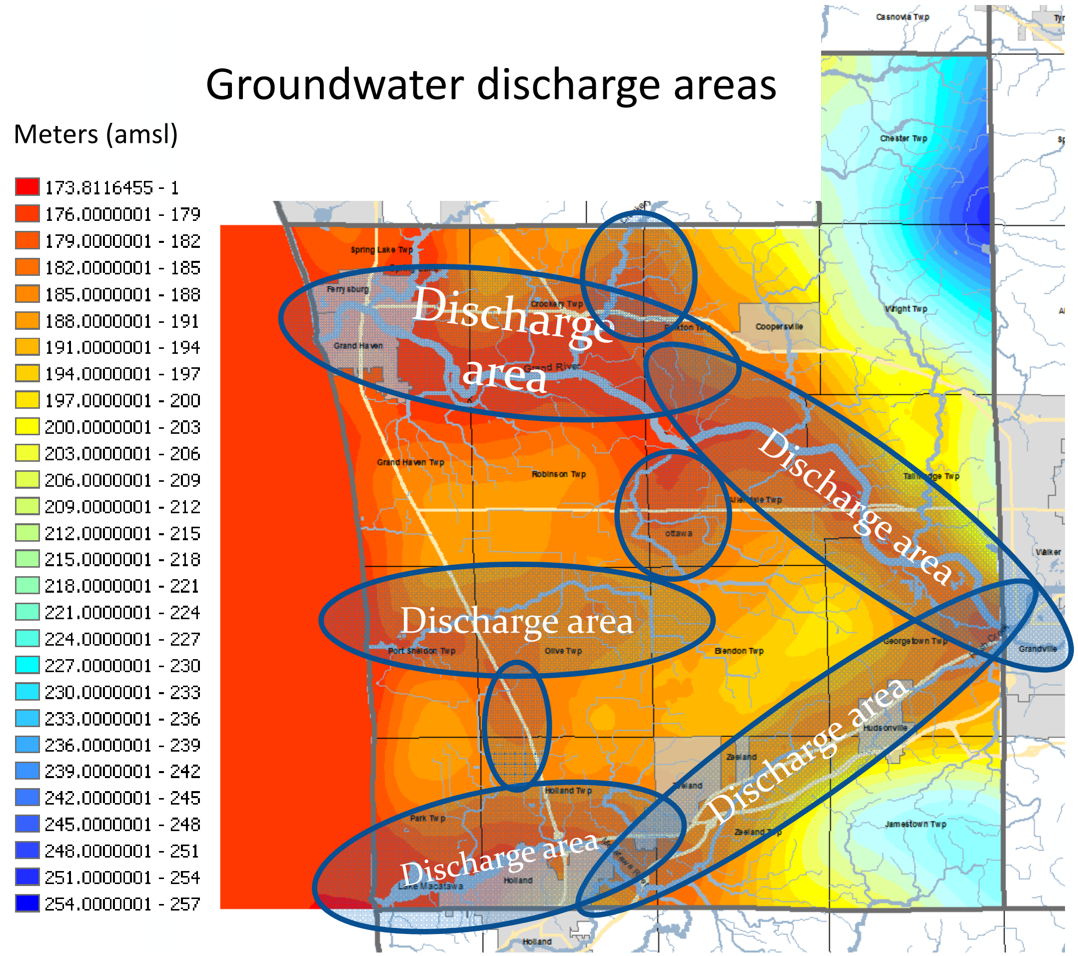


Glacial Aquifer Discharge Areas

The areas highlighted on this map are the SWL depressions – the major groundwater discharge areas in the County.

The rivers and streams can be visualized as lines of natural, continuous groundwater pumps.

The water extracted by these natural pumps is essentially the base flow to the rivers/streams.



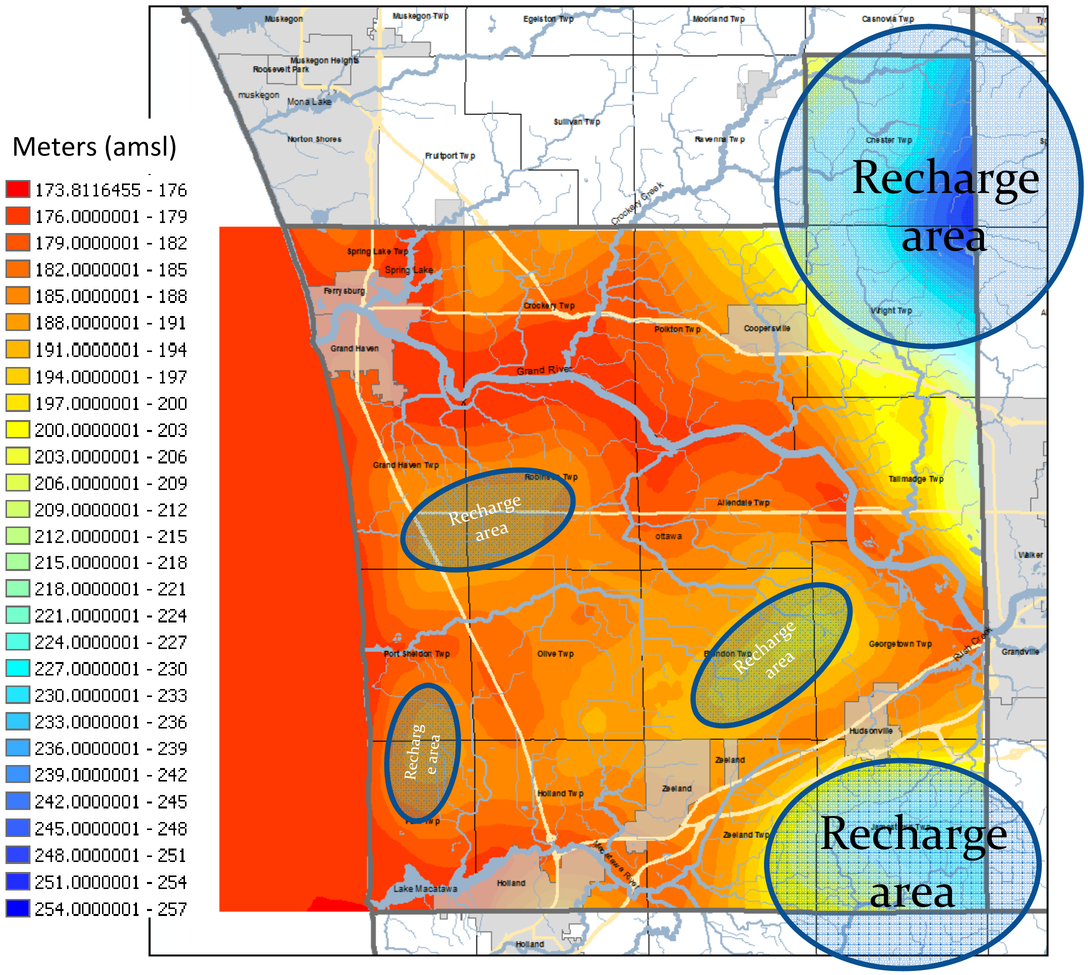
Glacial Aquifer Recharge Areas

This slide highlights the groundwater recharge areas within the County.

The master recharge areas for the unconfined glacial aquifer occur in Chester and Wright townships in northeastern Ottawa County, and in Jamestown Township in the southeast corner of the County.

Due to the heterogeneous nature and finer texture of the glacial sediments in both of these areas, recharge to the unconfined glacial aquifer is limited. Groundwater replenished by the recharge area in Chester and Wright townships discharges primarily to the Grand River limiting the recharge flow to the areas south of the Grand River where groundwater withdrawal needs are the greatest.

Groundwater replenished by the Jamestown Township recharge area discharges, in part, to the Macatawa River and Rush Creek. As a result, this recharge also does not appreciably help the central County region.



Bedrock Static Water Levels, Recharge and Discharge areas

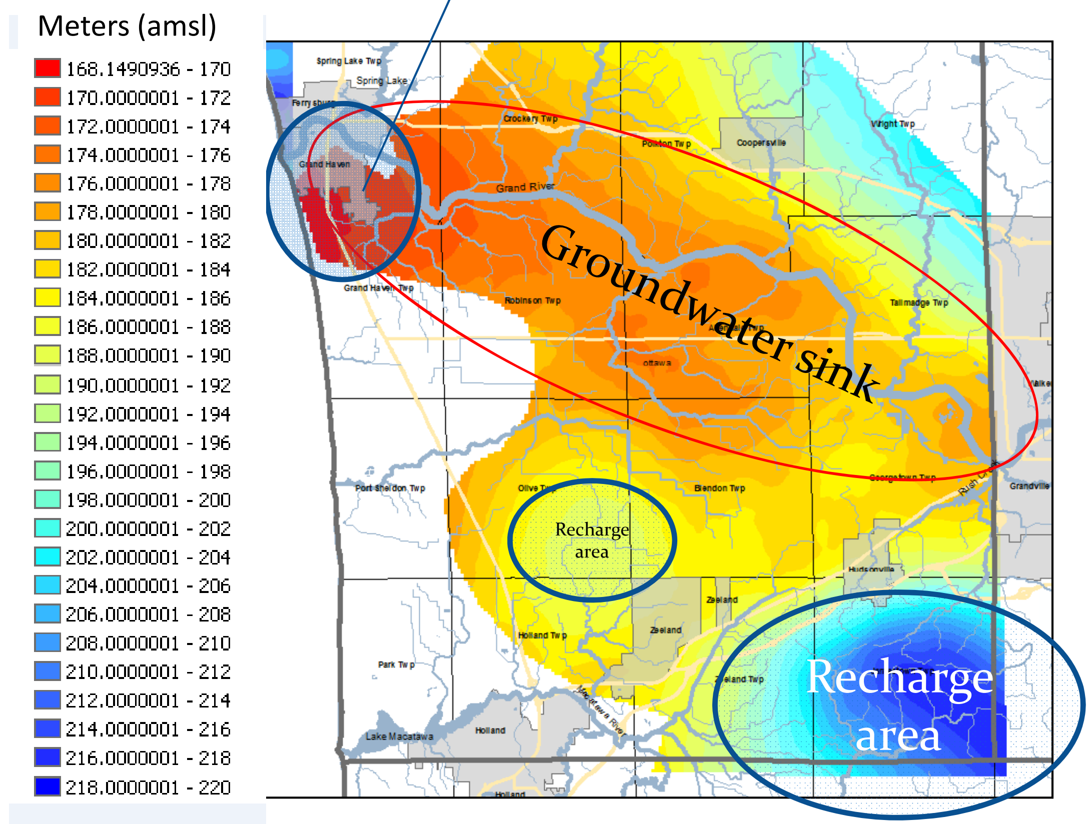
This slide shows the long term average static water level in the bedrock aquifer (1966-2012).

The blue areas are where the SWLs are at high elevations (groundwater recharge areas) and the red areas where SWLs are at low elevations (groundwater discharge areas). The maximum static water level difference is approximately 50 ft.

Note the footprint of the Grand River can be seen even in the SWL of the bedrock aquifer. The SWL in the area around the Grand River is generally the lowest serving as a groundwater sink.

The master recharge area for the confined, bedrock aquifer occurs in Jamestown Township in the southeast corner of the County. Due to the heterogeneous nature and finer texture of the glacial sediments in this area, however, recharge to the confined, bedrock aquifer from this landscape is limited. It is most likely that the majority of recharge to the Marshall Formation occurs outside of Ottawa County to the northeast, east and southeast.

Note the SWL predicted in this area is more uncertain, since there are very few bedrock wells in this area.



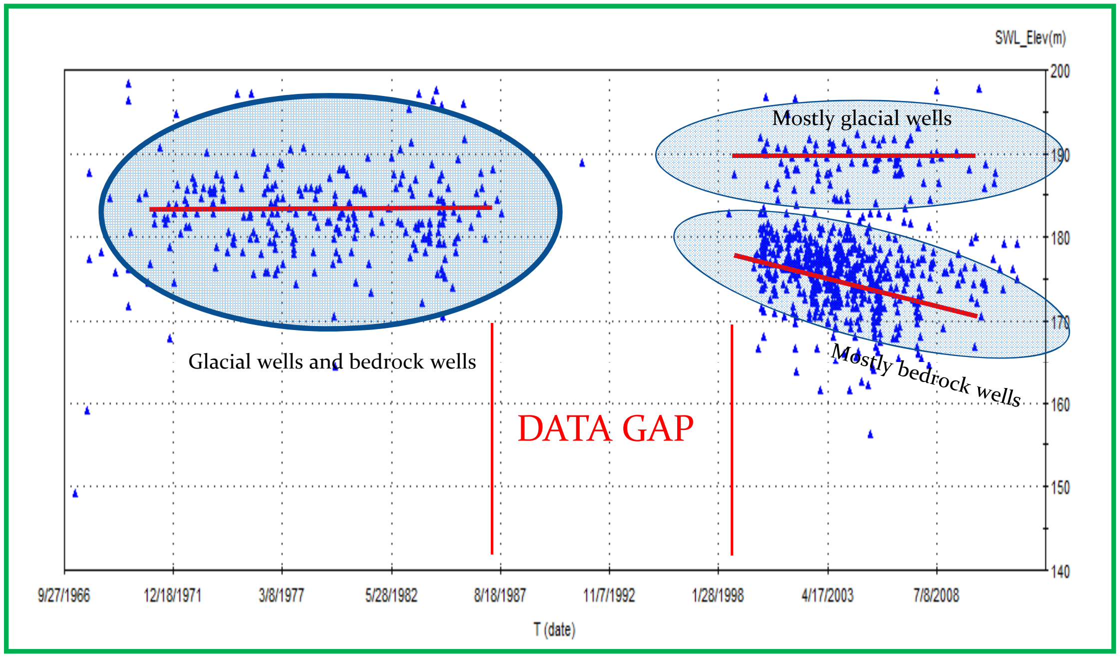
Temporal Trends in SWL

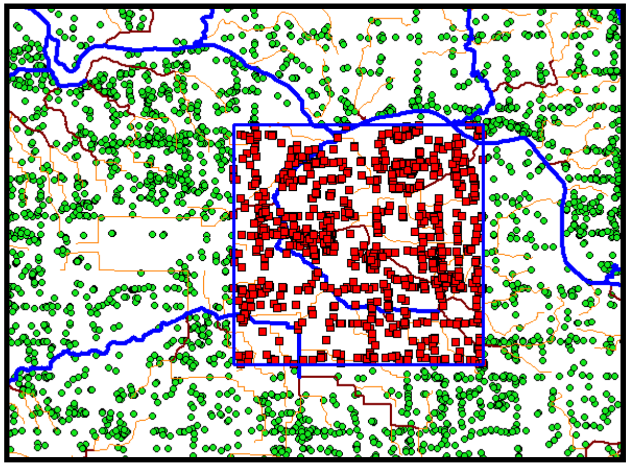
This slide shows the raw static water level data over time in wells in the Allendale township area (highlighted in red) from 1966 to 2012.

Note that since 1999, the head differences in the glacial wells and bedrock wells have increased due to increased pumping in the bedrock aquifer.

Also note that since 1999, the static water levels in the bedrock aquifer show a marked downward trend.

Such declines in the static water levels in the bedrock aquifer suggest that the current volume of groundwater withdrawals from the Marshall Sandstone may be unsustainable in the long run. Further study, however, will be necessary in order to forecast the sustainability of groundwater withdrawals from either the glacial or bedrock aquifer.



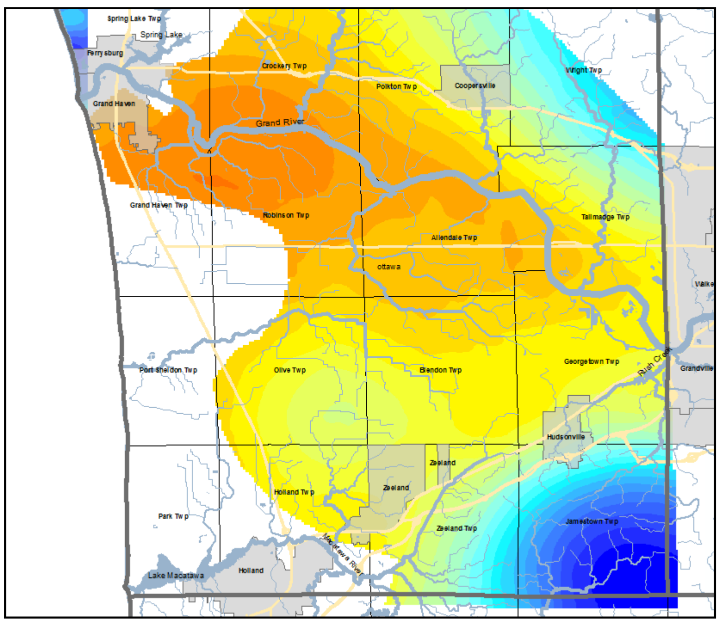


Temporal Trends in SWL within the Bedrock Aquifer

This slide compares the piezometric (pressure) head in the bedrock aquifer for two time periods: 1966-1999 and 2000-2012.

Note that since 1999, the static water levels in the bedrock aquifer have declined in parts of Ottawa County. The decline in Allendale Township and north-central Blendon Township appears to be one of the most significant SWL changes in the County.

Such declines suggest that the current volume of groundwater withdrawals from the Marshall Sandstone may be unsustainable in the long run. Further study, however, will be necessary in order to forecast the sustainability of groundwater withdrawals from either aquifer.



1966-1999

Meters (amsl)

- 168.1490936 - 170
- 170.0000001 - 172
- 172.0000001 - 174
- 174.0000001 - 176
- 176.0000001 - 178
- 178.0000001 - 180
- 180.0000001 - 182
- 182.0000001 - 184
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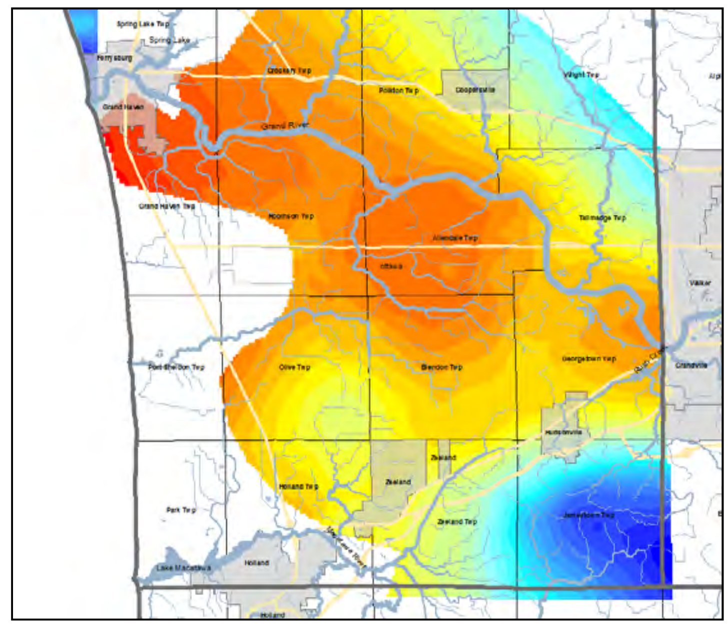
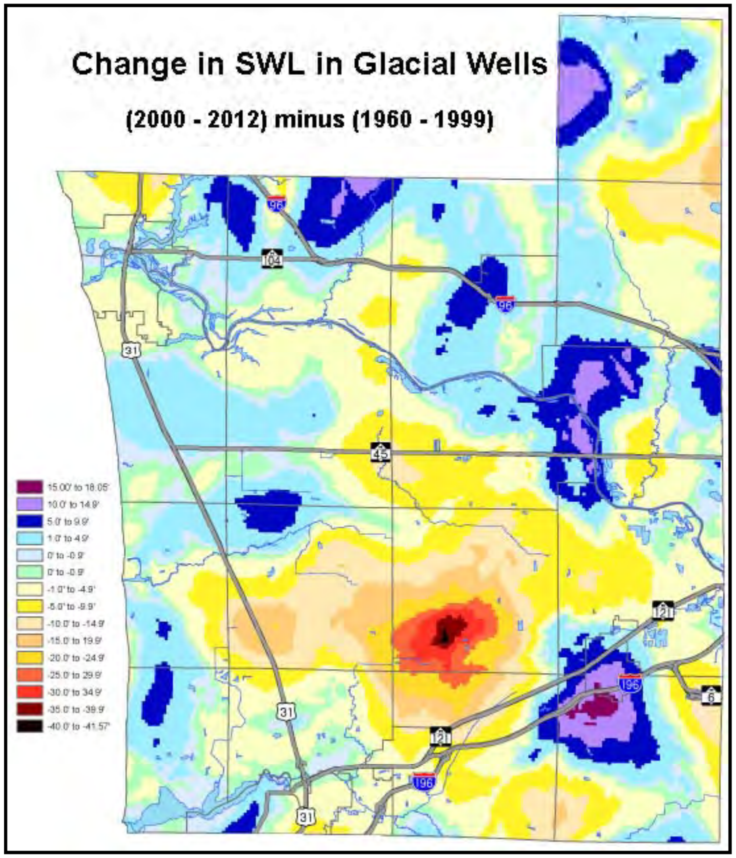
- 218.0000001 - 220

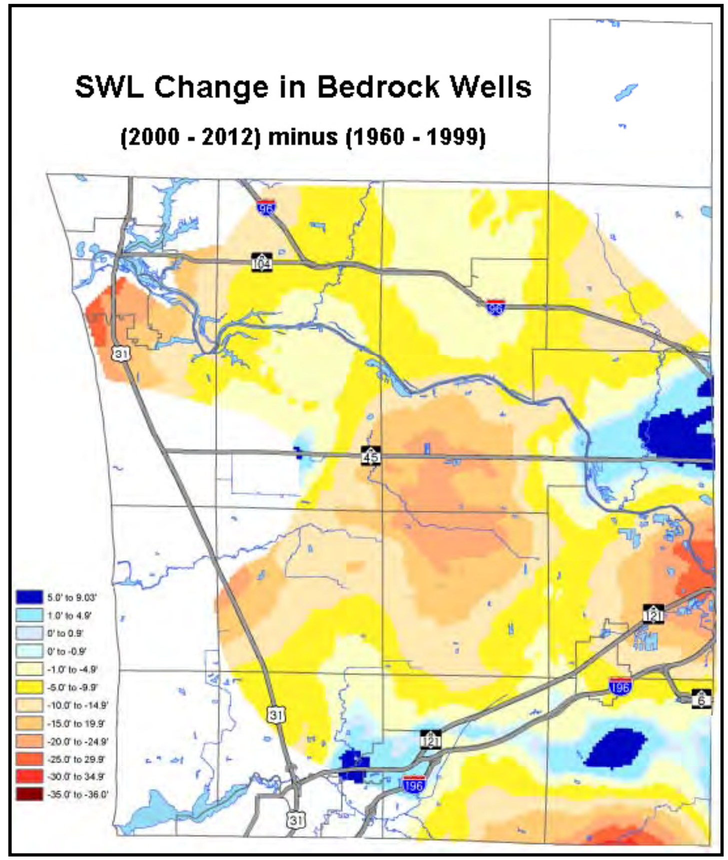


2000-2012

Temporal SWL Trends Within Both Aquifers

Mapping temporal trends in static water levels is problematic, except in areas with lots of data more or less evenly spread across the time intervals of interest. Many parts of Ottawa County lack such data. Interpolating across each of two point data sets with notably different spatial distributions of wells can cause significant spatial variation in the estimation uncertainty. Numerically differencing these two surfaces to calculate spatial change (shown below) can cause large errors in the estimated change, especially in regions were one data set had many fewer sample points than the other. However, these maps provide a generalized illustration of the areas of static water level decline."





Phase-1 Study Limitations – SWL Temporal Trends

Temporal trends in static water levels are difficult to determine, except in areas with a very high data density (which many parts of Ottawa County lack). A spatially equal data distribution may no longer exist when the well data are subdivided into time segments . Interpolating across each of two point data sets with notably different spatial distributions of sample points can cause significant spatial variation in the estimation uncertainty. Numerically differencing these two surfaces to calculate spatial change can cause large errors in the estimated change, especially in regions were one data set had many fewer sample points than the other.

There is, however, a high confidence in the conclusion that the static water levels in Allendale Township have declined significantly, because there is lots of data in that area. In other parts of the County, the data distribution is more problematic when segmented into two age cohorts. In the Phase-2 study, calibrated local simulation models will be used to predict the static water level trends in different local areas; focused monitoring in potential water-shortage hotpots is recommended and planned. Long-term SWL monitoring in each local modeling area is recommended. For the Phase-2 project, it is recommended that multiple long-term monitoring wells be installed to support this recommendation.

Phase-1 Study Limitations - Bedrock Aquifer

Compared to the glacial deposits in Ottawa County, the Marshall Sandstone aquifer is much more homogeneous both laterally and vertically. Nonetheless, based on the static water level distribution in the bedrock aquifer system in Ottawa County, it appears that the Marshall aquifer may not be as permeable as was initially thought. If the transmissivity of the Marshall Formation beneath Ottawa County is relatively small, local features , processes and recharge zones will exert a greater control on the groundwater flow in the aquifer and, ultimately, will also control the brine upwelling dynamics.

The Phase-1 study was not designed to address this issue, but the monitoring wells, aquifer test and regional flow model proposed for Phase-2 will go a long way to determining the effect of these relatively local features , processes and recharge zones in the Marshall aquifer.

The Groundwater “Bank Account"

Even in a county next door to Lake Michigan, strong, persistent pumping can locally lower groundwater levels in isolated or overlapping “cones of depression”.

Groundwater stored in aquifers can be compared to money kept in a bank account. If you withdraw money at a faster rate than you deposit new money, you will eventually start having shortfall problems. Cumulative withdrawals that remove groundwater faster than it is replenished by recharge over the long-term can cause hydrologic shortfalls. The long-term sustainability of any groundwater supply is dependent on keeping the water “account” in balance. Removing groundwater at a pace that excessively depletes the account can cause numerous negative effects on local water resources.

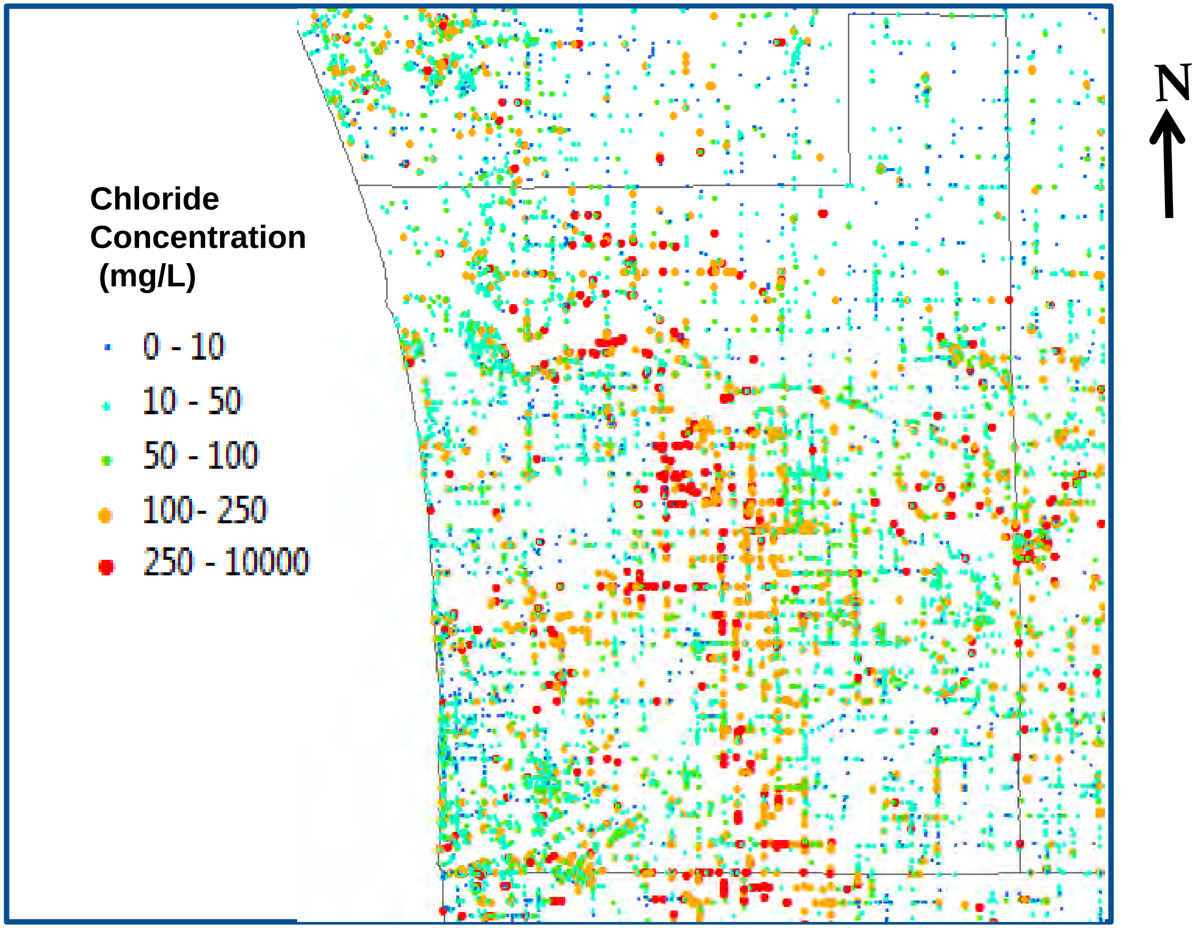
GROUNDWATER QUALITY

In this section we map and analyze the groundwater quality in Ottawa County, focusing on salinity and nitrate contamination issues.

Chloride Concentrations (1980-2010)

This slide shows the chloride concentrations observed in water samples from wells throughout the County tested from 1980 through 2010.

Note that the chloride concentrations in many wells are significantly elevated (at or above the recommended limit of 250 mg/l). The background concentrations in the state are 10-30 mg/l.



USEPA Secondary drinking water Regulation for Chloride; Recommended Level is 250 mg/l. Maximum values were used when multiple samples exist in one well.

Irrigation Water Quality Criteria

High concentrations of chloride make groundwater unfit for human consumption and for many agricultural uses and are detrimental to the environment. When salt water is introduced to areas unadjusted to saline conditions, it damages sensitive crops, causes habitat losses, adversely impacts groundwater dependent ecosystems, and contaminates drinking water.

The drinking water recommended standard for chloride is 250 mg/l.

The table below shows irrigation water quality criteria.

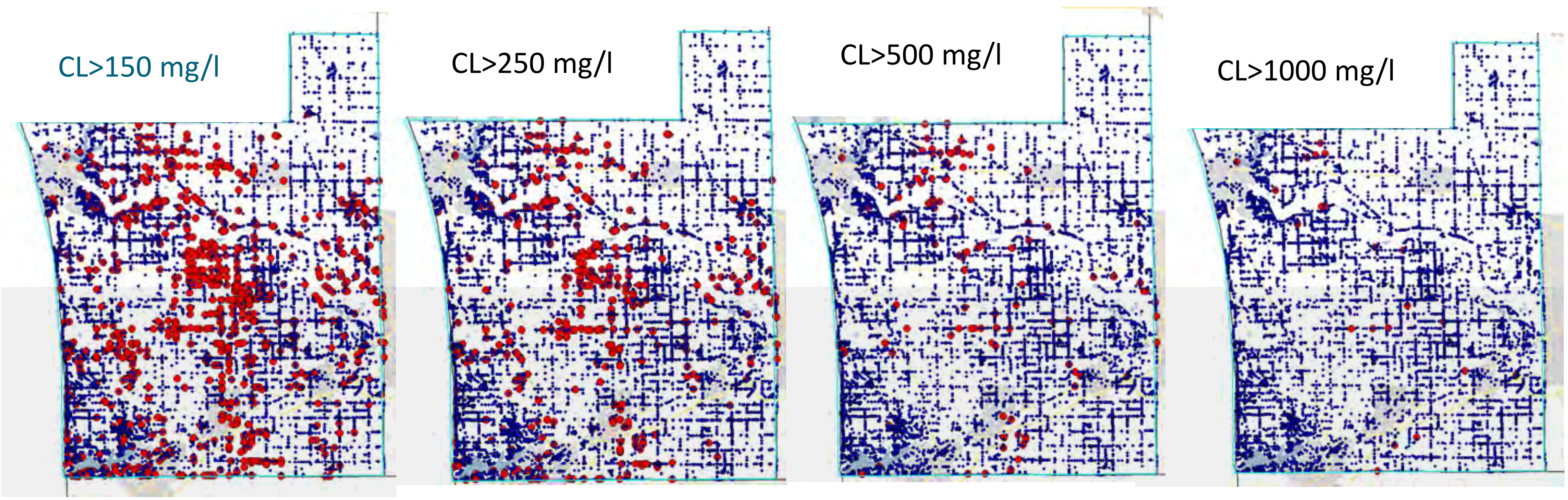
Chloride (mg/L or ppm)	Effect on crops	Susceptible plants
below 70	Safe for most plants	Rhododendron, azalea, blueberry, dry beans
70–140	Sensitive plants show injury	Onion, mint, carrot, lettuce, pepper, grape, raspberry
140–350	Moderately sensitive plants show injury	Potato, alfalfa, sudangrass, squash, wheat, sorghum, corn, tomato
above 350	Can cause severe problems	Sugarbeet, barley, asparagus, cauliflower

Source: Adapted from Ayers and Westcot (1985).

Chloride Concentrations Above Select Threshold Values

This slide shows the chloride concentrations in wells higher than selected threshold values in the County.

Note a significant number of the samples (especially in Crockery township) show very high chloride concentrations, exceeding 500 mg/l.



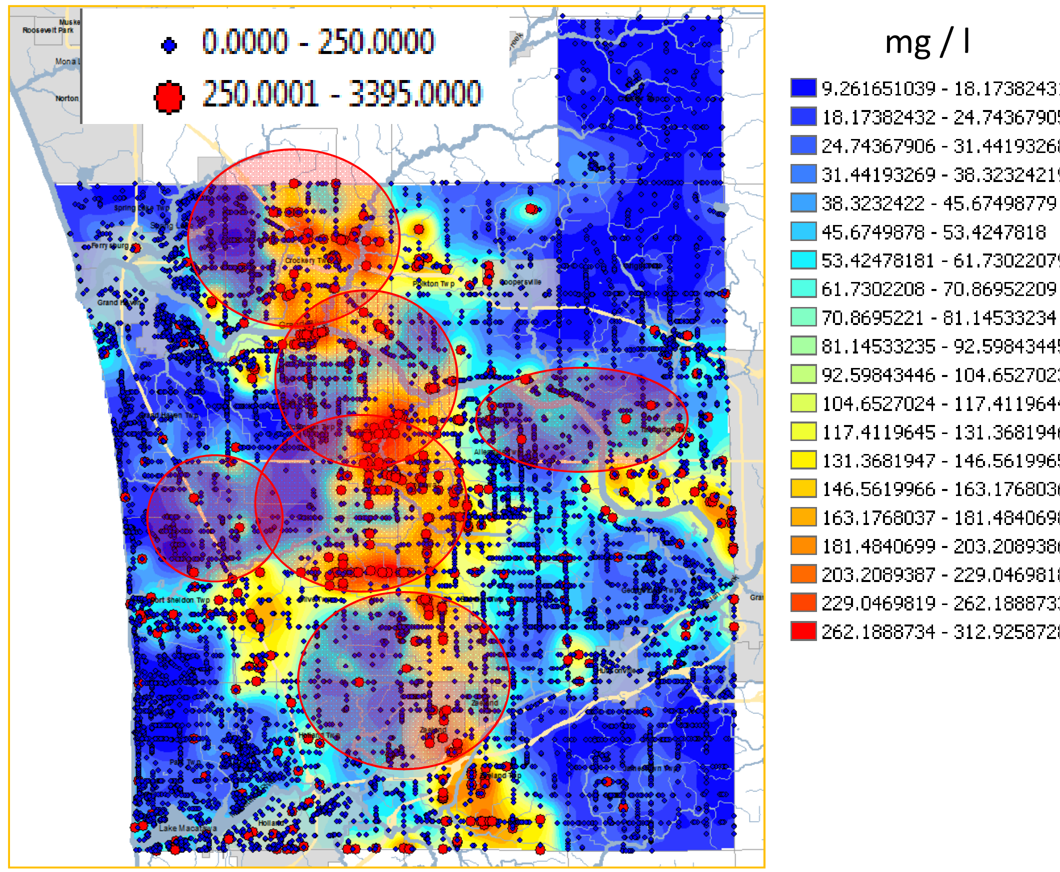
Areas with Significantly Elevated Chloride Concentrations in Groundwater

This slide shows an overlay of scattered chloride concentration values (point symbols) and their moving window average (continuous color backdrop).

This map is useful in identifying the broad trends and patterns in the spatial distribution of chloride concentrations.

Note the chloride concentrations in the following areas are significantly elevated (>100 mg/L):

1. Crockery Township and northern end of Robinson Township
2. West Allendale Township and east Robinson Twp.
3. Northern part of Blendon Township
4. Northeastern corner of Olive Township
5. Southern Zeeland Township
6. Southern Tallmadge Township (north side of the Grand River corridor).



Phase-1 Study Limitations – Chloride Concentration Mapping

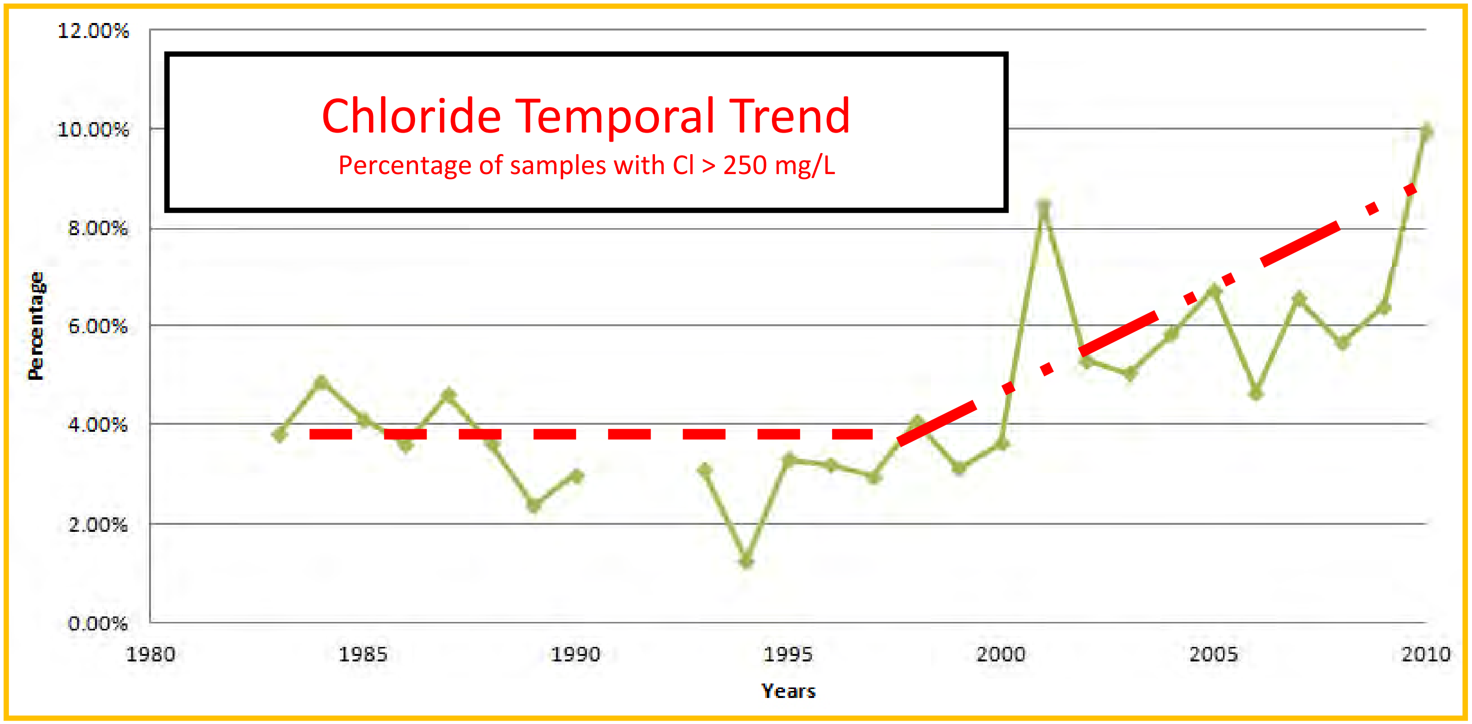
The characterization of the chloride concentrations in water well samples in the Phase-1 study presented largely 2-D spatial characterization. In reality, of course, there is a strong 3-D component to this issue, as illustrated by the well depth vs. chloride concentration plot. Knowing the vertical location of the brine "plumes" is a requirement before we can predict how groundwater with high levels of sodium chloride moves , mixes, or upwells in response to both natural and human-use stresses. The data requirements increase exponentially when a 3-D interpolation is needed. Doing so will require a significant sampling effort, focused especially in the key local hotspot areas.

Temporal Trends in Chloride Concentrations

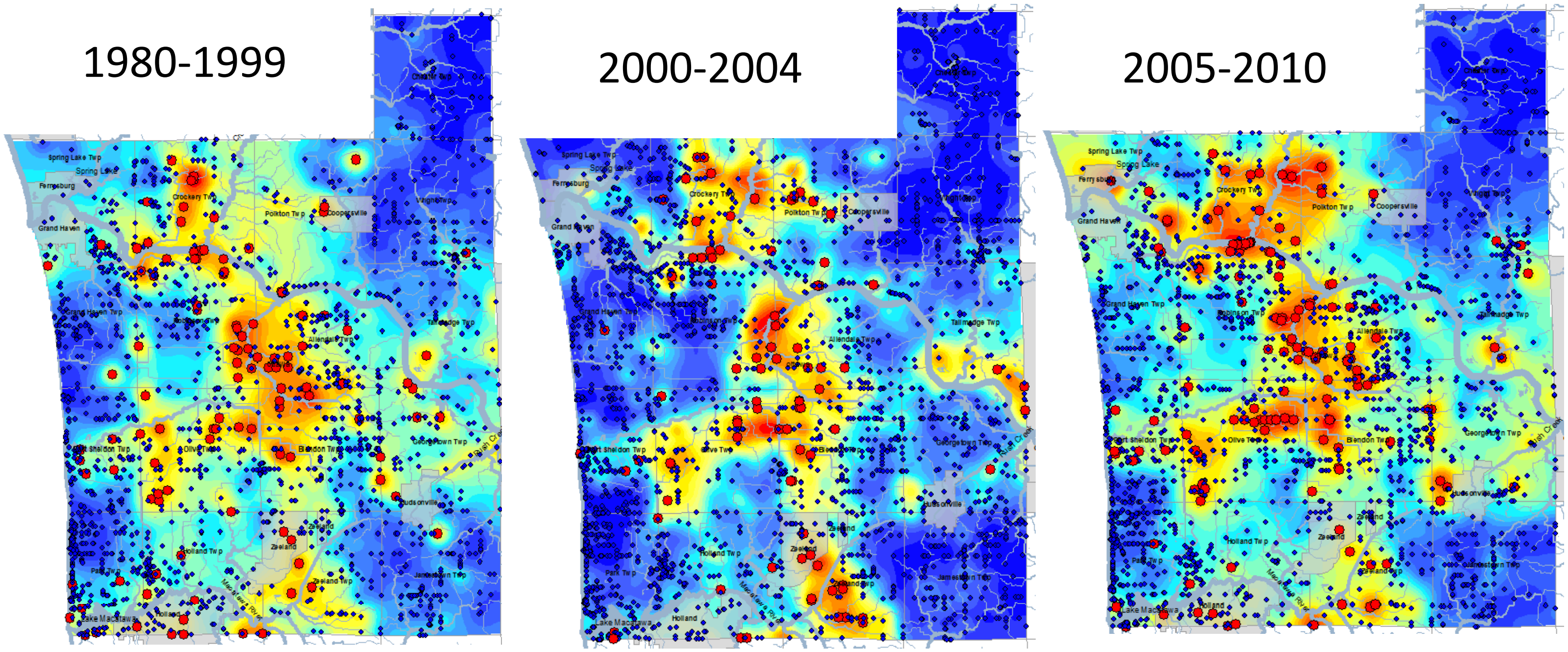
This slide shows the percentage of water well samples in Ottawa County with concentrations higher than the drinking water standard.

Note that groundwater in Ottawa County is becoming more saline as shown by increasing chloride concentrations through time. Prior to 2000, generally less than 4% of all the groundwater quality samples in Ottawa County showed chloride concentrations above 250 mg/l. In the 2000 – 2010 period, 6 – 10% of the samples showed chloride concentrations above 250 mg/l.

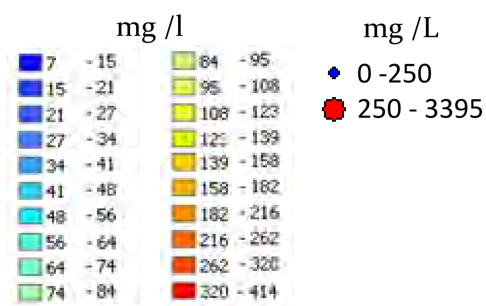
The percentage of drinking water exceedances at a more local scale or in a particular township can be significantly higher.



Spatial/Temporal Trends of Chloride Concentrations in Groundwater Samples



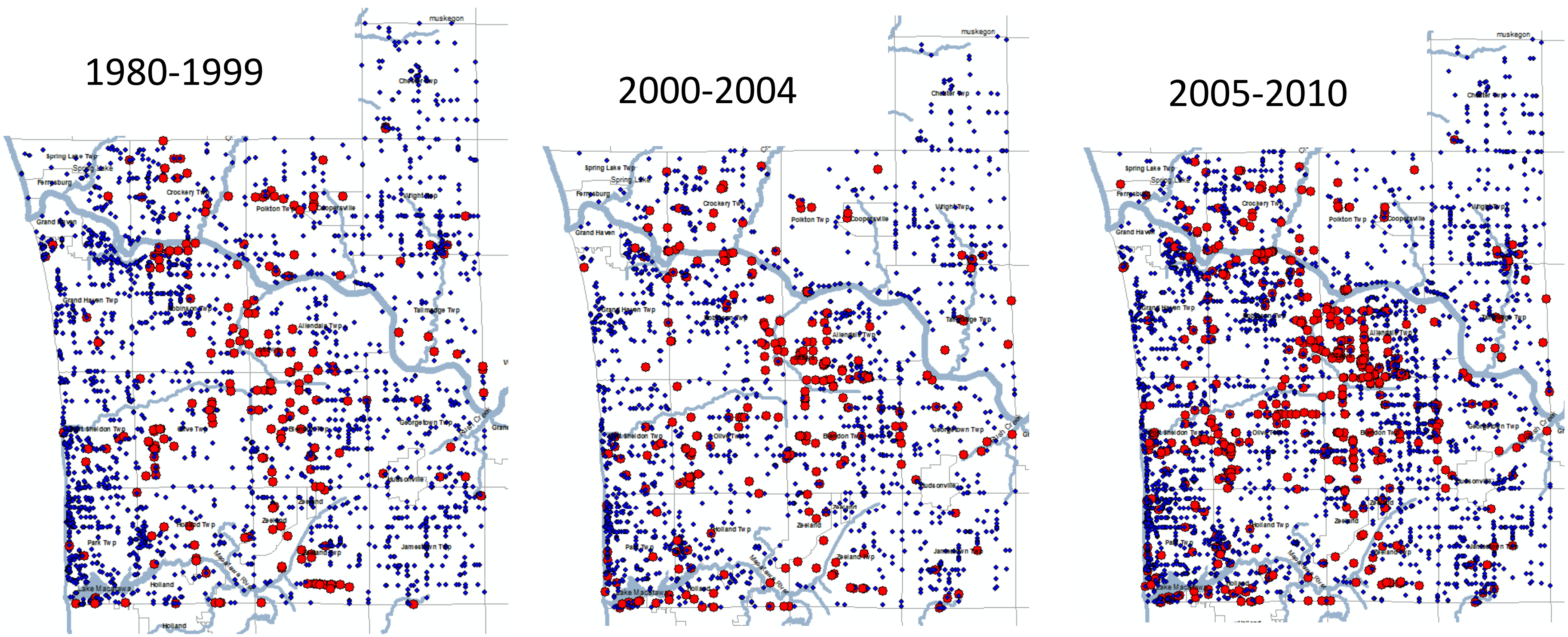
Recommended Safe Drinking Water Standard: < 250 mg / l



This slide shows a map overlay of scattered CL concentration values and their moving window average for three time periods. Note that the areas with significantly elevated concentrations are expanding over time. The red dots are wells with concentrations higher than 250 mg/l.

Spatial/Temporal Trends of Chloride Concentrations > 150 mg/l in Groundwater Samples

This slide highlights wells with chloride concentrations higher than 150 mg/l in three time periods. Note that the number of wells with significantly elevated concentrations has increased over time.



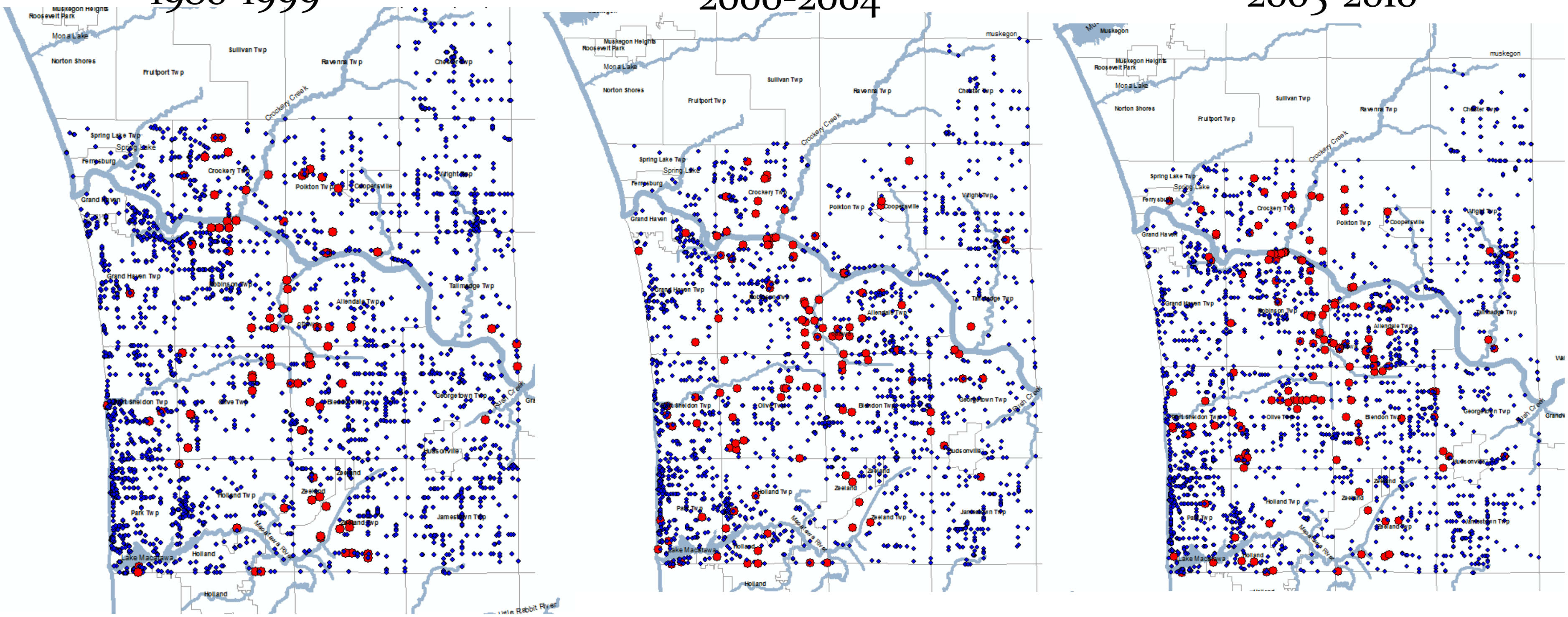
RED>150 mg/l
Blue<150 mg/l

Chloride >150 mg/l

Spatial/Temporal Trends of Chloride Concentrations >250 mg/l in Groundwater Samples

This slide highlights wells with chloride concentrations higher than 250 mg/l in three different time periods. Note that the number of wells with concentrations exceeding the drinking water standard has increased over time.

1980-1999 2000-2004 2005-2010



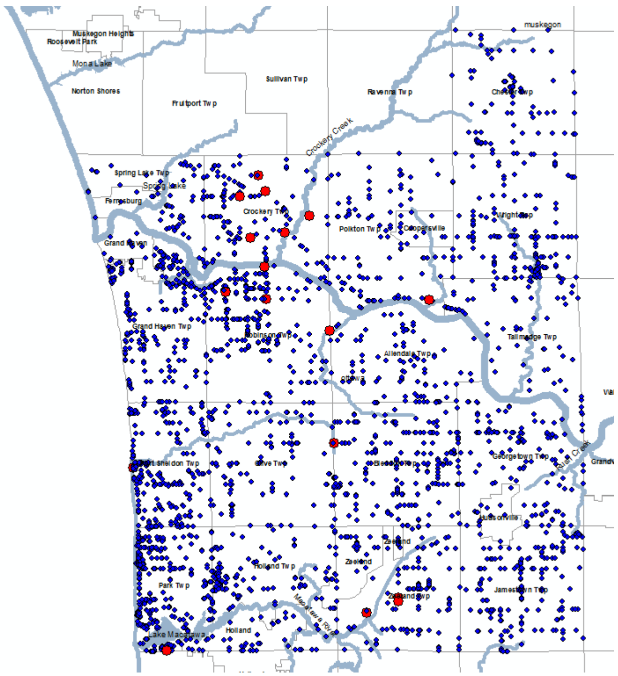
RED>250 mg/l
Blue<250 mg/l

Chloride> 250 mg/l

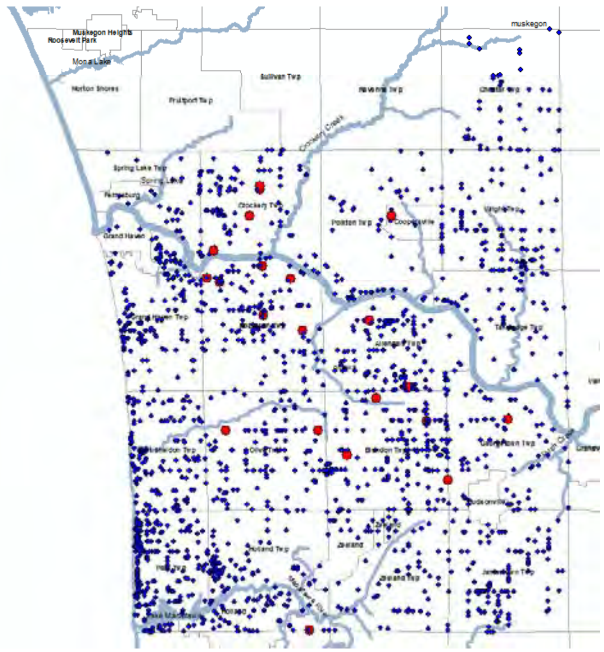
Spatial/Temporal Trends of Chloride Concentrations >500 mg/l in Groundwater Samples

This slide highlights wells with chloride concentrations higher than 500 mg/l in three time periods. Note that the number of wells with CL concentrations higher than 500 mg/l has increased over time.

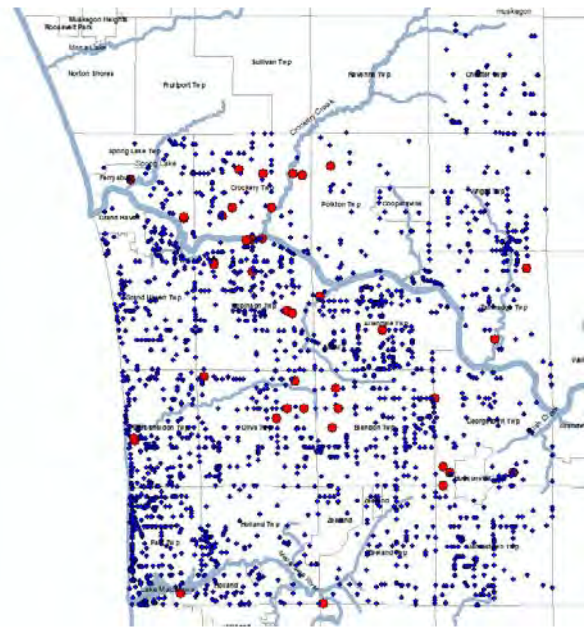
1980-1999



2000-2004



2005-2010



RED>500 mg/l
Blue<500 mg/l

Chloride> 500 mg/l

Phase-1 Study Limitations – Chloride Concentration Trend Mapping

The Phase-1 characterization of chloride concentrations in water well samples only reflects county-wide statistics. Local temporal trends can be significantly different from the large area trends. The rate of change in chloride concentrations varies from one area to another depending on local heterogeneity, hydrogeological features, and source concentrations.

Focused chloride monitoring in areas in and around the identified hotspot is required and is critically important to understanding the temporal dynamics of this issue. In Phase-2, one long-term chloride-monitoring well is recommended in each focused study area. It is recommended that a calibrated water quality model be developed for each hotspot area in order to predict long-term chloride trends under different water use/management scenarios. The predictive capability of these models depends on whether the chloride "plumes" can be mapped vertically and horizontally.

What is the Cause of Chloride Contamination in the Groundwater of Ottawa County?

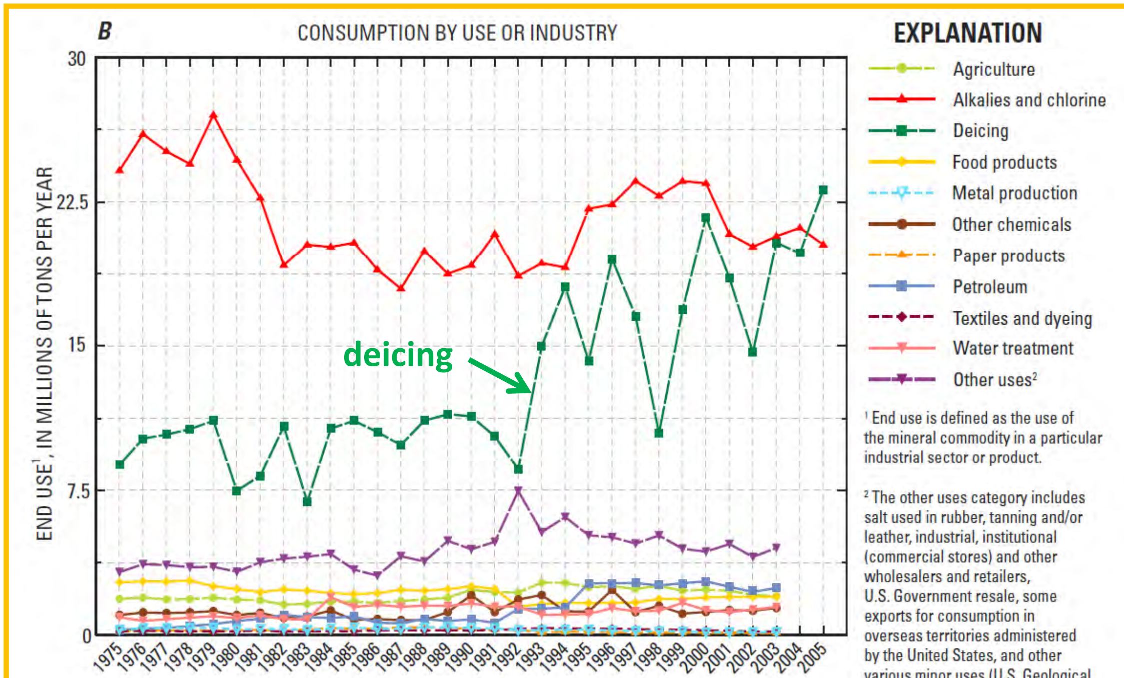
Highway Deicing?

One possible source is contamination caused surface activities, particularly the use of road salt in highway deicing that has increased significantly over the past 20 years.

The process of road salting, which involves the application of large quantities of salt to the roads to deice them, has negative effects on the ground water systems. Salt from the highway is introduced into the groundwater through a number of ways:

- When runoff occurs from highways, flows are sometimes carried to ditches and unlined channels through which the water infiltrates into the soil and eventually into the groundwater.
- Also, when snow is plowed together with the salt, the pile that is accumulated on the roadside melts during warmer weather. The meltwater that results contains dissolved salt which can also infiltrate to groundwater.

Salt Consumption in the US by Use or Industry



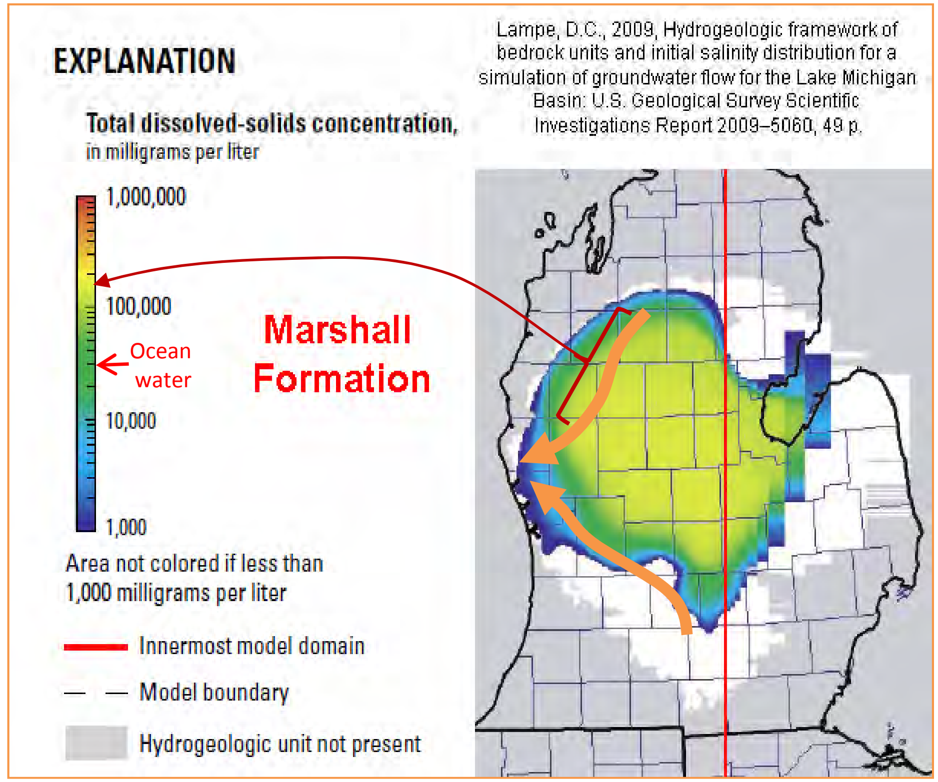
The Salt Institute

Natural Brine Upwelling

Another possible source is natural brine upwelling from deep geological formations.

A number of papers and reports have documented that the state's fresh groundwater sits on a massive pool of highly concentrated brine having high concentrations of Cl, Ca, and Br, (e.g., Lane, 1899; Case, 1945; Cook, 1914; Wilson and Long, 1993a;b; Hoaglund et al., 1994; Clayton et al., 1966; Long et al., 1988; Meissner et al., 1996; Wahrer et al, Hoaglund et al., 1996; Ging et al., 1996).

Saline water actually underlies the entire Lower Peninsula of Michigan at various depths (Mandle and Westjohn, 1989; Westjohn and Weaver, 1998).



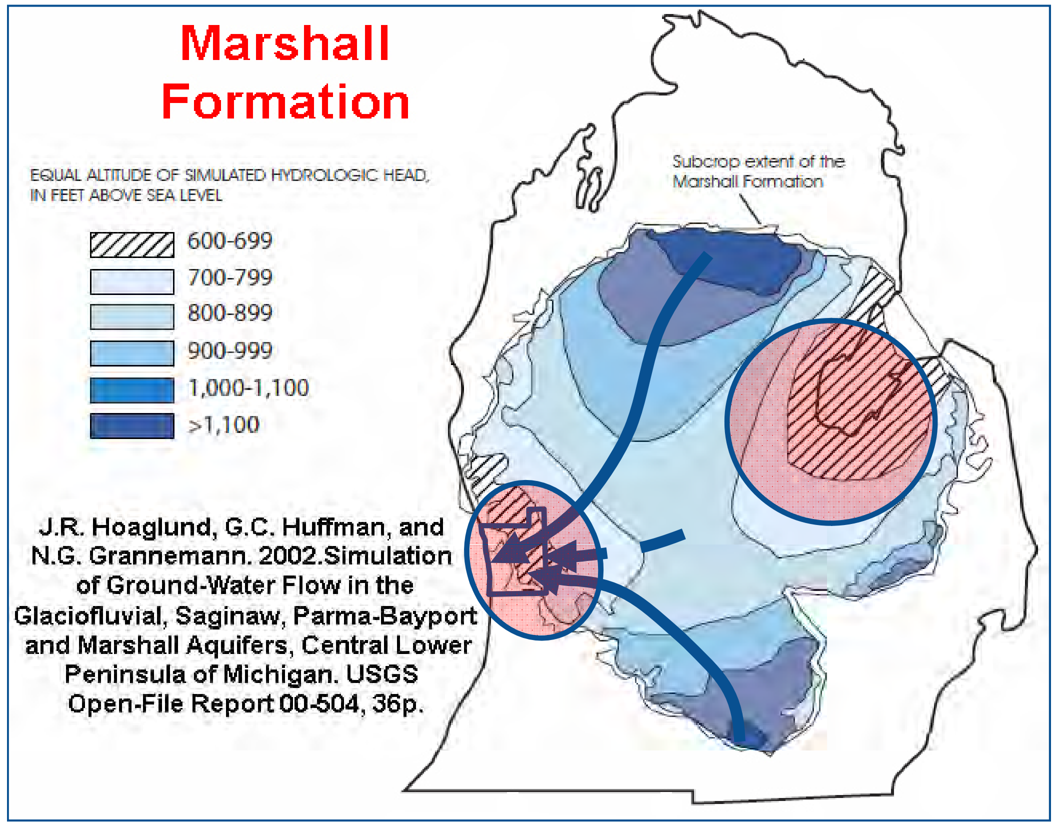
Michigan's fresh groundwater sits on a massive pool of brine [Figures 1 and 2, Hoaglund et al, 2002; Lampe, 2009].

Basin-scale Groundwater Dynamics

Basin-scale hydrologic research also suggests that the naturally occurring saline water in the deep formations is inching upward toward the surface, particularly in the lowland areas, or the regional groundwater discharge areas of the state (*e.g.*, Mandle and Westjohn, 1989; Westjohn et al., 1994; Westjohn and Weaver, 1996a, b, c; Holtschlag, 1996, 1997; Ging et al., 1996; Meissner et al., 1996; Wahrer et al., 1996; Hoaglund et al., 2002b).

Computer simulation showed that the Grand River flowing across the Lower Peninsula created both a topographic and water table depression. Model simulations inferred that these areas are likely to be basin-scale groundwater discharge regions, because of the presence of saline groundwater near the land surface in these lowlands.

Steady-state simulations of regional groundwater flow suggest that the presence of saline groundwater in the regional discharge areas results from the upwelling of deep saline groundwater within the regional groundwater flow system. (See also W90-08400) (Mandle and Westjohn, 1989).

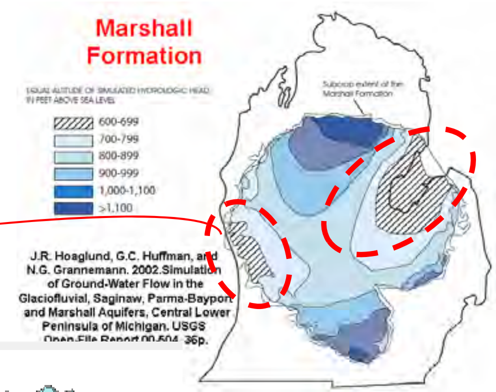


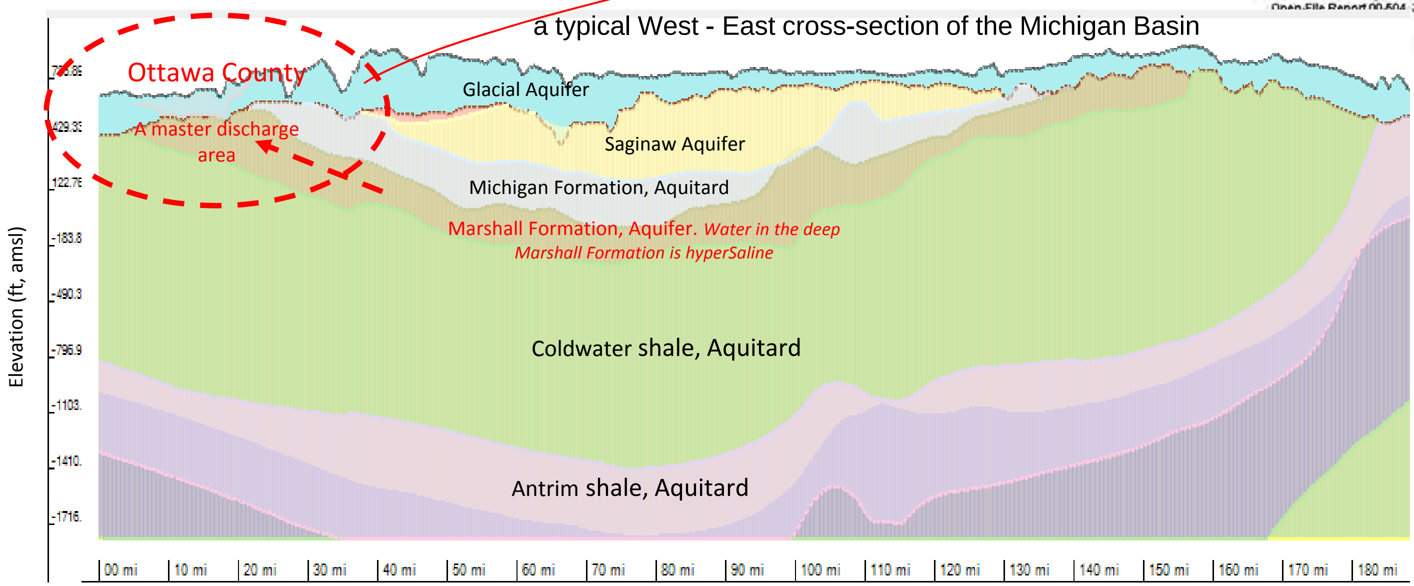
Ottawa County is part of the western master discharge zone for the Marshall Formation

Master Discharge Areas

The exchange of water and solutes between the Michigan Basin and the large, freshwater lakes of the Great Lakes region **gives rise to one of the highest known salinity gradients on earth** (Fig. 4.7 in Hanor, 1979).

Mandle and Westjohn (1989) stressed that availability of adequate amounts of potable groundwater is already limited in many areas of the state by the presence of saline groundwater (dissolved solids concentration of 1,000 to 100,000 mg/l).



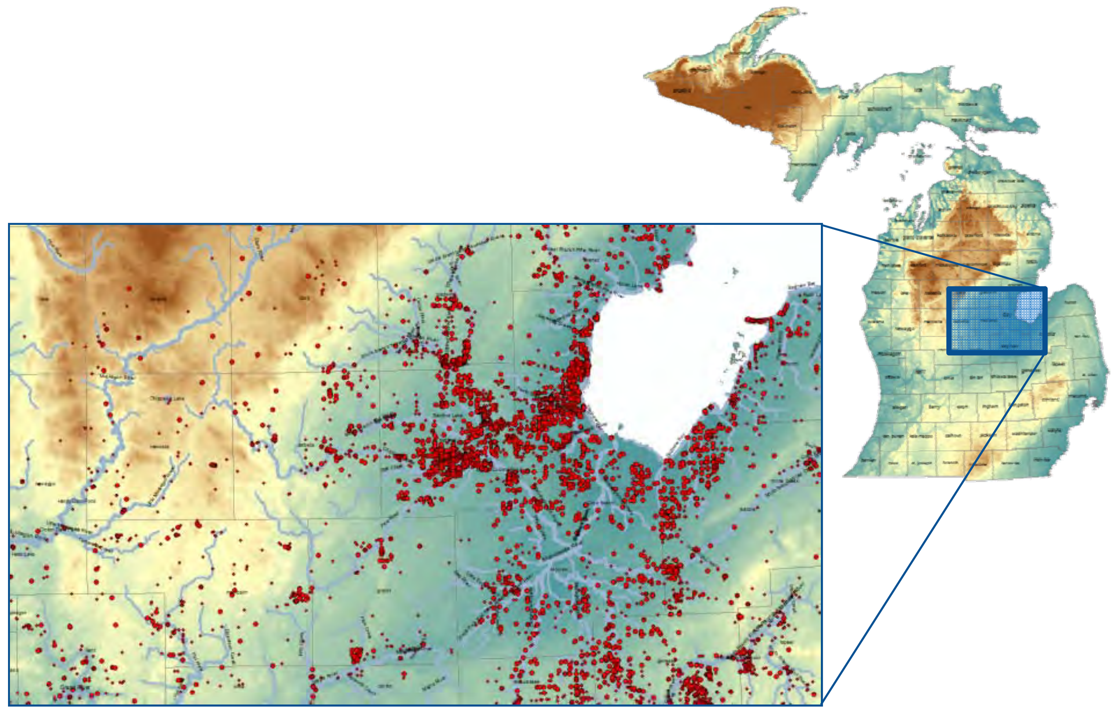


Saginaw Bay and Ottawa County are the two master discharge areas for the Marshall Formation. Saline groundwater in the deep formations is inching upward toward the top of the Marshall bedrock aquifer.

Chloride Contamination in the Saginaw Lowlands

Long and his group were among the first to show that the source for the high salinity waters in the Saginaw Lowlands was the result of upwelling brines (*e.g.*, Long, et al., 1988; Takas, et al., 1988). Documentation was made though geochemical and isotopic analyses, geochemical modeling and an interpretation of groundwater flow.

Albert (2001) and Kost et al. (2007) documented the presence of a number of salt springs occurring on mineral soil saturated by sodium- and chloride-laden groundwater from natural brine aquifers. These inland salt marshes were all found along the Grand River and Maple River valleys, around Saginaw Bay, and in other lowlands or groundwater discharge areas, where glacial drift is thin enough to permit brine from deep, saline, bedrock aquifers to remain concentrated and emerge at discrete points.



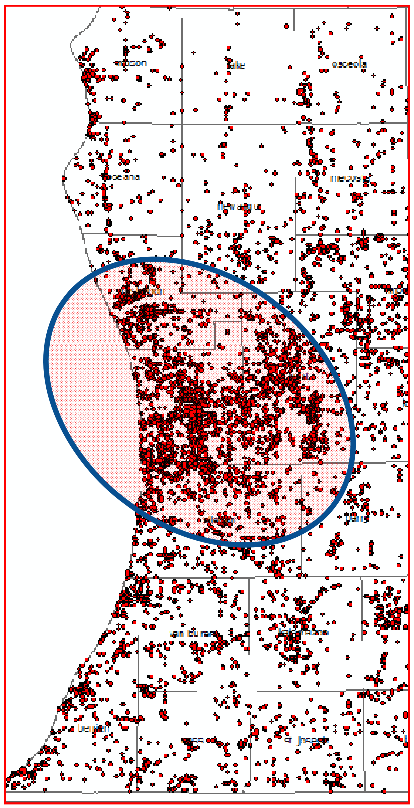
Wells in Saginaw Lowlands with CL concentrations higher than 250 mg/l

Is the Chloride Contamination in Ottawa County also Caused by Brine Upwelling?

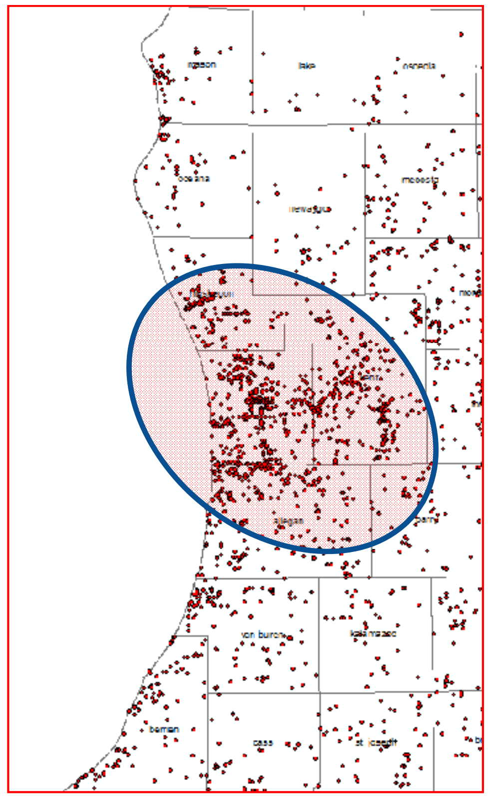
We address this question by systematically investigating the chloride concentration patterns, with particular emphasis on their correlation with groundwater flow.

Regional Context

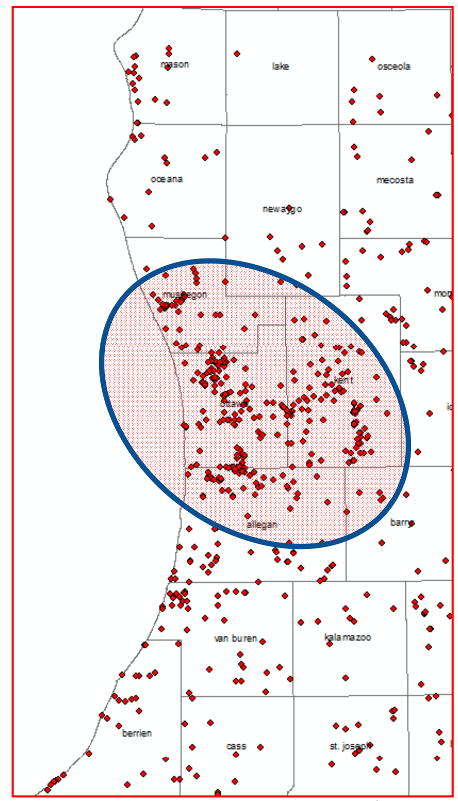
First we visualize chloride contamination in Ottawa County within a regional context. This slide shows the Chloride concentration exceedances of various threshold values in western Michigan's groundwater. The results clearly show that, among all the counties in west Michigan, the chloride contamination in Ottawa County stands out. The number of wells with elevated chloride concentrations in Ottawa County and its immediate vicinity (SW Muskegon, N. Allegan, W. Kent) is significantly higher than elsewhere in western Michigan.



CL>100 mg/l



CL>250 mg/l



CL>500 mg/l

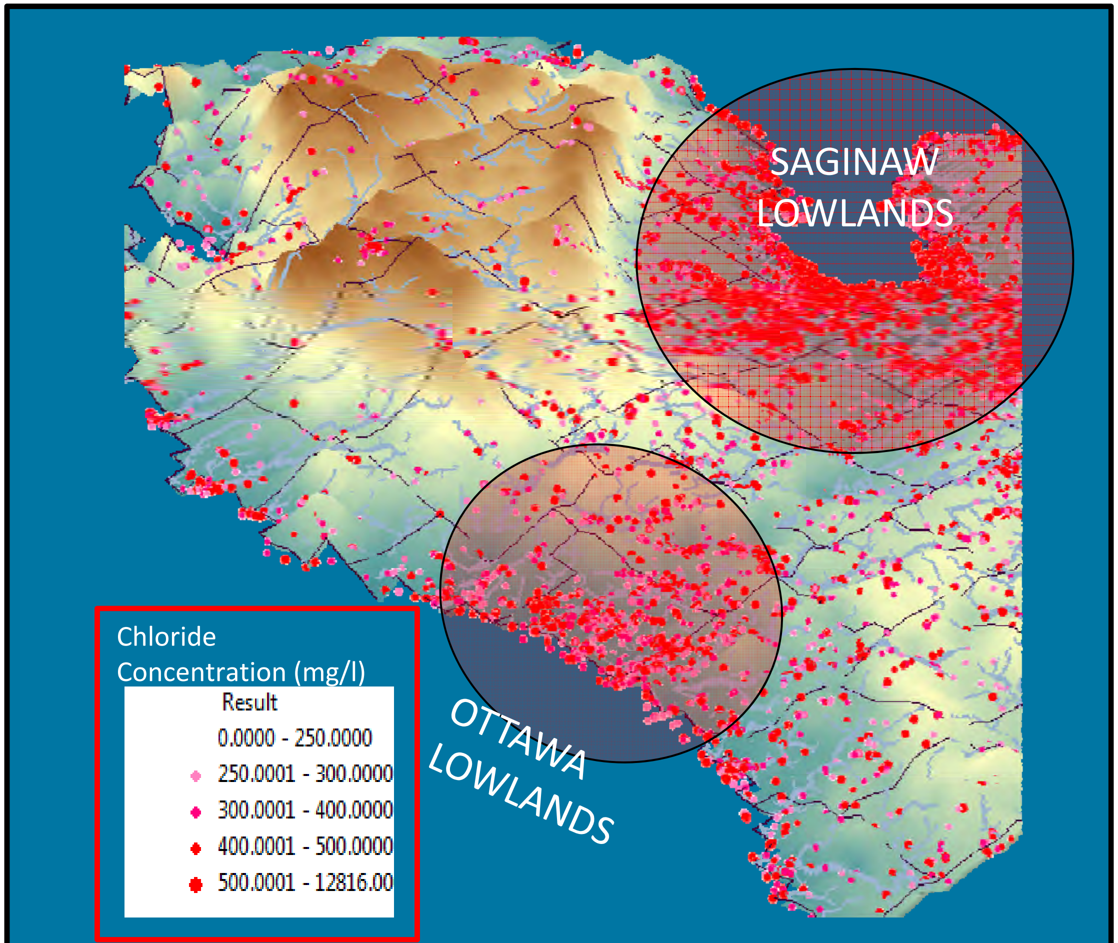
Chloride Contamination in the Saginaw and Ottawa Lowlands

In this slide we visualize Ottawa Lowlands and Saginaw Lowlands in 3D and compare side by side their chloride concentration distribution. The red dots represent wells with chloride concentrations higher than the drinking water standard.

The results clearly show that the two master groundwater discharge areas of deep geological formations stand out in elevated chloride concentrations.

The Saginaw and Ottawa lowlands share the following common characteristics:

- Coastal areas at low elevations in Michigan.
- Master discharge areas of deep geological formations.
- Presence of an extensive surficial clay layer limiting natural recharge to the deep bedrock aquifer.



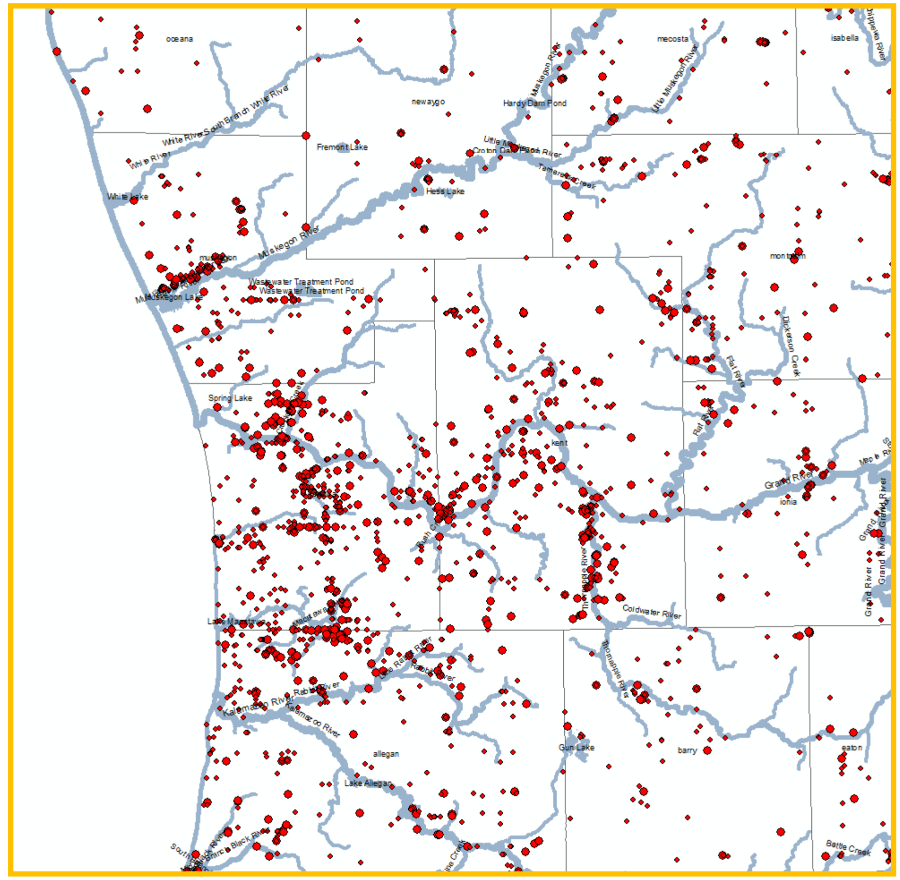
Saginaw and Ottawa Lowlands are the two master discharge areas of saline groundwater in the Deep Marshall Sandstone Formation.

Ottawa Co. Chloride Contamination and River Systems

This slide overlays the stream network and well samples with chloride concentrations higher than the drinking water standard.

Note that elevated chloride concentrations occur predominantly within the river corridors, areas where static groundwater levels are often lowest and the net groundwater movement is upward.

Under normal conditions, fresh water flows from inland aquifers and recharge areas toward the discharge areas along rivers and streams.



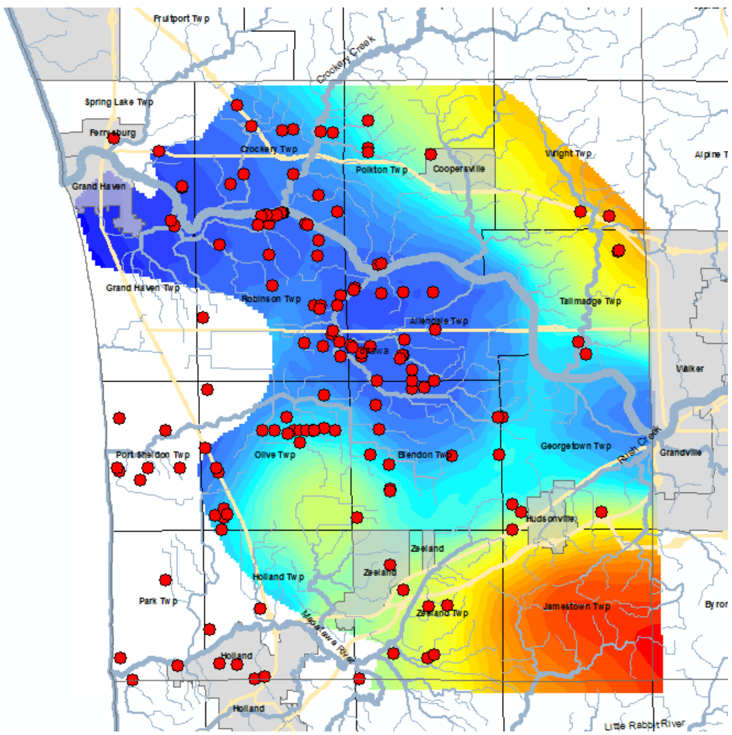
Chloride Concentration (mg/l)

Result
0.0000 - 250.0000
250.0001 - 500.000
500.0001 - 12816.0

Chloride Contamination and Static Water Levels

This slide overlays the static water level maps and well samples with chloride concentrations higher than the drinking water standard. Note that virtually all drinking water exceedances occur in the groundwater discharge areas, where the static water levels are low and groundwater moves upward. The red dots are wells with concentrations higher than 250 mg/l.

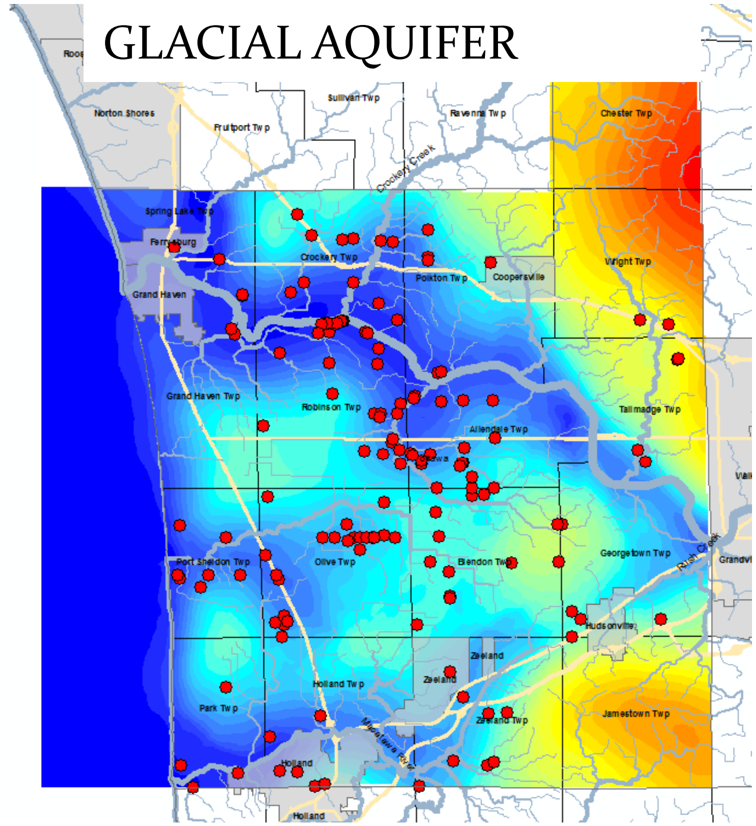
BEDROCK AQUIFER



CL>250 mg/l

VIRTUALLY ALL DRINKING WATER EXCEEDANCES (RED DOTS) ARE IN SWL DEPRESSIONS/ GROUND WATER DISCHARGE AREAS (BLUE AREAS) !!

GLACIAL AQUIFER

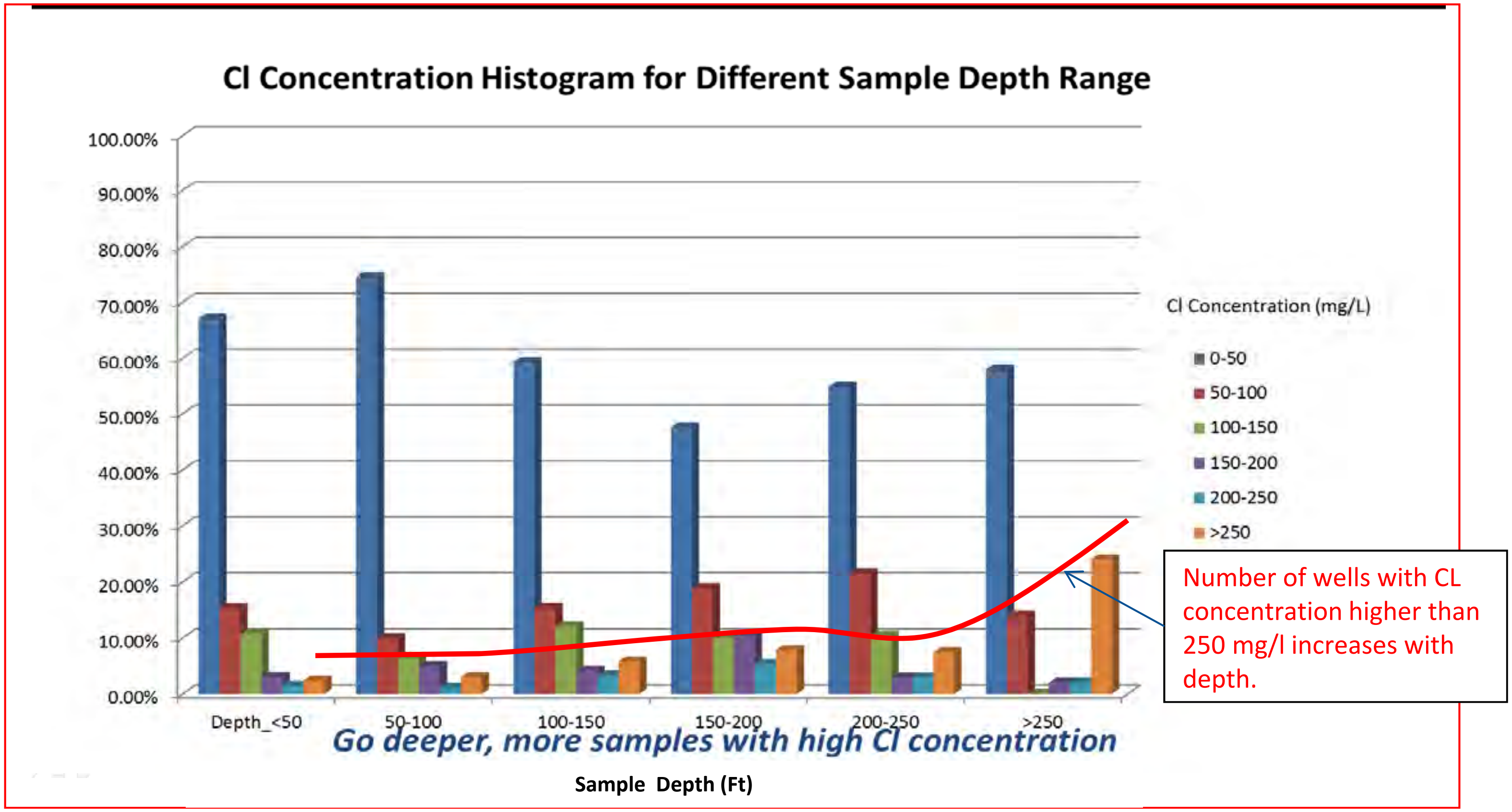


CL>250 mg/l

Chloride Concentration Versus Depth

This slide shows the percentage of well samples with Chloride concentrations exceeding selected threshold values at different aquifer depth intervals .

Note that the percentage of drinking water exceedances increases systematically with depth.



Chloride Concentration Versus Depth

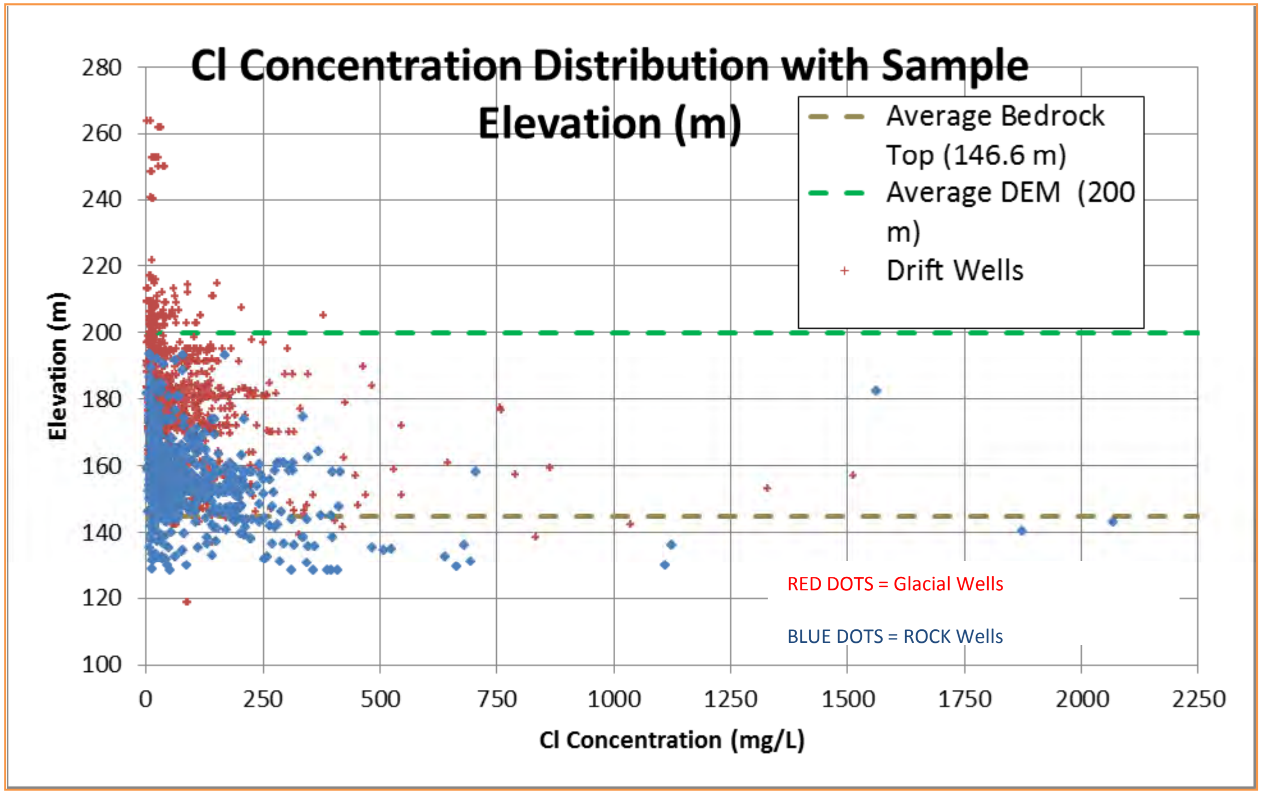
This slide shows the chloride (CL) concentration distribution with well depth.

Note that CL concentrations in both the bedrock aquifer and the glacial aquifer increases with depth.

This vertical trend suggest that both the shallow and deep aquifers have been impacted by the upwelling brine.

This vertical trend of concentration distribution also suggest that impacted wells are in the salt-water mixing zone and the contamination is likely caused by diffusion and dispersion of upwelling brine.

The boundary between salt water and fresh water is not distinct; the zone of dispersion, transition zone, or salt-water interface is brackish with salt water and fresh water mixing.



Note the vertical trends – higher concentrations over depth in both the glacial and the bedrock aquifers

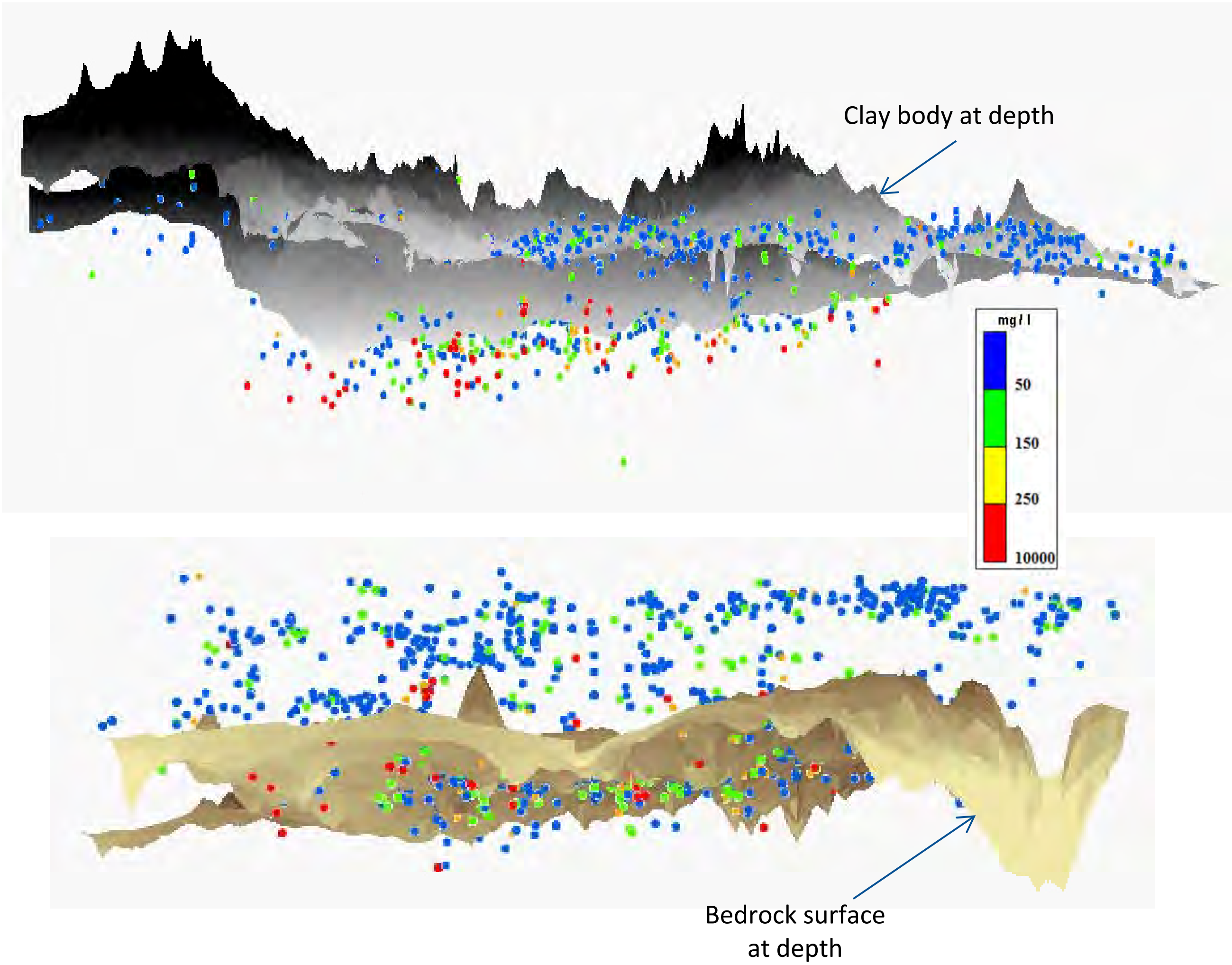
3-D Visualization of Chloride Contamination in Water Wells

This slide presents a visualization of the -3D distribution of chloride concentration.

Note chloride concentration increases with depth in both the glacial and the bedrock aquifers.

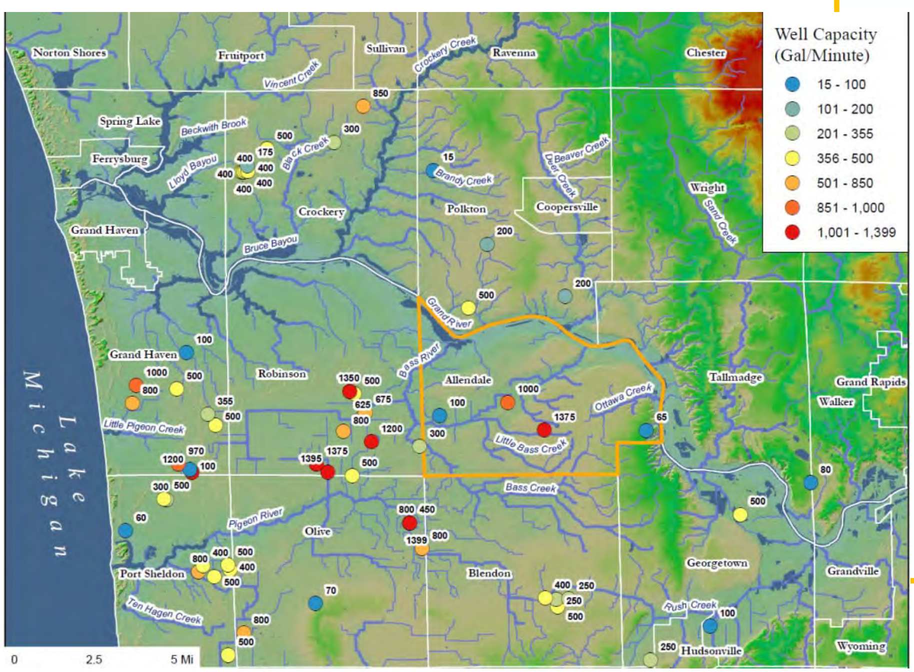
Both the shallow and deep aquifers are contaminated by saline water.

Chloride contamination is most severe in the bedrock aquifer .

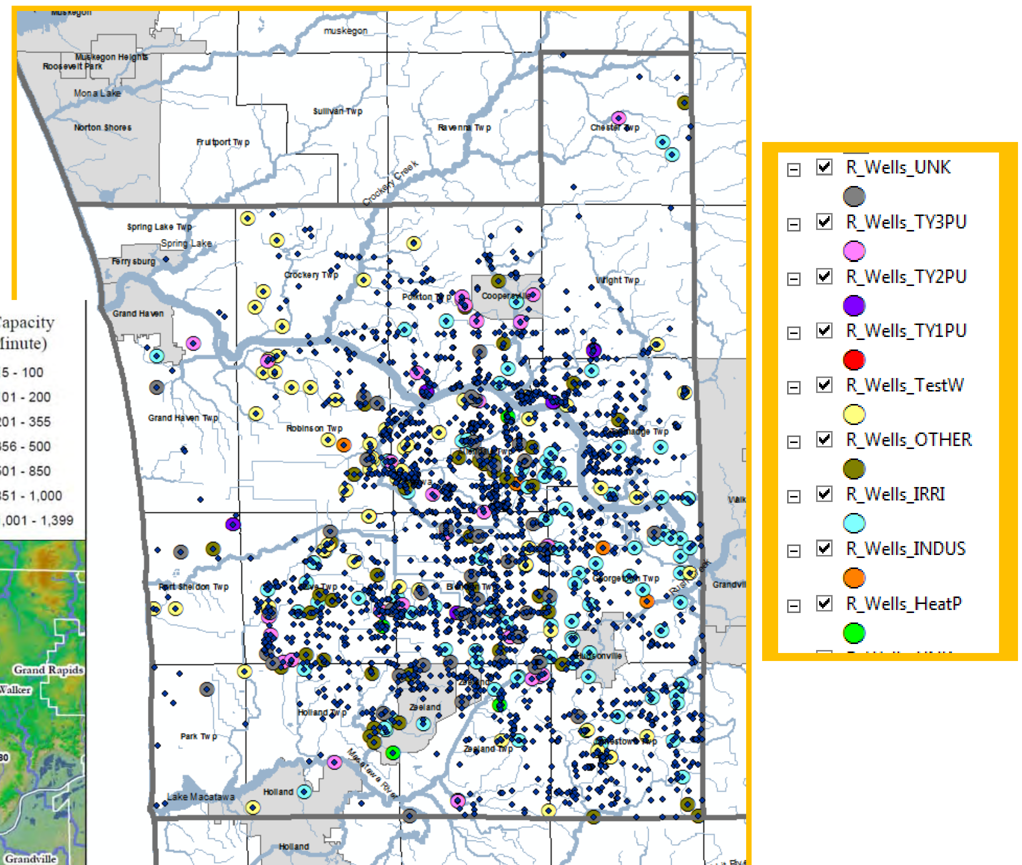


Impact of Water Withdrawals

The number of groundwater wells in Ottawa County has steadily increased over the past decades. It is likely that the increasing cumulative withdrawals from both the glacial and bedrock aquifers have allowed saline groundwater from deeper in the bedrock aquifer system to migrate upward toward the top of the Marshall Formation and into the scattered deep glacial aquifers beneath central Ottawa County.



New large-quantity withdrawals registered with the MDEQ 2010 – 2012.



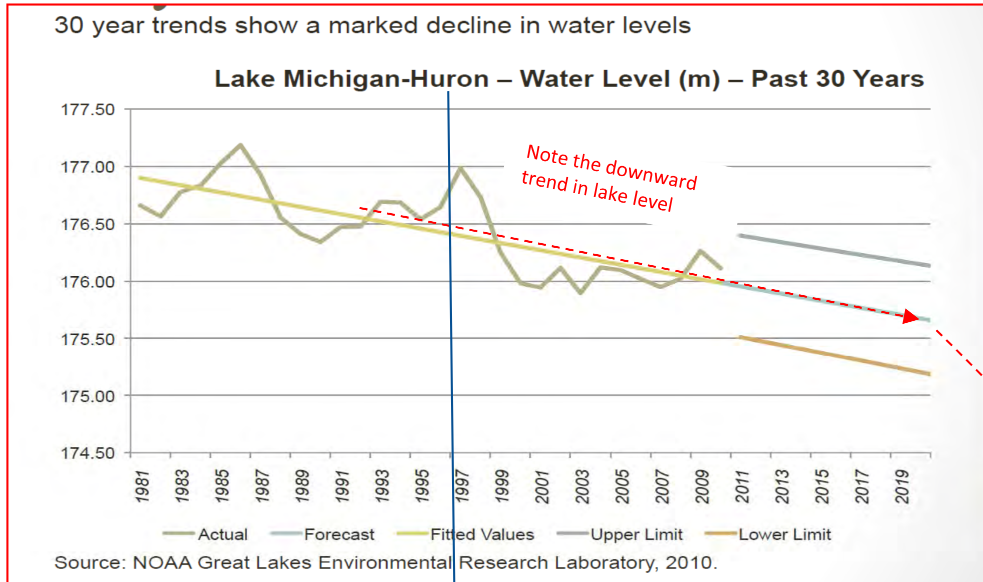
Water wells in the bedrock aquifer

Impact of Lake Michigan Levels

It appears that declining Lake Michigan levels may be accelerating the brine upwelling.

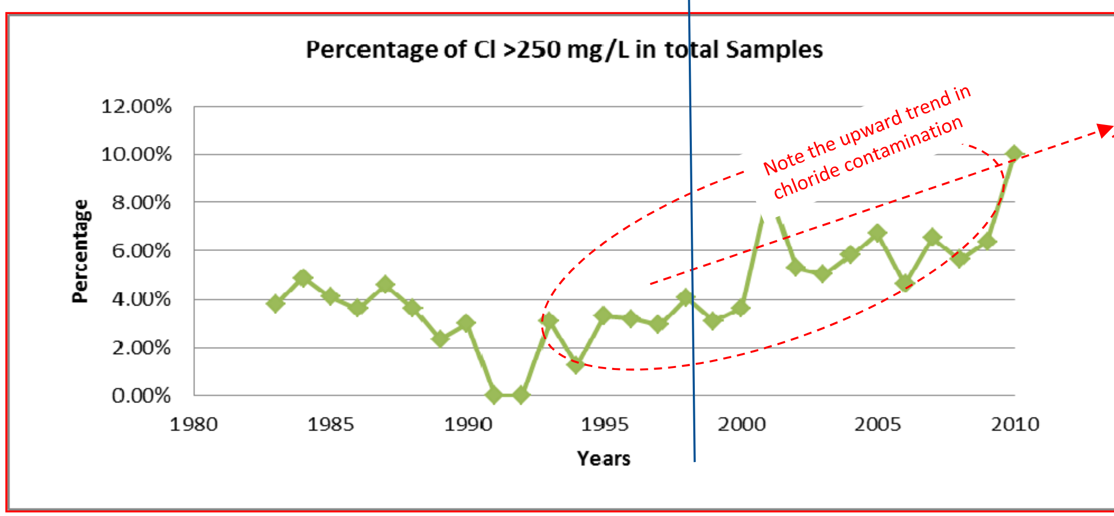
Lake Michigan water levels represent the base level for both aquifers and a decline in lake levels will translate into a decline in the aquifers, streams, and inland lakes.

The degree of coupling between changing levels in Lake Michigan and groundwater flow regimes in both the glacial and bedrock aquifers in Ottawa County remains unclear. The modeling effort in the proposed Phase-2 study will improve our understanding of these complex relationships.



Is this related?

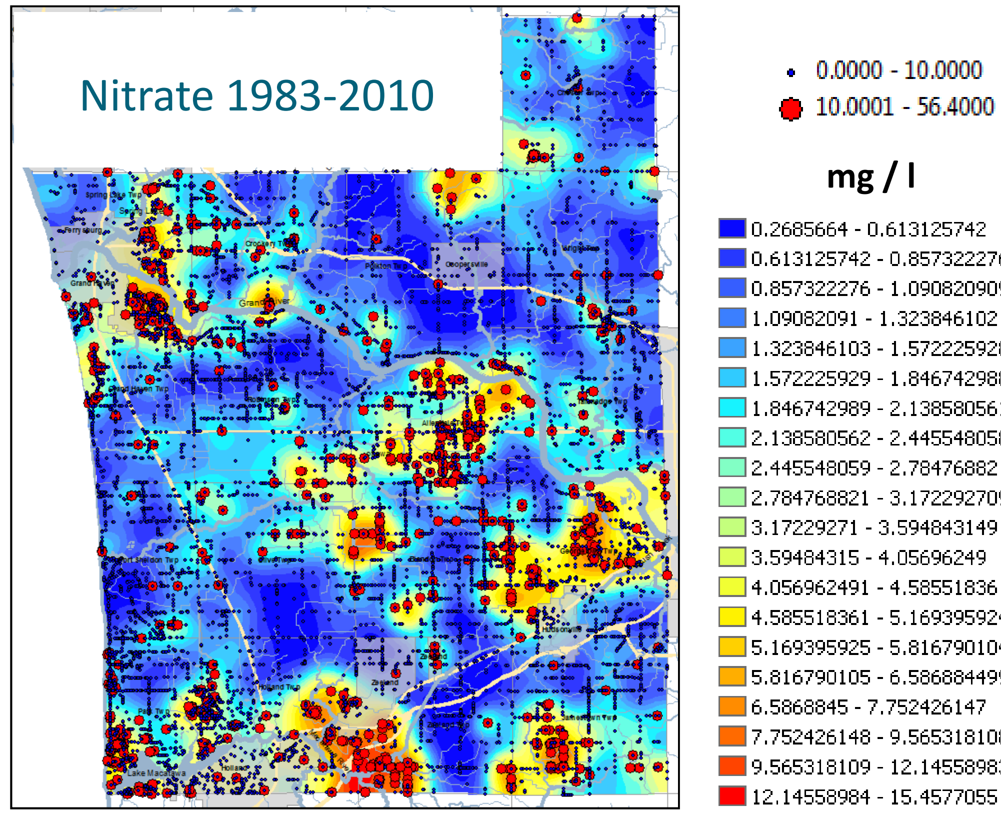
To what degree is this related?



Nitrate Contamination

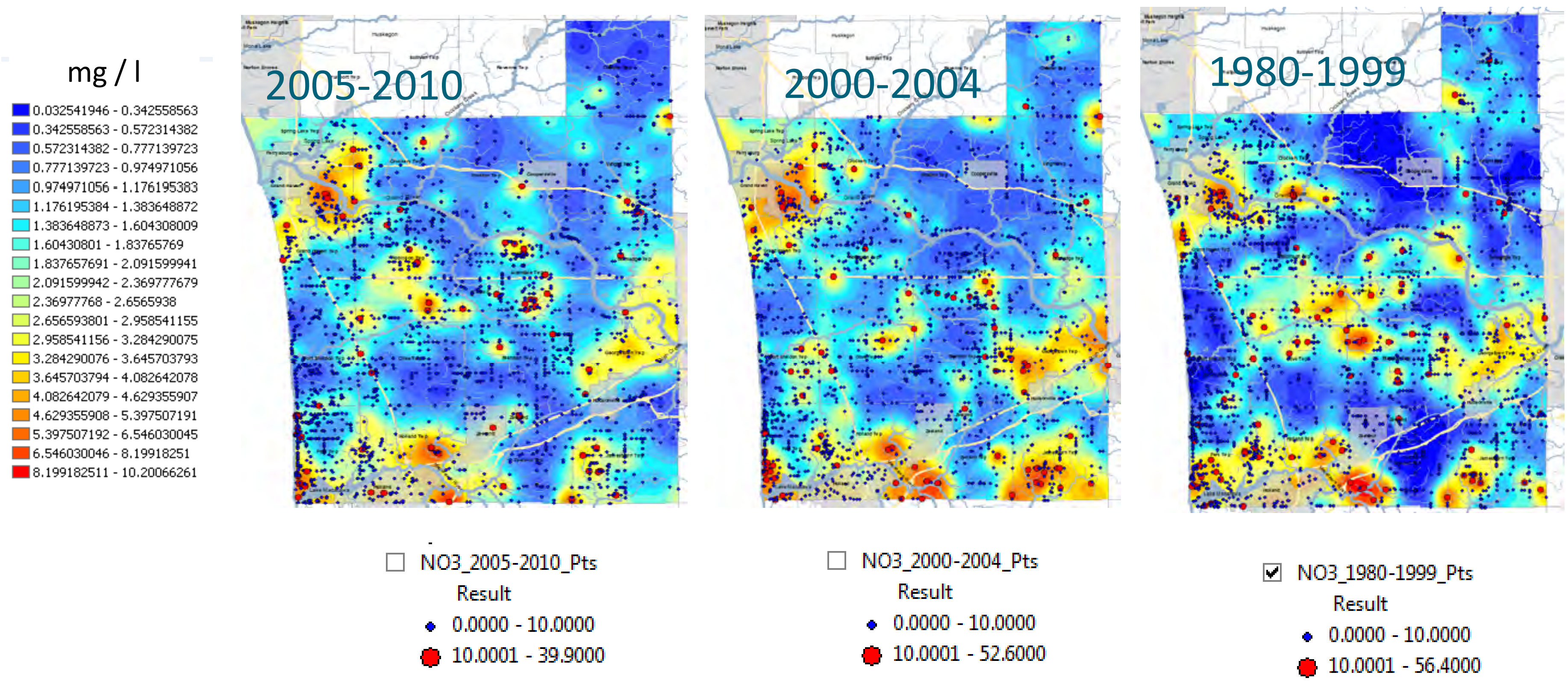
This map shows the results of using a moving window averaging routine to interpolate nitrate concentrations Countywide from the 1983-2010 samples. Note that nitrate concentrations are elevated (*i.e.*, > 3 mg/L) in many areas of the County. There are numerous hotspots throughout the County, especially in the areas just east of Ferrysburg and Grand Haven, south and southeast of Zeeland, in central and western Allegan Township, in central Georgetown Township, and in southwest Jamestown Township. In many of these hotspots, the nitrate concentrations are 2 - 5 times the drinking water standard of 10 mg/L.

Although there are some natural sources of nitrogen that can pollute groundwater with nitrates, anthropogenic sources can also cause high nitrate concentrations in groundwater.



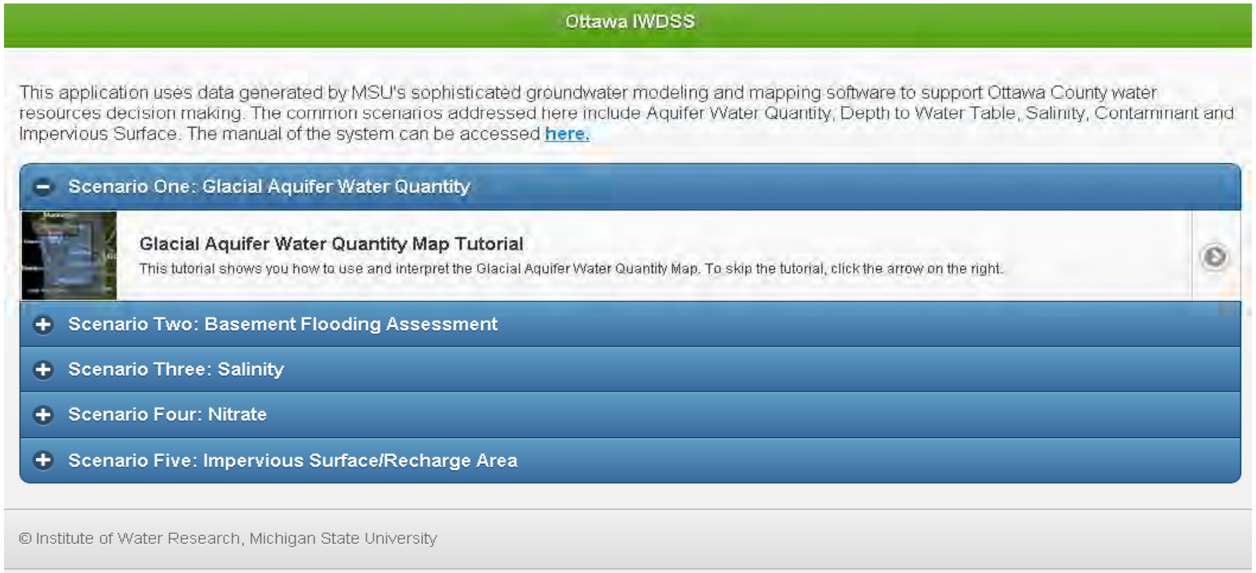
Spatial/Temporal Trends in Nitrate Contamination

This slide shows a map overlay of scattered nitrate concentration values and their local spatial average for three time periods. There seems to be no strong temporal trend in the nitrate concentrations at the County scale.



INTERACTIVE WATER RESOURCE DECISION SUPPORT SYSTEM

Utilizing results from the groundwater study and geospatial data gathered from the State and Ottawa County, the IWR team worked closely with Ottawa County officials to develop the Ottawa County Interactive Water Resources Decision Support System based on ESRI's state-of-the-art WebGIS technology. The system is designed to facilitate the decision-making process by County and township officials in water resources management issues. The system includes the following five scenarios: (1) Glacial Aquifer Water Quantity, (2) Basement Flooding Assessment, (3)Salinity, (4)Nitrate, and (5) Impervious Surface/Recharge Area.



IWDSS

The IWDSS uses a web-based environment with GIS capabilities and provides interactive plan-view maps and cross-sectional views of portions of the County to: (a) determine the aerial extent and large-scale variation in aquifer characteristics, (b) provide a depiction of the general groundwater flow regime (direction and rate), (c) map the concentrations of sodium, chloride, nitrate, and arsenic from water well samples, and (d) determine the fluctuations of water table depth.

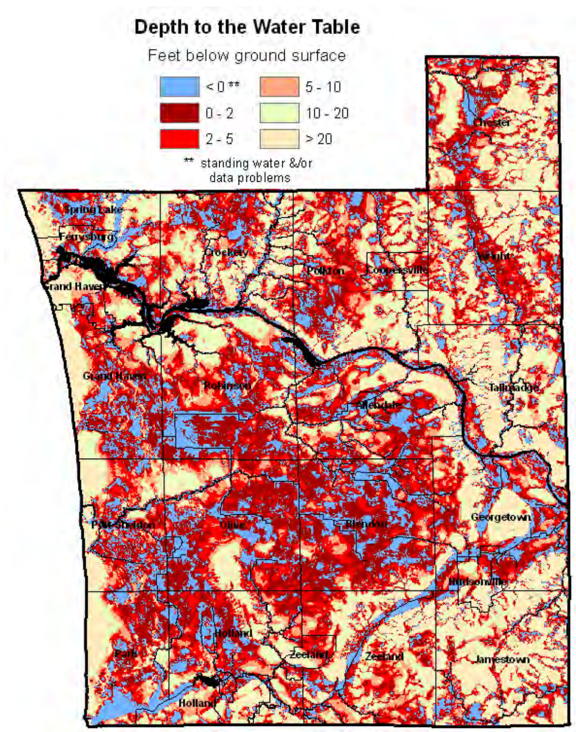
In order to let users determine the amount of water available in the shallow glacial aquifer, the Glacial Aquifer Water Quantity scenario allows them to identify the glacial aquifer yield (gpm) by clicking any location on the map. This yield is calculated on the fly based on the data in the system. Since the system will be used mainly by County and township officials, it has the capabilities to locate any address or township/city so local users can orient themselves on the map quickly. The mapping interface allows users to browse the map and control the display by turning on and off map layers. The address matching and mapping interface are all based on ESRI's ArcGIS JavaScript API.

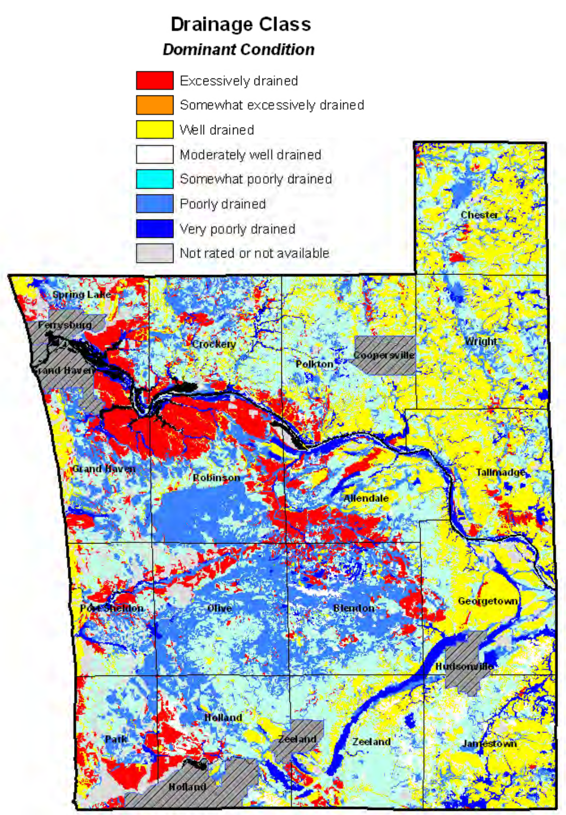
IWDSS Scenarios – Glacial Aquifer Water Quantity

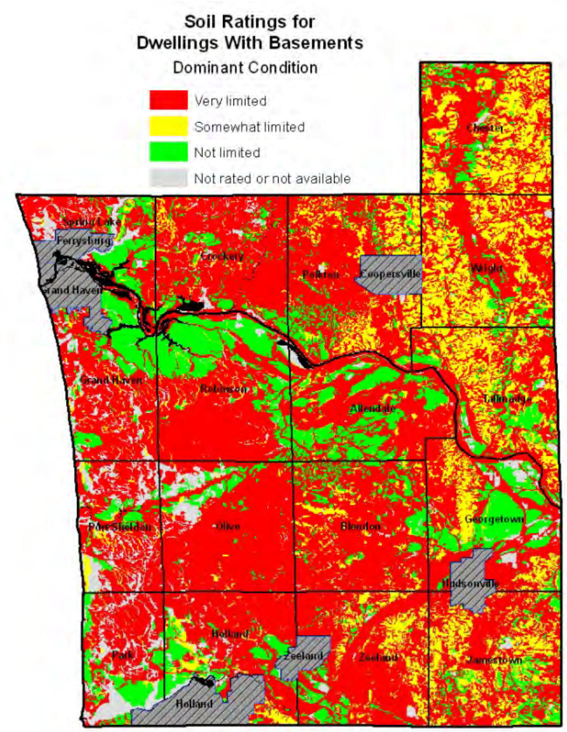
In Scenario One of the IWDSS, users can locate places of interest with the address place finder function or the zoom-pan tools, and then select either the glacial aquifer yield or the bedrock aquifer yield map as the active layer. Once active, a mouse-button click will evoke a pop-up information window providing the yield (gallons per minute) information from the MDEQ Groundwater Inventory and Mapping Project.

IWDSS Scenarios – Basement Flooding Assessment

The Basement Flooding Assessment scenario allows users to identify potential problem areas for basement flooding by displaying the color-coded depth to the water table map. This scenario also involves a cursor inquiry of the water table depth, soil drainage class and soil ponding frequency values at any location on the map.

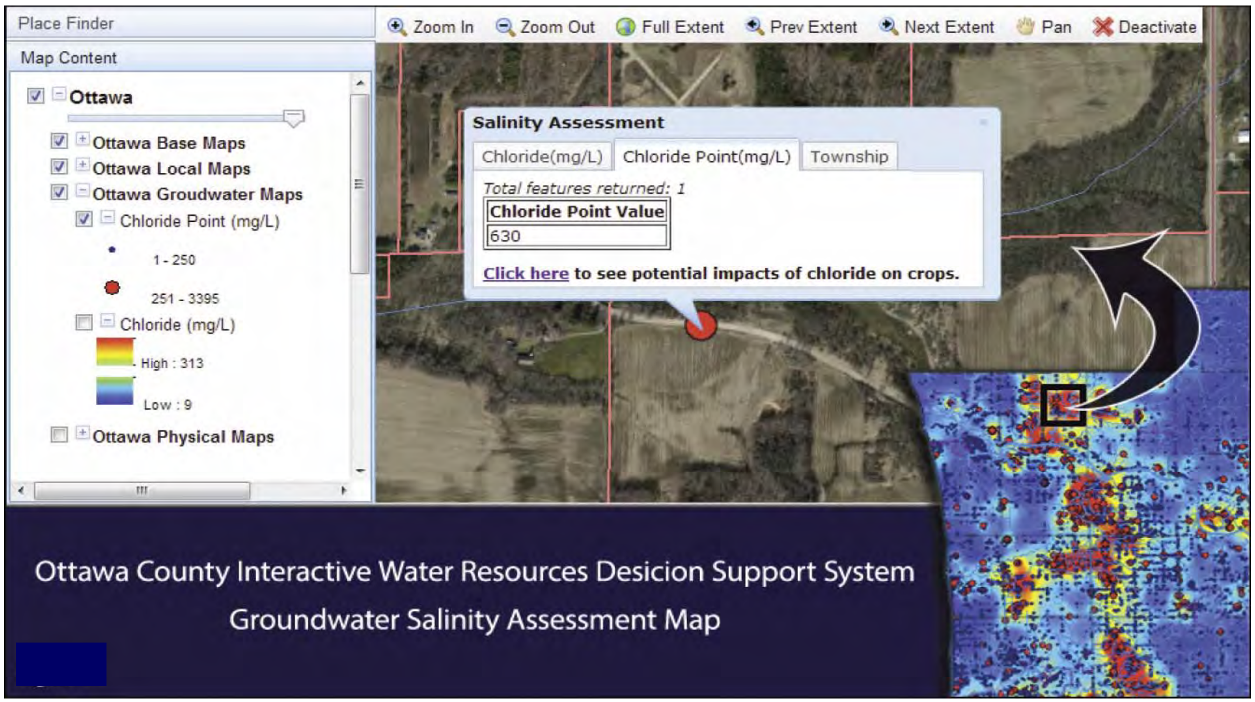






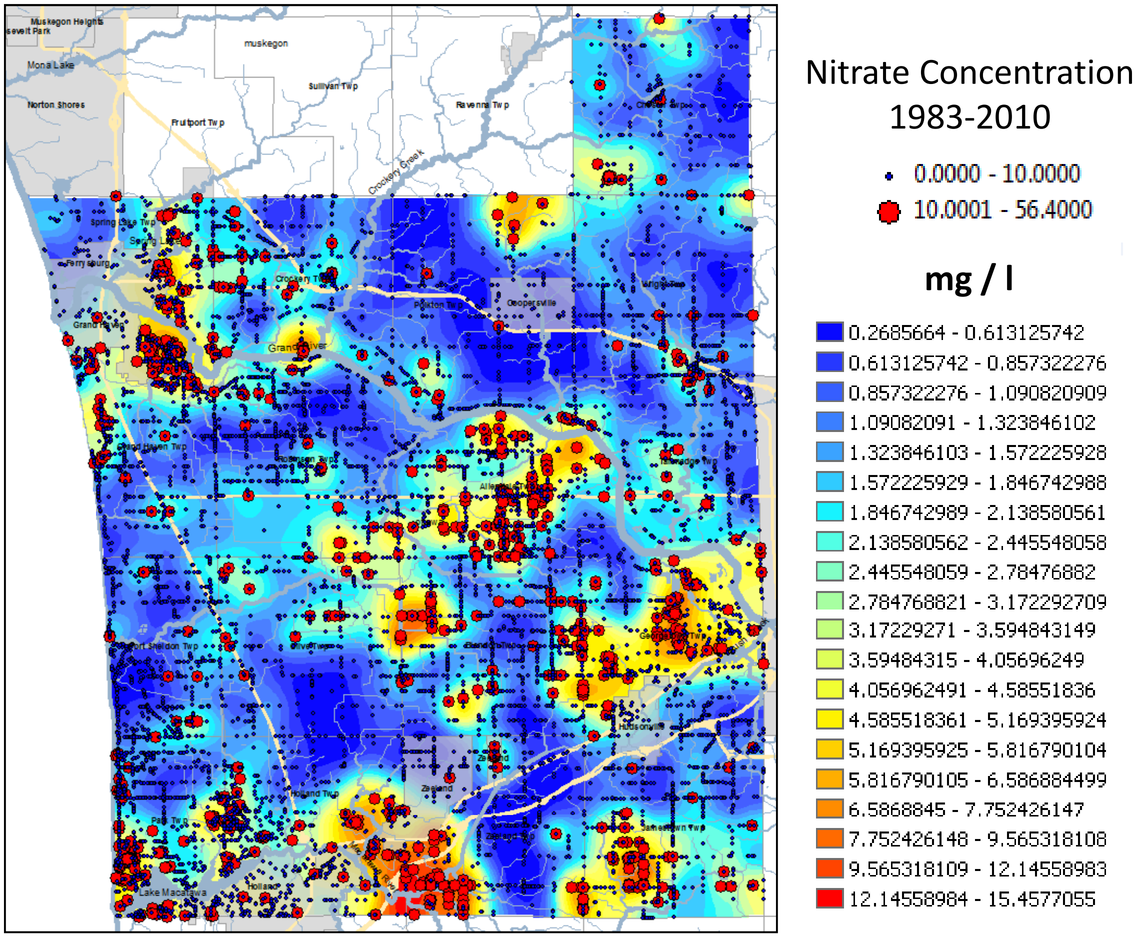
IWDSS Scenarios - Salinity

In addition to displaying the color-coded map showing the estimated concentrations of Chloride in groundwater across the County, the IWDSS also supports a Salinity Assessment tool that allows the user to select any location in the County with the mouse cursor and be shown the estimated chloride concentration in that vicinity. The Salinity scenario allows users to identify areas with high chloride concentrations and enables them to see the spatial correlation between bedrock aquifer pumping and high saline water in the bedrock aquifer.



IWDSS Scenarios – Nitrate

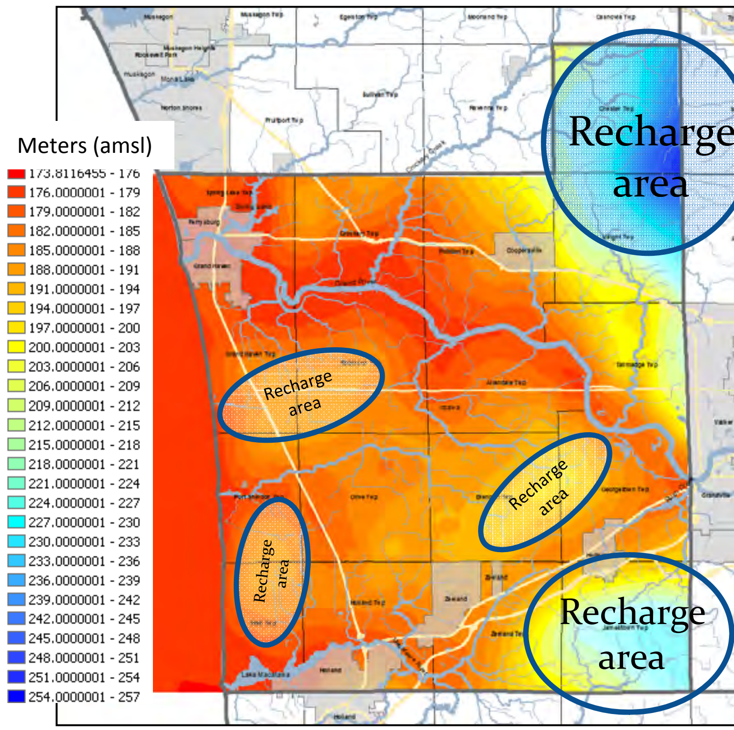
The Nitrate scenario allows users to identify areas with high nitrate concentrations and displays the color-coded map showing the estimated concentrations of Nitrate in groundwater across the County.



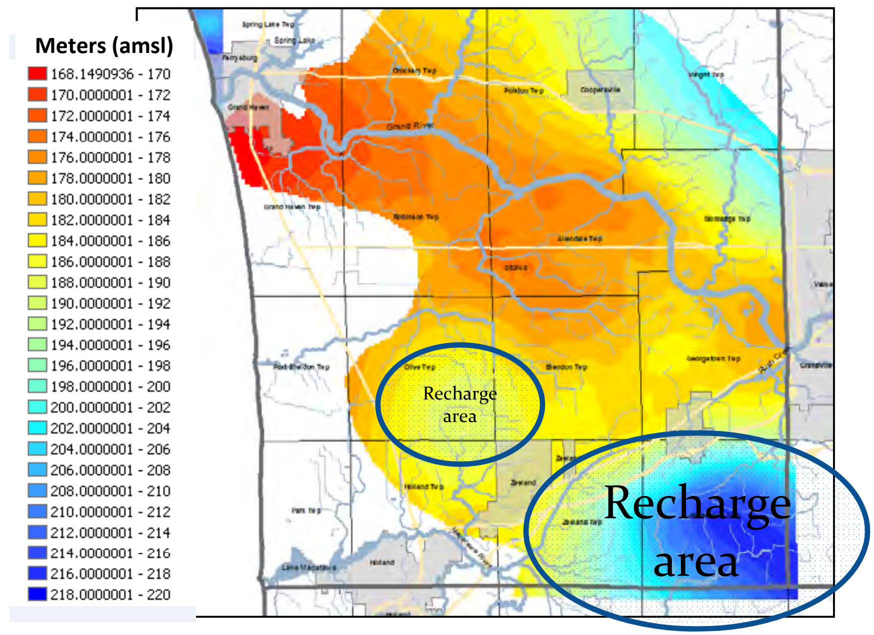
IWDSS Scenarios – Impervious Surface / Recharge Areas

The Impervious Surface/Recharge Area scenario displays State Water Levels along with flow directions enabling users to identify regional and local recharge areas. The regional recharge areas for the unconfined, glacial aquifer occur in Chester and Wright townships in northeastern Ottawa County and in Jamestown Township in the southeast corner of the county. Jamestown Township also serves as a recharge area for the confined, bedrock aquifer. However, the heterogeneous layering and generally fine texture of the glacial sediments in both of these areas, limits the recharge potential to aquifers. As such, intensive planning and management of impervious surface amounts in these areas does not appear to be warranted.

SWL in the Glacial Aquifer



SWL in the Bedrock Aquifer



IWDSS Tutorials

The system also contains manual and tutorials for end users to get familiar with the usage of the system. The manual and tutorials explain all functions in the system and how to use them. They also contain information on data layers. Please refer to Appendix A to see a detailed list of the all data layers included in the system. System manual and tutorials can all be accessed online.

CONCLUSIONS

Mounting evidence suggests that brine upwelling from deep geological formations is beginning to impact the Ottawa lowlands. This natural upwelling process is likely accelerated by increased pumping in parts of the County and the declining Lake Michigan levels.

In particular, the study shows: 1) since 1999, increasing groundwater withdrawals from both the glacial and the bedrock aquifers has resulted in a modest, but significant lowering of the static water levels in both aquifers, 2) the groundwater in the bedrock aquifer and deep portion of the glacial aquifer is becoming more saline as shown by increasing chloride concentrations through time and with depth, and 3) the areas of most severe saline contamination coincide with the areas where static water levels are lowest or groundwater upwelling is strongest. The spatial pattern of the chloride concentration increases clearly shows that the majority of it is NOT a surface contamination problem (*e.g.*, road salt). Rather, it is coming from below within the bedrock aquifer. It is likely that the increasing withdrawals from the bedrock aquifer have caused saline groundwater from deeper in the bedrock aquifer system to migrate upward toward the top of the Marshall Formation beneath central Ottawa County.

Nitrate concentrations are elevated (i.e., > 3 mg/L) in many areas of the County. There are numerous hotspots throughout the County, some with nitrate concentrations 2 - 5 times the drinking water standard. Although there are some natural sources of nitrogen that can pollute groundwater with nitrates, it is much more likely that anthropogenic sources have caused the high nitrate concentrations. The lack of a strong temporal trend in the nitrate concentrations at the County scale implies that the sources are ubiquitous and persistent.

The basement flooding problems that have been experienced in some parts of the County are, in part, related to the wide spread shallow depth to the water table. The spatial uncertainty associated the Phase-1 analysis of the temporal trend in static water levels in the glacial aquifer precludes any local-scale assessment of neighborhood basement flooding. More information will be needed about the exact nature of the basement flooding (e.g., floor drains that backed up, poor footing drain infrastructure, failed sump pumps, etc.) in order to begin any local-scale study.

RECOMMENDATIONS

Further research is needed to quantify the sustainability of groundwater use in Ottawa County. This would require:

- Test well monitoring of the glacial and bedrock aquifers for quantity and quality, including

    1) synoptic, County -wide sampling
    2) focused sampling in the general areas with significantly elevated chloride concentrations, and
    3) automated, long-term sampling at individual contamination hotspots.

- Development of calibrated flow and water quality models of the glacial and bedrock aquifers at the County scale, township scales, and local hotspot scales

- Modeling of different impact scenarios based on usage, climate, and policies

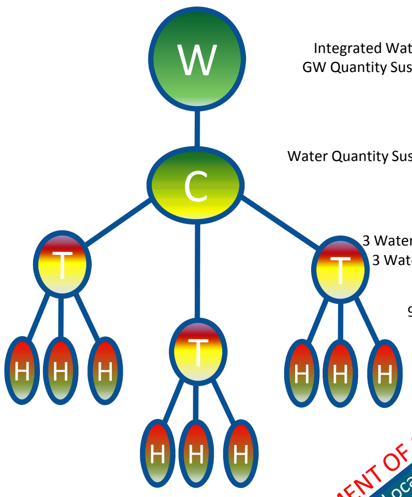
- Solutions to address declining groundwater levels and increasing salinity concentrations

The questions that can be addressed with such a "multi-scale" sampling and modeling approach are shown the next slide.

THINK GLOBALLY, ACT LOCALLY

OTTAWA COUNTY

HIERARCHICAL GROUNDWATER SIMULATION AND DECISION SUPPORT SYSTEM



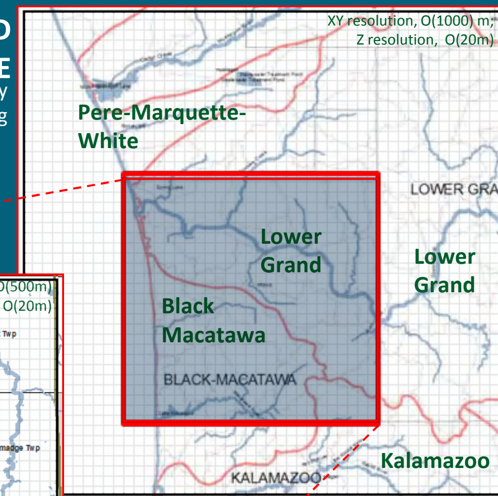
Model Hierarchy

INTEGRATED MULTISCALE MANAGEMENT OF OTTAWA COUNTY'S WATER RESOURCES

From Strategic Regional Planning to Local Operational Management and Site-Specific Problem Solving

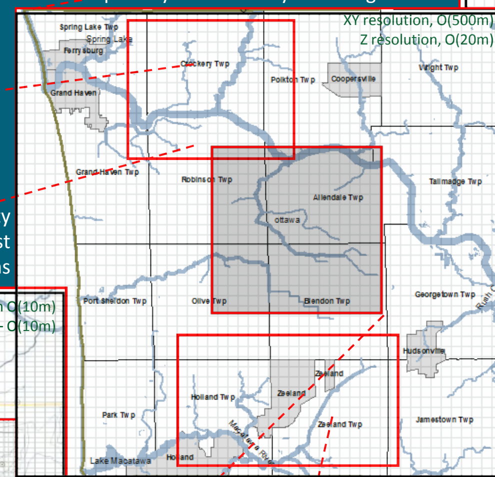
WATERSHED SCALE

Water quantity sustainability modeling



COUNTY SCALE

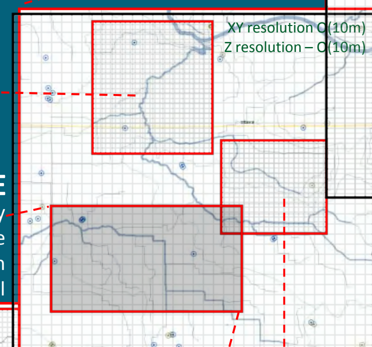
Water quantity sustainability modeling



Where are Ottawa County's major recharge areas? What are the dominant sources of water in the bedrock aquifer? Is groundwater flow across the County boundaries into Ottawa from other neighboring Counties significant? To what degree water resources sustainability in Ottawa County depends on water use/ management practices in other Counties ?

TOWNSHIP SCALE

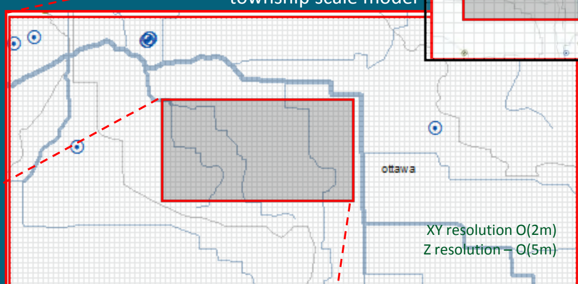
Water quantity & quality sustainability modeling in 3 most "problematic" regions



How fast is the static water level declining regionally? Is groundwater mining occurring in the Marshall Sandstone aquifer? Where are the most problematic areas? How large/deep is the current regional drawdown cone of depression? How much longer can the Marshall aquifer be used? How will the static water level dynamics change with different future groundwater use/Lake Michigan level change scenarios?

SITE SCALE

Water quantity & quality sustainability modeling for three "hotspot" areas within each township scale model

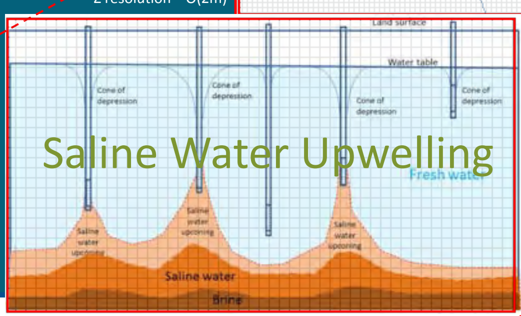


How fast is the saline water moving upward? To what extent is the bedrock aquifer contaminated by brine upwelling? To what extent is the glacial aquifer impacted by the saline water? Where is approximately the brine-freshwater interface? To what degree natural brine upwelling is accelerated by increased groundwater withdrawals? To what degree is upwelling affected by the Lake Michigan level dynamics

HOTSPOT

Water quantity & quality sustainability modeling

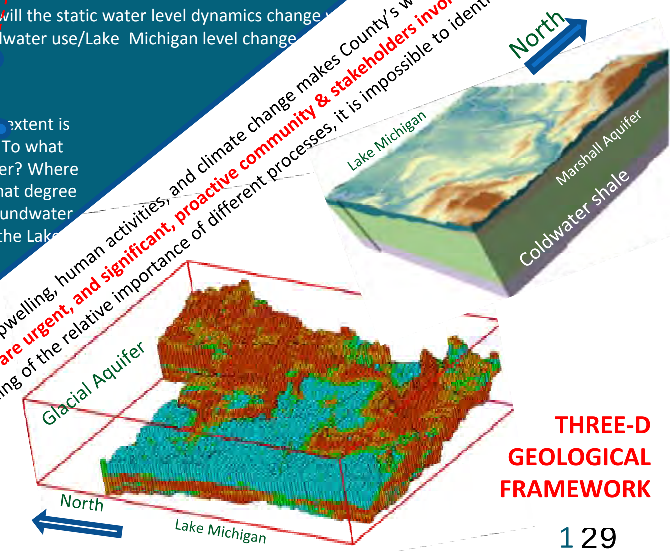
XY resolution O(1m)
Z resolution – O(2m)



How are the dynamics of well drawdown and chloride upwelling correlated? How deep are the drawdown cones of depression in the Chloride hotspot areas? What is the critical rate of pumping from a given zone which could mobilize saline groundwater into a freshwater aquifer? How can the space-time pumping patterns be managed to maximize the safe/sustainable yield? How will the well drawdown/chloride upwelling dynamics change with different future groundwater use/lake level change scenarios?

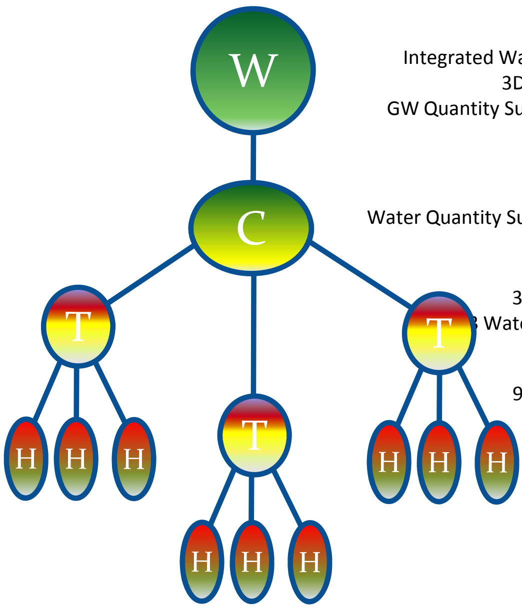
What will be the extent of saline water contamination, both horizontally and vertically, 10, 20 , 50, or 100 years from today?

The complex interplay of natural brine upwelling, human activities, and climate change makes County's water problem particularly "wicked". **Stakes are high, decisions are urgent, and significant, proactive community & stakeholders involvement is required.** Without a clear, holistic understanding of the relative importance of different processes, it is impossible to identify the best corrective action



THREE-D GEOLOGICAL FRAMEWORK

Hierarchical Groundwater Modeling



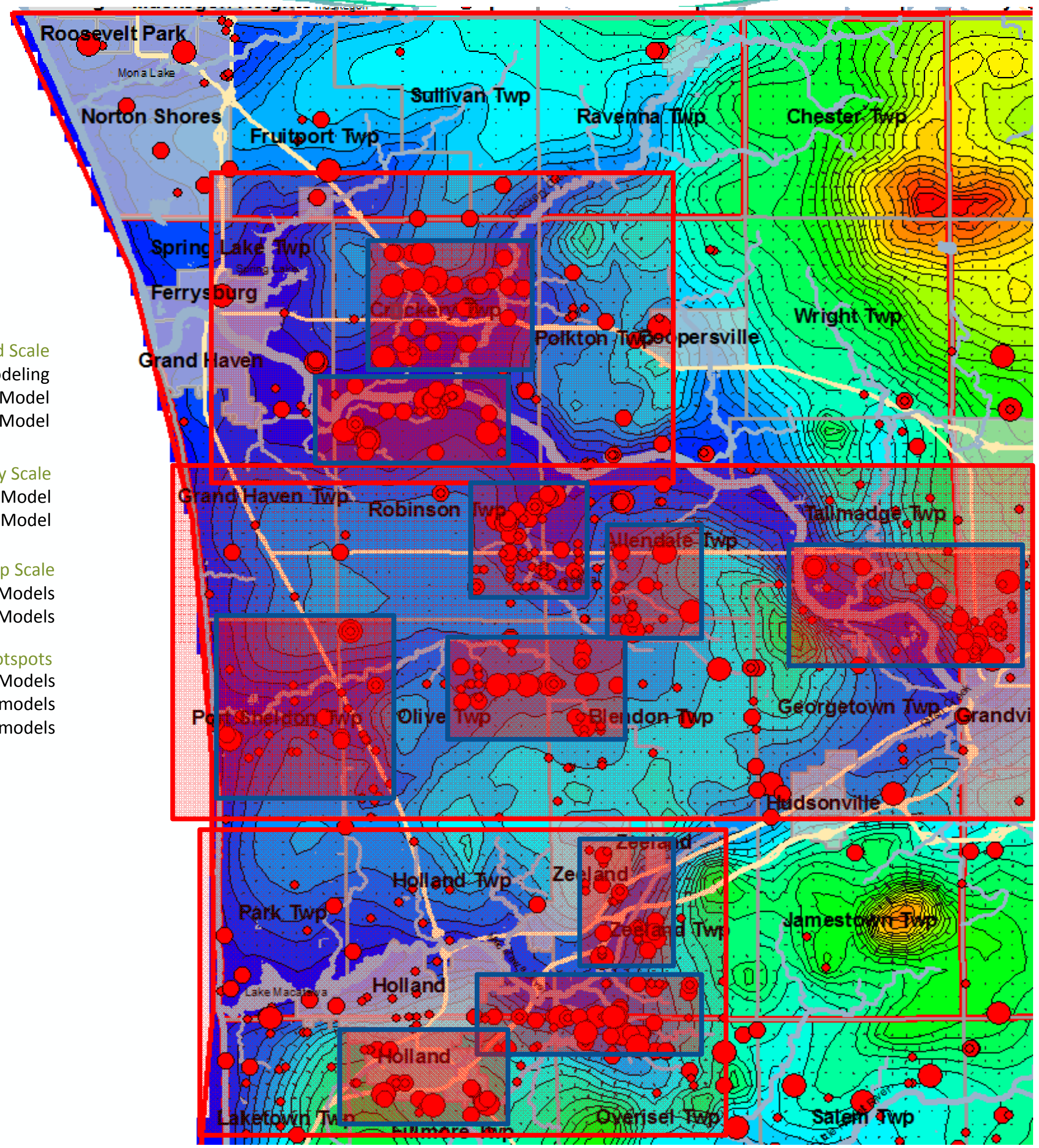
Watershed Scale
Integrated Watershed Modeling
3D Geological Model
GW Quantity Sustainability Model

County Scale
Geological Model
Water Quantity Sustainability Model

Township Scale
3 Geological Models
3 Water Quantity Models

Hotspots
9 Geological Models
9 quantity models
9 quality models

Model Hierarchy



Water Sustainability Questions

- How fast is the water level in the aquifers declining? Where does the maximum drawdown occur?
- How much longer can the groundwater be used?
- What will be the extent and rate of aquifer drawdown 10, 20, 50, or 100 years from now, given various projected climate and water use scenarios?
- What are the limiting factors controlling groundwater sustainability in different aquifers and in different parts of the County?
- How fast is the chloride plume moving upward toward the top of the bedrock aquifer?
- How will the rate of chloride upwelling change with different projected groundwater use scenarios?
- What is net impact of pumping on saline water upwelling?
- What is the critical rate of pumping from a given zone which could mobilize saline groundwater into a freshwater aquifer?
- To what degree the chloride plume is already impacting the glacial aquifer? Which area in the glacial aquifer is most affected by the saline water contamination? How fast is chloride contamination spreading in the glacial aquifers?
- What will be the extent in chloride contamination in 10 years in both the bedrock and the glacial aquifers? How about 50 years from today?
- How does chloride upwelling change with the rate of natural recharge in the glacial aquifer?
- Is there a threshold recharge rate or a minimum static water level in the 'salt-hazard' zone that must be maintained to forestall the saline upwelling from the deeper formations?
- What will be the effect of a potential sustained multi-year drought on saline water upwelling? How will the extent of chloride contamination change if the level in Lake Michigan decreases systematically as predicted in many of the climate change scenarios?
- How will nitrate concentration pattern change with groundwater flow over time?
- How will the nitrate plume move in response to increased groundwater use?
- What will be nitrate contamination pattern look like 10 years from today?
- How can we optimize groundwater use to minimize the potential to capture either the chloride or nitrate contaminated water?
- How can we predict contaminant fate and transport from other sources of contamination (e.g., a leaky landfill, an industrial spill, a leaky underground storage tank)?
- How can we proactively and holistically manage Ottawa's water resources as a system, taking into account the hydrological constraints, geological constraints, water quality constraints, ecological constraints, and legal constraints?

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APPENDIX 1 – IWDSS DATA LAYERS

	Description	Source
Ottawa Base Maps	Ottawa Base Maps contain basic County data layers such as township and city boundaries. These layers are automatically turned on when you load a scenario's map. This layer group is nested under the "Ottawa" layer group.	
County	Ottawa County boundary	Michigan Geographic Data Library
Township	Ottawa County township boundaries	Michigan Geographic Data Library
City	Ottawa County city boundaries	Michigan Geographic Data Library
Stream	Ottawa County streams	Michigan Geographic Data Library
Water Body	Ottawa County water bodies	Michigan Geographic Data Library

Ottawa Local Maps	This group contains local County data layers for *Impervious Surface, Buildings,* and *Parcels.* These layers are scale dependent; they are only accessible when zoomed in on the map.	
Impervious Surface	Highlights roads, parking lots, access drives and driveways	Ottawa County Planning Department
Buildings	Digitized buildings	Ottawa County Planning Department
Parcels	Parcel boundaries	Ottawa County Planning Department

APPENDIX 1 – IWDSS DATA LAYERS

	Description	Source
Ottawa Groundwater Maps	This is the largest subgroup of layers in the Ottawa IWDSS. Data layers relating to water quantity and quality are found in this subgroup. In each scenario map you open, certain layers relevant to that scenario will automatically be turned on. For instance, the Nitrate Assessment map will automatically load the *Nitrate* layer and the Aquifer Quantity map automatically loads the *Water Wells* layer.	
Water Wells	Distinguishes between shallow glacial drift well (blue) and deep bedrock wells (red)	Michigan Geographic Data Library
Active NTR Type 2 Wells	Non-community non-transient system wells that serve at least 25 of the same individuals for at least six months	Michigan Geographic Data Library
NTR Type 2 Provisional WHPAs	Provisional delineations of wellhead protection areas for NTR Type 2 systems. Provisional WHPA's still need traditional WHPA delineations.	Michigan DEQ
Active Type 1 Wells	Community water supply systems that offer year round service to at least fifteen living units or twenty-five residents.	Michigan Geographic Data Library
Depth to Water Table (ft)	Depth to water table in feet. Areas shaded with blue have a low depth to water table, which means the water table is close to the surface. The areas in red have a water table that's farther away from the surface.	Generated by MSU using Wellogic Data
Ottawa Soil WT Depth Jan-Dec (ft)	For places in Ottawa County where the water table is within the soil zone (~ upper 1.8 meters of the unconsolidated deposits in the County), this layer has far better spatial and vertical resolution than the interpolated "Depth to Water Table" layer.	Generated by MSU using SSURGO soil data
Ottawa Soil Drainage Class	Indicates the natural drainage conditions of the soil and ranges from very poorly drained to excessively drained.	NRCS Soil Survey Geographic Database (SSURGO)
Ottawa Soil Ponding Frequency	Shows areas prone to frequency water ponding.	NRCS Soil Survey Geographic Database (SSURGO)
Glacial Aquifer Flow Direction	Shows the groundwater flow pattern in the drift aquifer.	Generated by MSU using Wellogic Data
Glacial Static Water Level Contours (10ft)	Change in static water level by ten foot contours. This layer is using an average of the glacial static water level data from 1960-2012.	Generated by MSU using Wellogic Data
Glacial Aquifer Static Water Level (ft)	Overall average of the glacial aquifer static water level data from 1960-2012 measured in feet.	Generated by MSU using Wellogic Data
Glacial Aquifer Static Water Level (2000-2012) Contours (10ft)	Change in static water level by ten foot contours. This layer is using an average of the glacial static water level data from 2000-2012.	Generated by MSU using Wellogic Data
Glacial Aquifer Static Water Level (2000-2012) (ft)	Average of glacial static water levels between 2000 and 2012.	Generated by MSU using Wellogic Data

APPENDIX 1 – IWDSS DATA LAYERS

	Description	Source
Glacial Aquifer Static Water Level Change Over Time (meters)	This layer was created by subtracting the "Glacial Aquifer Static Water Level (2000-2012) (ft)" raster layer from the "Glacial Aquifer Static Water Level (1960-1999) (ft)". It shows the change in static water level over time between the two time periods.	Generated by MSU using Wellogic Data
Transmissivity	Transmissivity is a measure of the capacity of an aquifer to transmit groundwater. It is expressed as area per day (in this case, square feet per day). Transmissivity is calculated by multiplying an aquifer's hydraulic conductivity by its saturated thickness. The areas shaded in blue have a higher transmissivity rate than the areas shaded with red.	Generated by MSU using Wellogic Data
Saturated Thickness	Shows the total water-bearing thickness of an aquifer. An aquifer can range from a few feet thick to hundreds of feet thick, and its saturated thickness can significantly affect its potential water yield. The drift aquifer is thicker in areas shaded with blue and thinner in areas shaded with red.	Generated by MSU using Wellogic Data
Saturated Hydraulic Conductivity (Ksat) (µm/s)	Saturated hydraulic conductivity, measured here in micrometers per second, is simply the hydraulic conductivity of a saturated soil and is also known as Ksat. In the Ottawa IWDSS, Ksat is divided into five classes, ranging from very low to very high.	Generated by MSU using Wellogic Data
Glacial Aquifer K (ft/day)	K stands for hydraulic conductivity. Hydraulic conductivity, measured in distance per time (for this system, feet per day), is the coefficient that describes the rate at which water can move through a permeable medium. The areas in blue have a higher K rate than areas shaded with red.	Generated by MSU using Wellogic Data
Bedrock Aquifer Flow Direction	Shows the groundwater flow pattern in the bedrock aquifer.	Generated by MSU using Wellogic Data
Bedrock Aquifer Static Water Level Contours (10ft)	Change in static water level by ten foot contours. This layer is using an average of the bedrock static water level data from 1960-2012.	Generated by MSU using Wellogic Data
Bedrock Aquifer Static Water Level (ft)	Overall average of the bedrock aquifer static water level data from 1960-2012 measured in feet.	Generated by MSU using Wellogic Data
Bedrock Aquifer Static Water Level (2000-2012) Contours (10ft)	Change in static water level by ten foot contours. This layer is using an average of the bedrock static water level data from 2000-2012.	Generated by MSU using Wellogic Data
Bedrock Aquifer Static Water Level (2000-2012) (ft)	Overall average of the bedrock aquifer static water level data from 2000-2012 measured in feet.	Generated by MSU using Wellogic Data
Bedrock Aquifer Static Water Level (1960-1999) Contours (10ft)	Change in static water level by ten foot contours. This layer is using an average of the bedrock static water level data from 1960-1999.	Generated by MSU using Wellogic Data
Bedrock Aquifer Static Water Level (1960-1999) (ft)	Overall average of the bedrock aquifer static water level data from 1960-1999 measured in feet.	Generated by MSU using Wellogic Data
Bedrock Aquifer Static Water Level Change Over Time (meters)	Created by subtracting the "Bedrock Aquifer Static Water Level (2000-2012) (ft)" raster layer from the "Bedrock Aquifer Static Water Level (1960-1999) (ft)". It shows the change in static water level over time between the two time periods.	Generated by MSU using Wellogic Data

APPENDIX 1 – IWDSS DATA LAYERS

	Description	Source
Chloride Point (mg/L)	Provides actual water test result data from the Department of Environmental Quality's (DEQ) Drinking Water Analysis Laboratory.	MI DEQ WaterChem Database
Chloride (mg/L)	Interpolated values of the "Chloride Point" layer.	Generated by MSU using Wellogic Data
Nitrate Point (mg/L)	Provides actual water test result data from the Department of Environmental Quality's (DEQ) Drinking Water Analysis Laboratory.	MI DEQ WaterChem Database
Nitrate (mg/L)	Interpolated values of the "Nitrate Point" layer.	Generated by MSU using Wellogic Data
Bedrock Surface Contours (20ft)	Bedrock surface elevation in twenty foot contours.	
Bedrock Surface (ft)	Bedrock surface elevation.	

Ottawa Physical Maps	Ottawa Physical Maps contains the following layers: *Wetlands Inventory*, *Soils*, *2001 Land cover*, *Digital Elevation Model*, and *1987 Bedrock Geology*. None of these layers are automatically loaded in a scenario's map.	
Wetlands Inventory	Identifies wetland areas in Ottawa County.	Michigan DEQ
Soils	Soil classification.	NRCS Soil Survey Geographic Database (SSURGO)
Land Cover 2001	Shows land cover categories for Ottawa County.	National Land Cover Database (NLCD)
DEM	Digital elevation model for Ottawa County.	
Bedrock Geology	Shows the geological formations of the bedrock in Ottawa County.	

Bedrock Aquifer Static Water Level 2000-2012	Refer to "Bedrock Aquifer Static Water Level" layers above. These data layers are repeated to give users the capability to adjust the transparency of these layers individually.	
Bedrock Aquifer Static Water Level 1960-1999	Refer to "Bedrock Aquifer Static Water Level" layers above. These data layers are repeated to give users the capability to adjust the transparency of these layers individually.	
Bedrock Geology 1987	Refer to "Bedrock Geology" layer above. This layer is repeated to give users the capability to adjust the transparency of this layer individually.	

World Boundaries and Places	This layer group provides place names and boundaries for features such as cities and counties.	ESRI
World Transportation	This layer group displays roads and highways.	ESRI
Base Imagery Map	This layer group provides low to high resolution aerial imagery.	ESRI