OTTAWA COUNTY WATER RESOURCE STUDY – PHASE II

FINAL REPORT

Prepared by

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ACKNOWLEDGEMENTS

The research described in the report was funded by the Michigan Department of Agriculture and Rural Development (MDARD) and the Ottawa County Planning Commission.

The project tasks were completed through a collaborative effort from different stakeholders, researchers, planners, and outreach specialists from Ottawa County and Michigan State University (see following slides).

Groundwater Research Team

Civil & Environmental Engineering, Michigan State University

- Shu-Guang Li, Ph.D, P.E., F. ASCE, F. GSA, Department of Civil & Environmental Engineering, Michigan State University
- Zachary Curtis, Ph.D. candidate, Department of Civil & Environmental Engineering
- Hua-Sheng Liao, Ph.D., Department of Civil & Environmental Engineering
- Prasanna V. Sampath, Ph.D., Indian Institute of Technology Tirupati

With Assistance from:

- David P. Lusch, Ph.D., Department of Geography, Environment, and Spatial Sciences

The groundwater research team was responsible for compiling datasets for multi-scale analysis and developing groundwater flow simulations to better understand the Ottawa County aquifer system. They also led the execution of a countywide field sampling campaign during the fall of 2014 and summer of 2015, including the recruitment, training, and involvement of over 50 undergraduate students from MSU.

Planning, Decision Support and Outreach

Planning and Performance Improvement Department (PPID), County of Ottawa

- Paul Sachs, Director
- Matthew Chappuies, Land Use Planning Specialist
- Shannon Virtue, Assistant Director
- Pam Vanden Heuvel, Senior Secretary
- *Previously*: Mark Knudsen, former Director and Aaron Badbyl-Mast, former Land Planning Specialist

The team from Ottawa County PPID was crucial in organizing and facilitating routine meetings between the MSU groundwater research team and the Groundwater Task Force – an external committee of technical experts, stakeholders (e.g., well drillers) and managers/decision-makers at the city, township and county levels. The PPID team also provided key data and information needed to analyze water quantity/quality dynamics in Ottawa County, and helped to organize the massive field sampling campaign by securing volunteer well sampling from properties across the county.

Planning, Decision Support and Outreach

Institute of Water Research (IWR), Michigan State University

- Jeremiah Asher, Assistant Director
- Jason Piwarski, GIS Specialist
- Laura Young, Research Associate
- *Previously*: Dr. Jon Bartholic, former Director, and James Duncan, Outreach Specialist

The team from MSU IWR helped to develop a web-based decision support system (DSS) designed to assist decision-making within the county. They also created a Management Guidebook for the county and a Statewide Action Plan based on the modeling and analysis completed by the groundwater research team.

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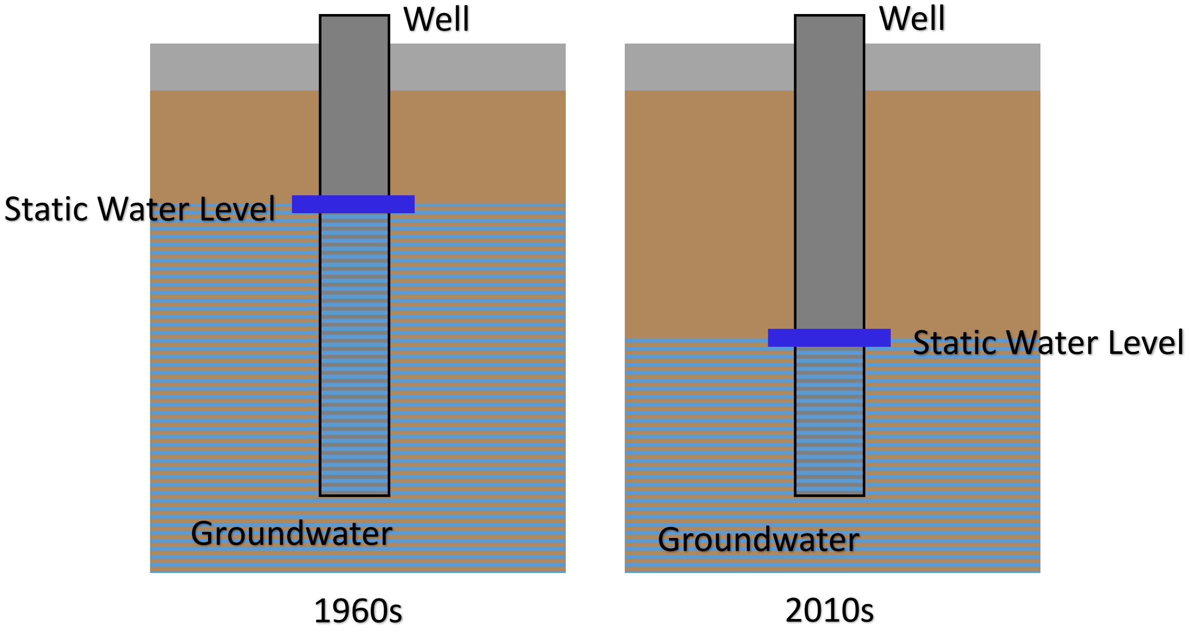
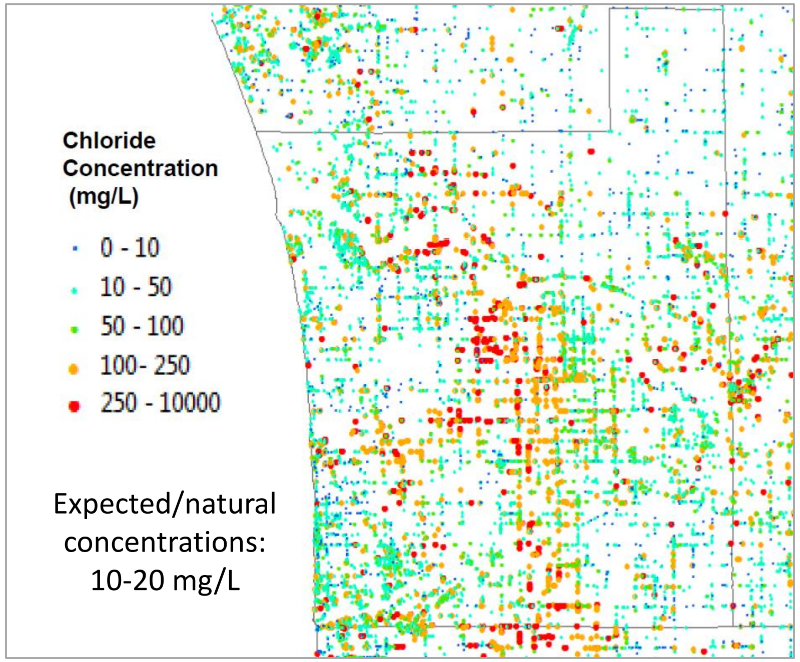
EXECUTIVE SUMMARY

BACKGROUND

In recent years, Ottawa County has experienced issues relating to its groundwater resources, including unreliable groundwater availability (quantity) and elevated groundwater salinity (quality) in certain areas of the County. A preliminary study (Phase I) based solely on existing data in state databases such as Wellogic (MDEQ 2014) and WaterChem (MDEQ 2010) showed modest to significant decline in static water levels (SWLs), especially for the bedrock aquifer. The Phase I study also showed that a significant number of water wells sampled over the last 30 years yielded chloride concentrations much greater than expected concentrations in groundwater. To better understand and protect Ottawa County's aquifer system, scientific data and precise modeling was needed to identify and confirm the exact causes and long-term implications of the above-mentioned groundwater issues.



SWL decline over recent decades



Cl Concentrations in the WaterChem database (from Phase I study)

KEY STUDY QUESTIONS

A series of several core research questions have driven this study, including:

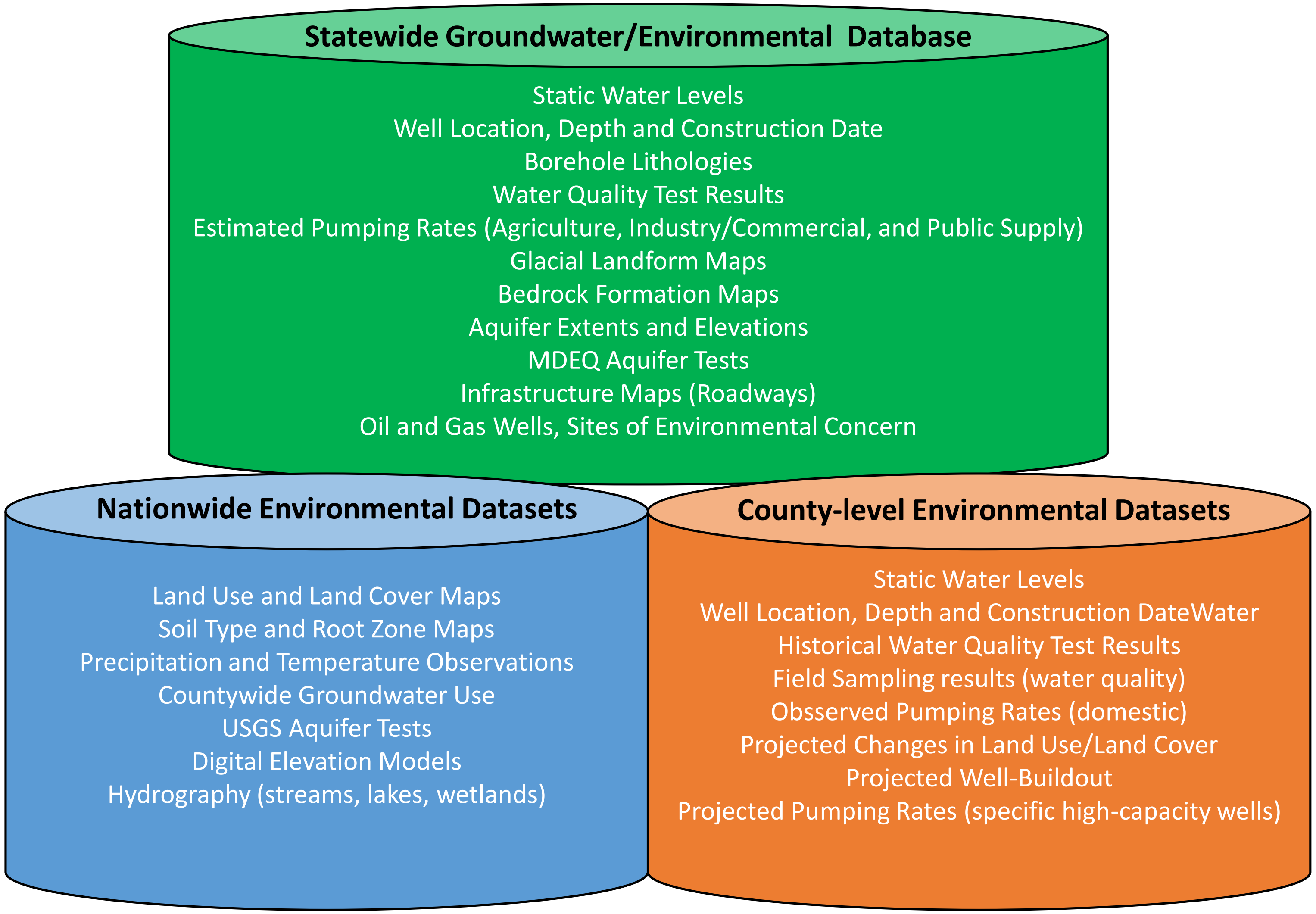
- Why is the groundwater salty in parts of Ottawa County? Is it getting saltier?
- What is controlling the occurrence of dry wells in parts of Ottawa County?
- Are the issues indicative of a larger, systemic issue?
- What are the statewide implications?
- What might the future conditions of groundwater look like over the next 20 years under projected land use and water use?

MULTISCALE DATA-INTENSIVE MODELING, VISUALIZATION AND ANALYSIS

This study is the first to characterize the integrated groundwater quality and quantity dynamics across the entire Peninsula, with detailed analyses at the statewide, regional and local scales.

This study capitalized on a vast amount of pre-existing groundwater/environmental data integrated into federal statewide databases, augmented with site-specific data and key feedback and information from Ottawa County. The massive, multiscale groundwater database assembled for this project enabled two distinct yet complimentary approaches for understanding groundwater conditions across multiple scales: data-driven modeling and process-based simulation.

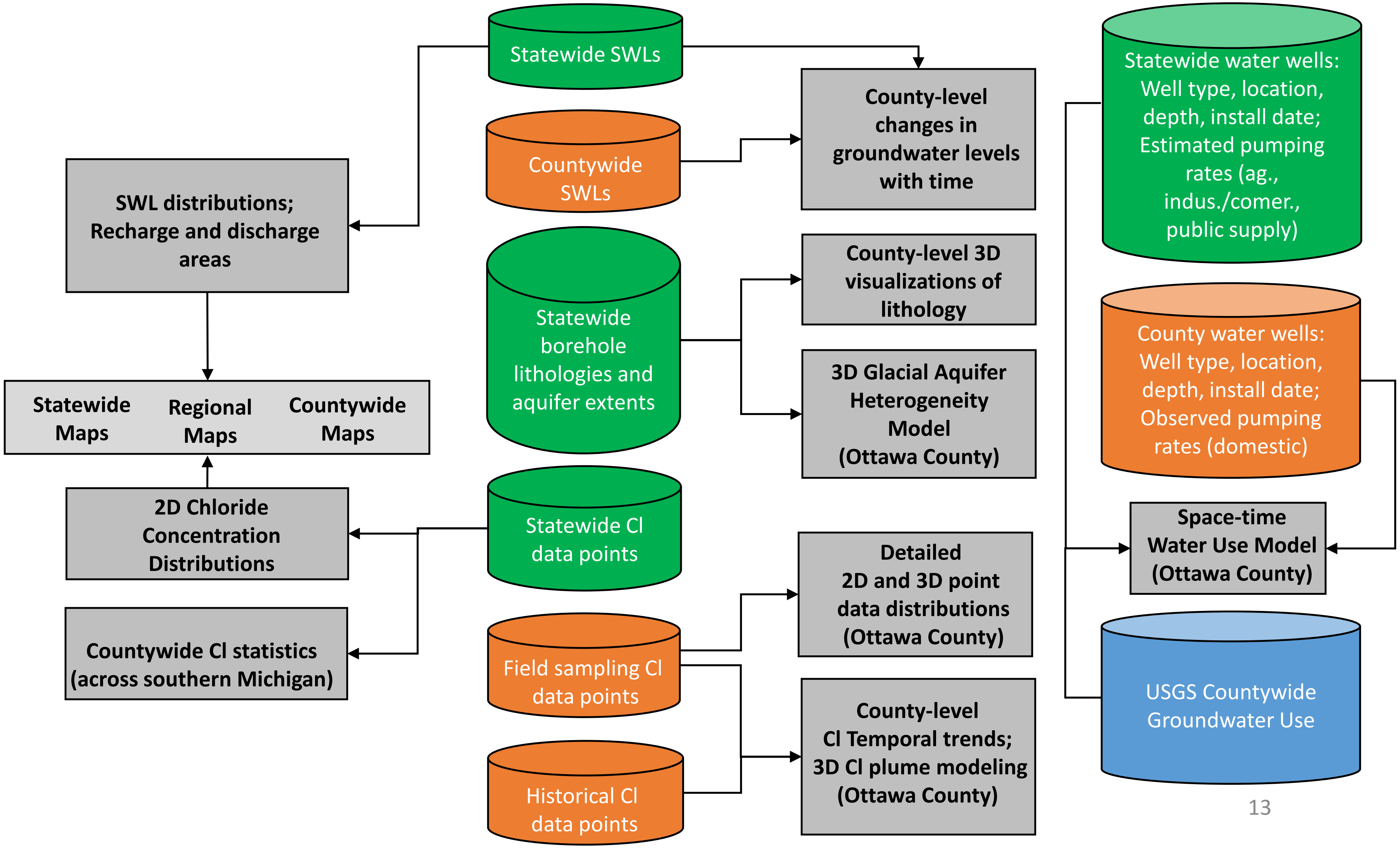
Data-driven modeling provides an efficient method for identifying patterns, relationships, and key areas across different scales without the need for understanding the underlying processes. Process-based simulation – although requiring significant expertise and resources – allows testing and refining understanding of the processes that control the observed patterns and relationships discovered through data-driven modeling. By integrating these two approaches, the valuable resources needed for process-based modeling are prioritized for better understanding key local systems identified during data-driven modeling, which in turn improves our global understanding of the system.



Data-driven Modeling Of Past And Current Groundwater Conditions

A suite of geospatial and geostatistical analyses were performed to characterize past and current conditions of groundwater quantity (SWL distributions) and quality (dissolved chloride concentrations) at multiple spatial scales (statewide, regional, and countywide) and across time. To better understand the important local-scale controlling processes of the occurrence of elevated chloride concentrations, detailed analysis of computer simulations of groundwater flow (see next slide) were combined with historical and field measurements of water quality in Ottawa County.

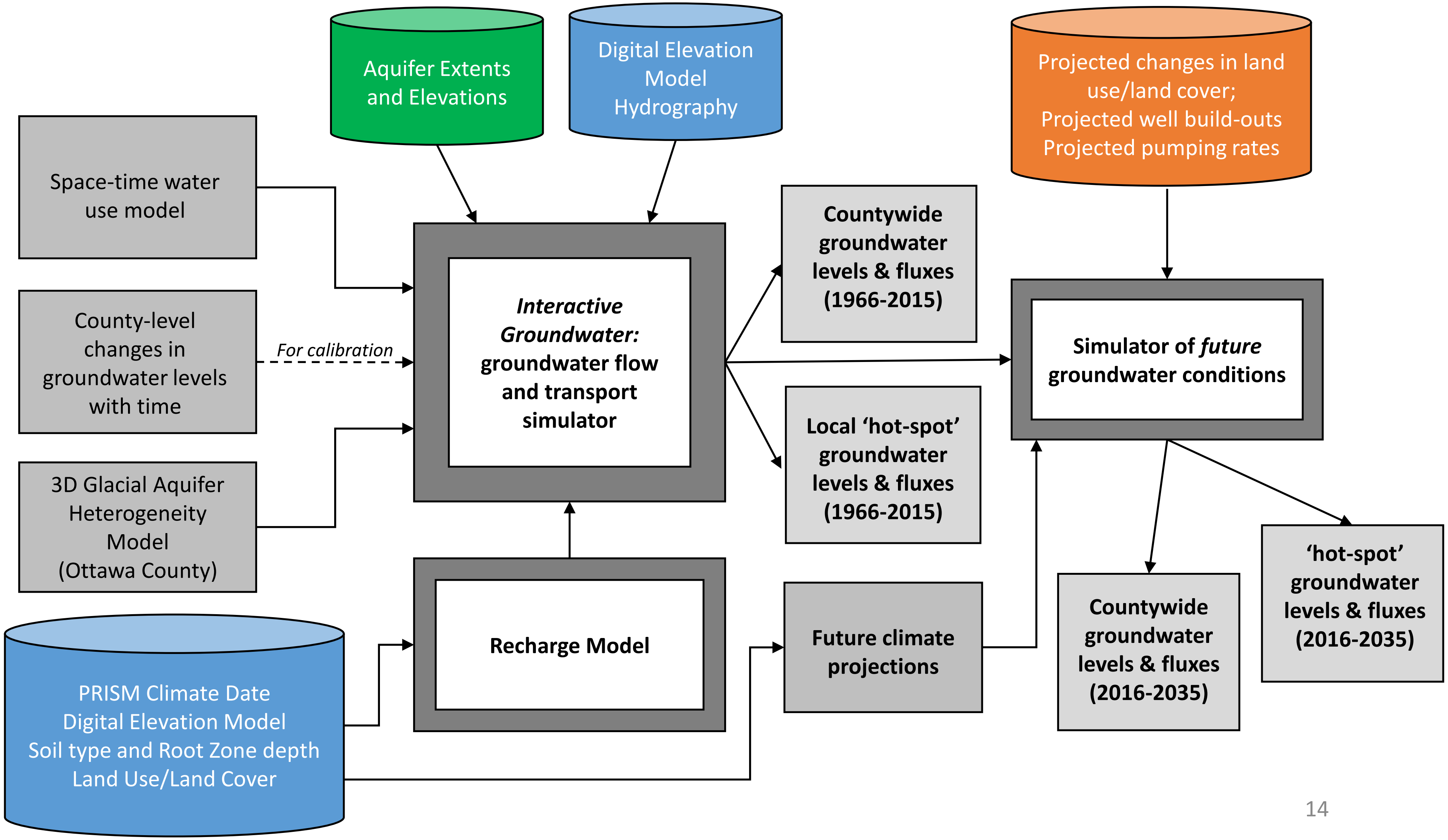
This slide shows how information from the nationwide, statewide and county-level datasets were utilized for data-driven modeling of past and current groundwater conditions.



Process-based Simulations (Ottawa County)

Process-based groundwater simulations developed for Ottawa County are based on physical groundwater flow equations, which are differential equations that are solved using numerical codes executed by computers. These simulations are 'fine-tuned' to reproduce past and current conditions that were identified through data-driven modeling. As mentioned before, they allow for understanding the processes that generate observed patterns, but may also be used to predict the effects of hydrological changes (like groundwater abstraction or climate change) on the behavior of the aquifer system.

This slide shows how the results from the data-driven modeling were combined with other aforementioned datasets to simulate past, current, and future groundwater conditions in Ottawa County.

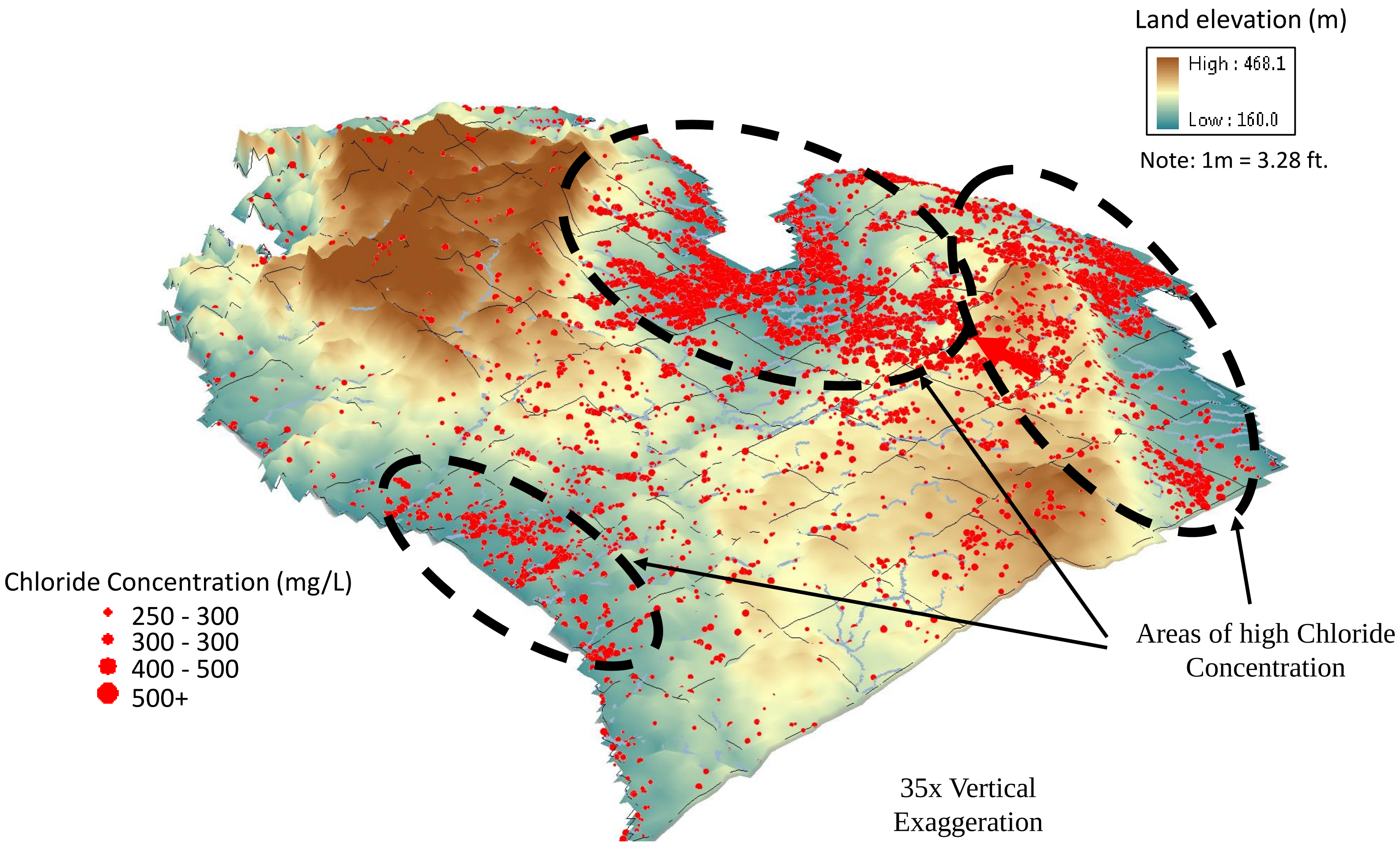


SHALLOW SALINE GROUNDWATER: A PENINSULA-WIDE ISSUE

This slide shows the locations of water wells yielding chloride concentrations (as a proxy for salinity) above 250 mg/L - the US Environmental Protection Agency (EPA) secondary drinking water standard. These "secondary maximum contaminant levels" or "SMCLs." are established only as guidelines to assist public water systems in managing their drinking water for aesthetic considerations, such as taste, color and odor. Chloride is one of the 15 parameters for which a SMCL has been established related to taste.

In addition to drinking water concerns, chloride concentrations elevated above natural conditions are detrimental to many types of crops, including many grown in the Lower Peninsula of Michigan (e.g., blueberries, potatoes, corn – see Ayers and Wescott, 1985).

Note that natural concentrations are typically less than 15 mg/L for most shallow aquifers in the mid-continent region of North America (Hem 1985, Wahrer et al., 1996), and thus, the wells shown here yield groundwater that is significantly elevated above natural concentrations.



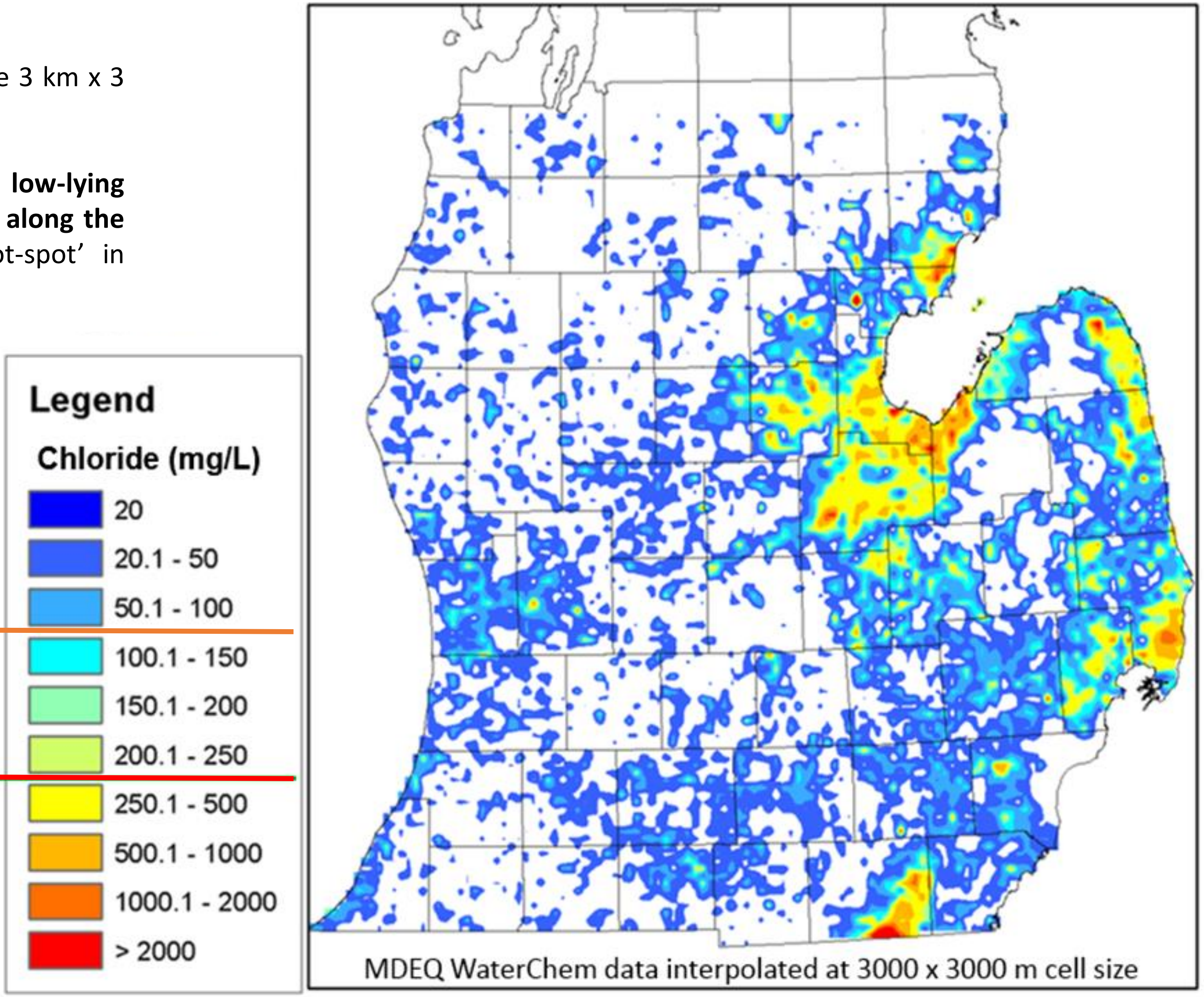
Basin-scale Analysis of Chloride Concentrations

Shown here are chloride concentrations interpolated at the 3 km x 3 km cell size, from the MDEQ WaterChem database.

Note that the highest concentrations are found in the low-lying areas near the Saginaw Bay (the Saginaw Lowlands) and along the coast of Lake Huron. There is also a significant 'hot-spot' in southeast southern Michigan (Lenawee County).

Concentrations problematic for many crops

US EPA secondary drinking water standard

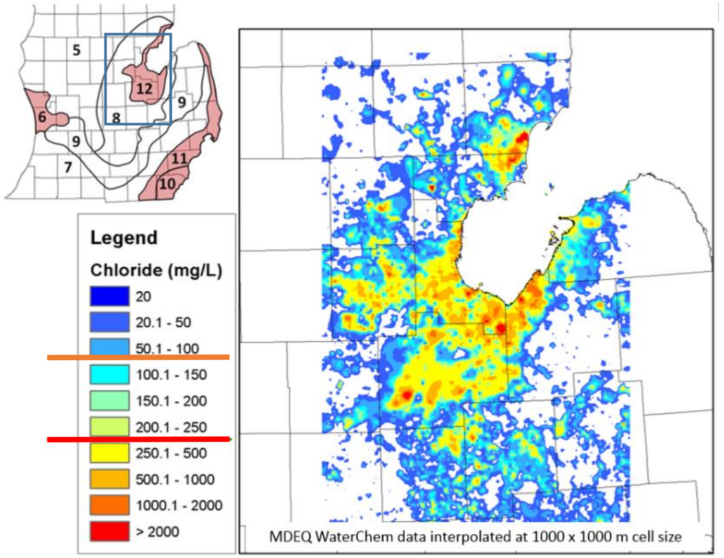


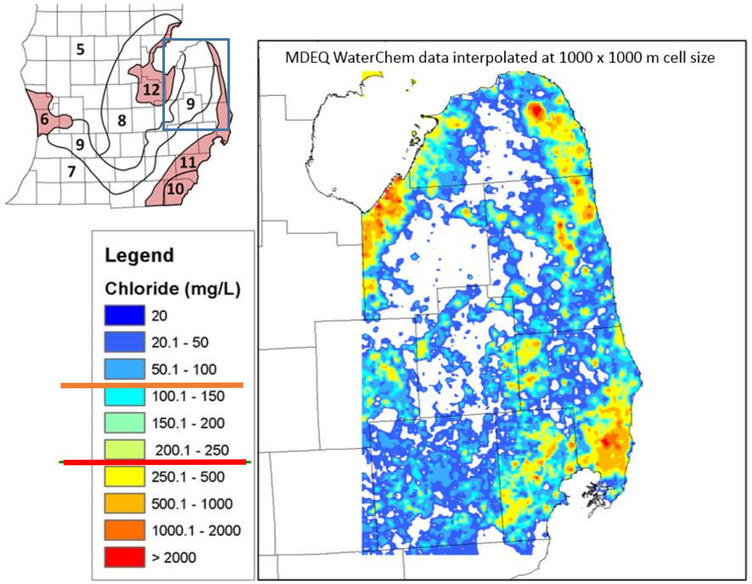
MDEQ WaterChem data interpolated at 3000 x 3000 m cell size

Regional-Scale Analysis of Chloride Concentrations

Higher-resolution regional analyses were performed to capture more details of the spatial variation of chloride concentrations in the Lower Peninsula of Michigan. Shown here are interpolated chloride concentrations at the 1 km x 1 km cell size.

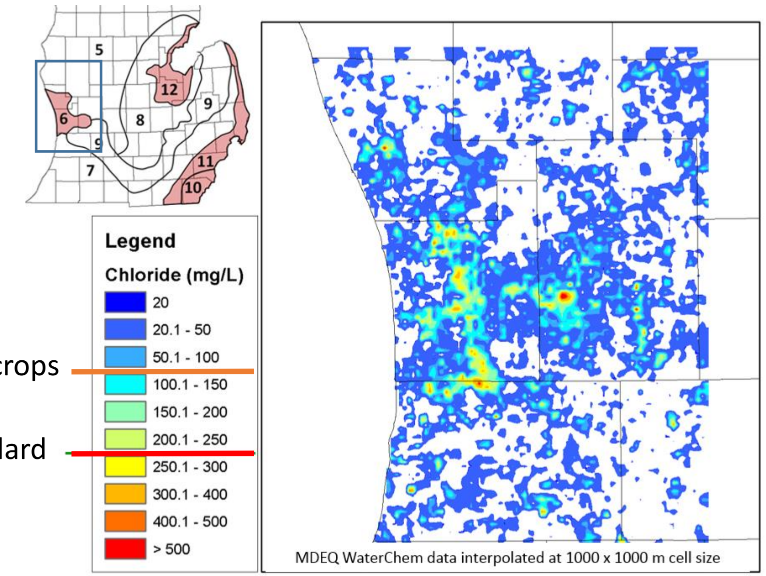
Note that concentrations are well above natural conditions throughout significant portions of the regions shown here.

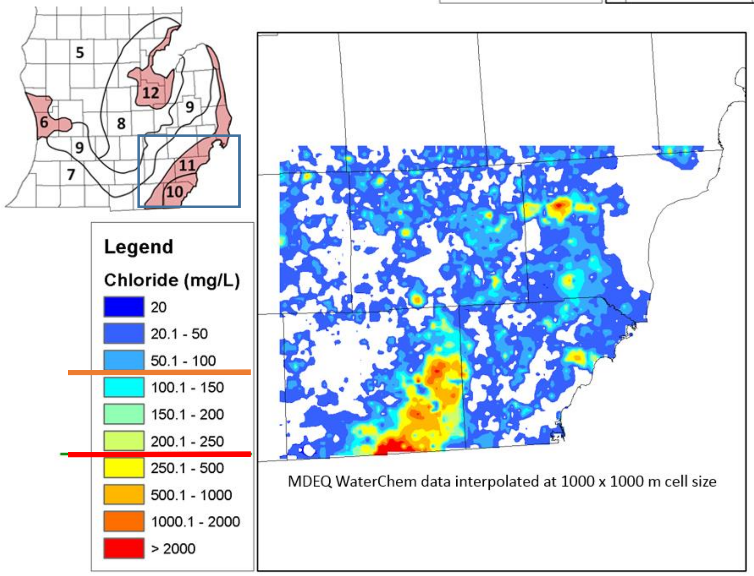




Concentrations problematic for many crops

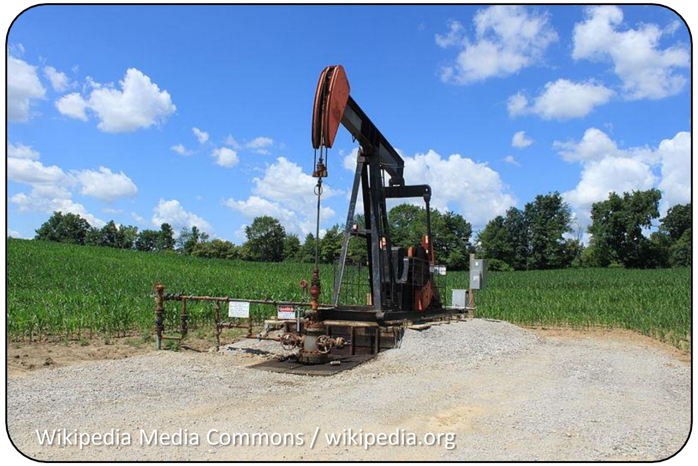
US EPA secondary drinking water standard





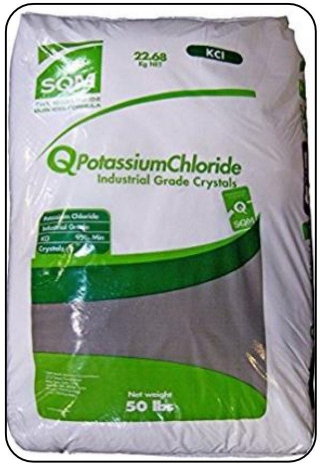
Anthropogenic Sources Of Elevated Chloride Concentrations

Road Salt (NaCl)



Leaky oil & gas wells

Septic Tank Effluent



Agricultural Fertilizer (KCL)

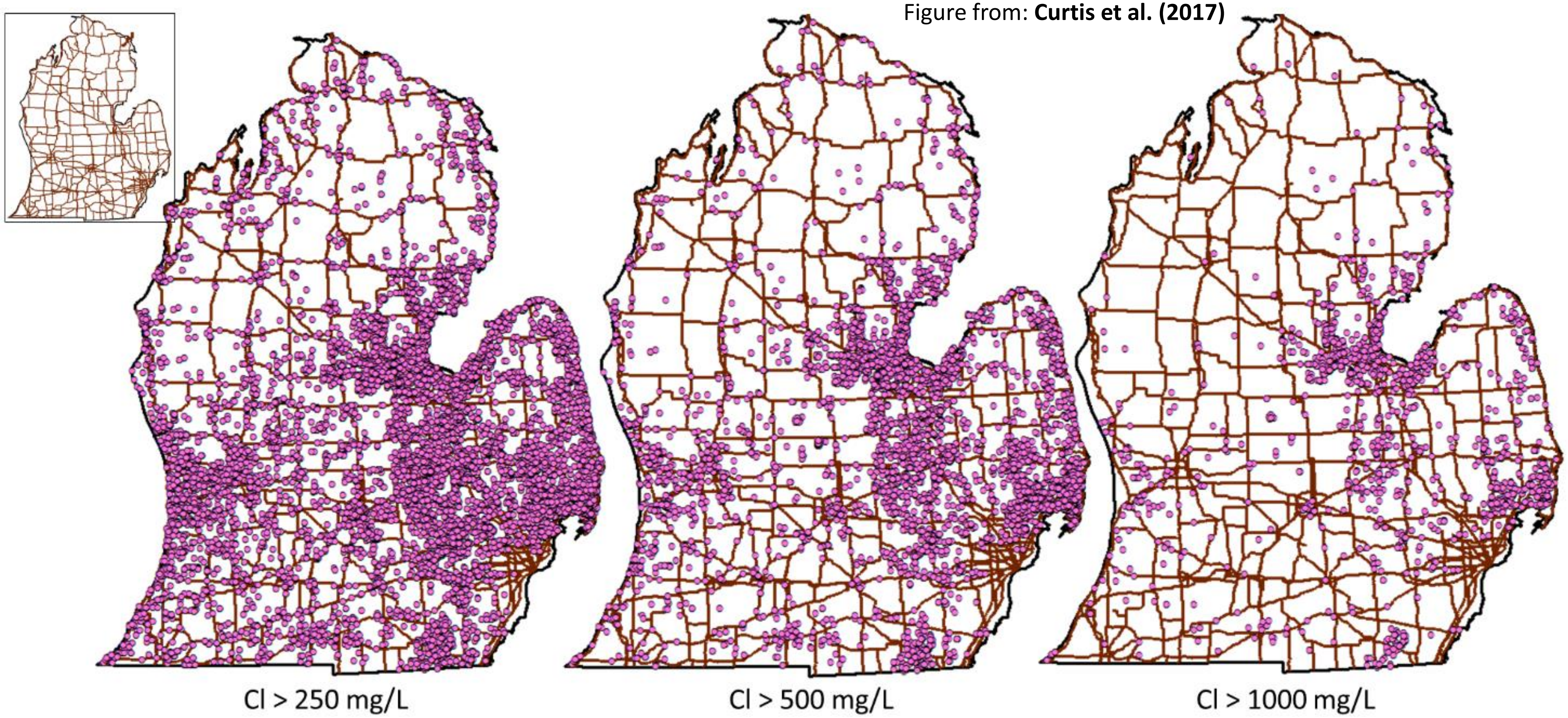
A key aspect of this study was to determine the primary source(s) of elevated chloride concentrations in the Lower Peninsula of Michigan. **Possible anthropogenic sources include roadway deicers (road salt), septic tank effluent, agricultural fertilizers (e.g., potassium chloride) and leaky oil/gas wells.** The table on the right presented expected chloride concentrations in groundwater due to these various sources.

Dissolved Road Salt	Mineralized water from leaky oil/gas pipe	Septic Tank Effluent	Dissolved Agricultural Fertilizer
On average: 100 mg/L (Williams et al. 2000) As high as: 275 mg/L (Perera et al. 2010) 476 mg/L (Howard and Haynes, 1993) 640 mg/L (Foos 2003)	Potential very high (well above 250 mg/L)	207 mg/L (Harman et al. 1996) 53 mg/L (Viraraghavan et al 1975) 20-100 mg/L (Katz et al. 2011)	Below 30 mg/L (Kelly et al. 2012)

Highway Network and Elevated Chloride Concentrations

A simple geospatial analysis was performed to assess the potential impact of anthropogenic sources on this study by overlying elevated Cl− concentrations (>250, >500, and >1000 mg/L) over a map of the Lower Michigan highway network. The clustering around population centers for the >250 mg/L threshold, for example, the suburbs of Detroit (southeast Lower Michigan) and the Greater Lansing area (south-central Lower Michigan), and the slight association for the >500 mg/L threshold, when considered with the expected concentrations found in the aforementioned literature, suggests that **anthropogenic sources are at least partially responsible for the clustering of elevated Cl^- concentrations at these thresholds. For the >1000 mg/L threshold, elevated Cl− concentrations are not associated with areas of dense road and highway networks.**

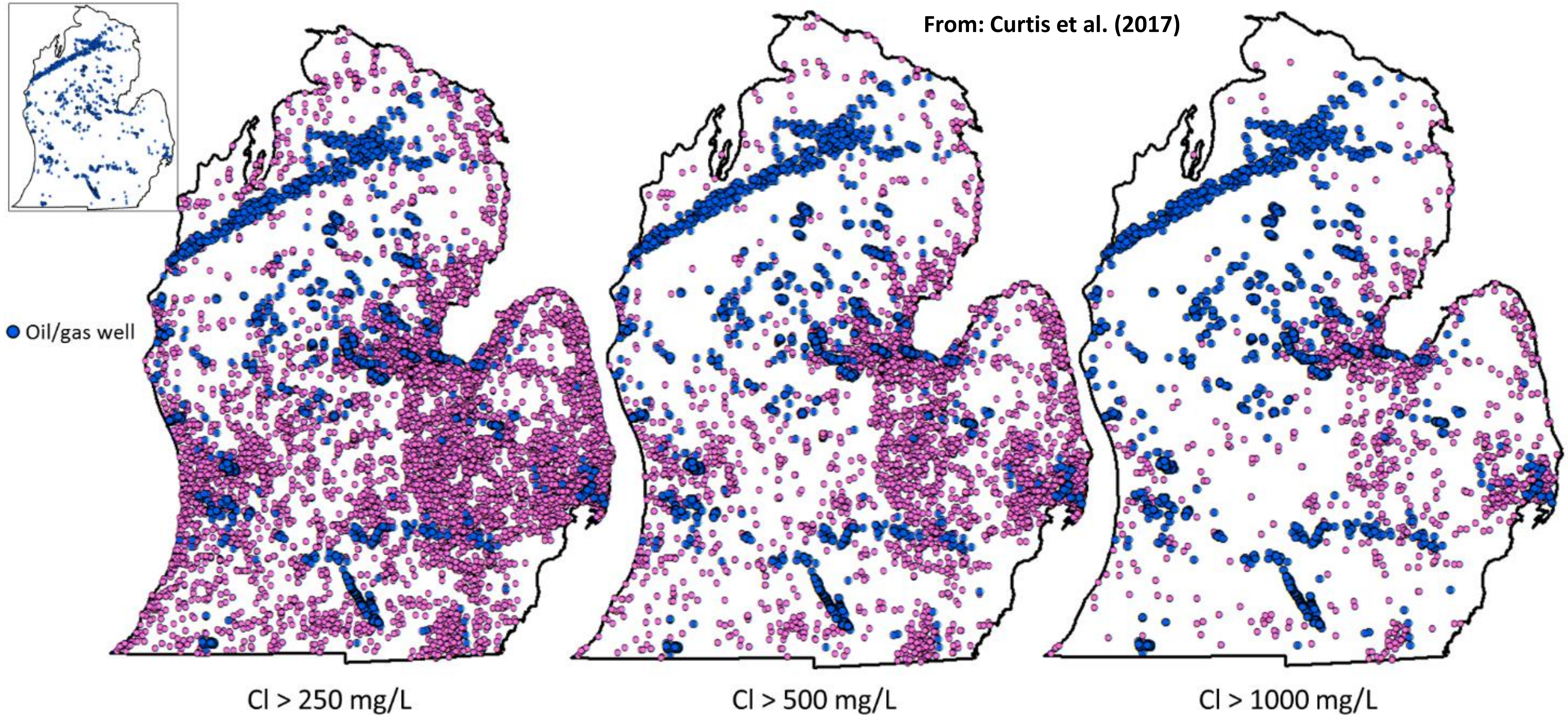
Figure from: **Curtis et al. (2017)**



Oil and Gas Wells and Elevated Chloride Concentrations

This slide presents overlays of elevated Cl− concentrations and oil and gas wells across the Lower Peninsula of Michigan. Although there are instances where elevated Cl− concentrations are in close proximity to oil/gas wells—even for the >1000 mg/L threshold—there are large clusters of oil/gas wells that are not associated any significant clustering of elevated Cl−. Thus, there may be localized instances where leaky oil/gas wells are impacting the near-surface environment, for example, in southeast Michigan along the coastline, but **there does not seem to be a significant peninsula-wide spatial correlation between oil/gas wells and elevated Cl− concentrations for the thresholds considered**.

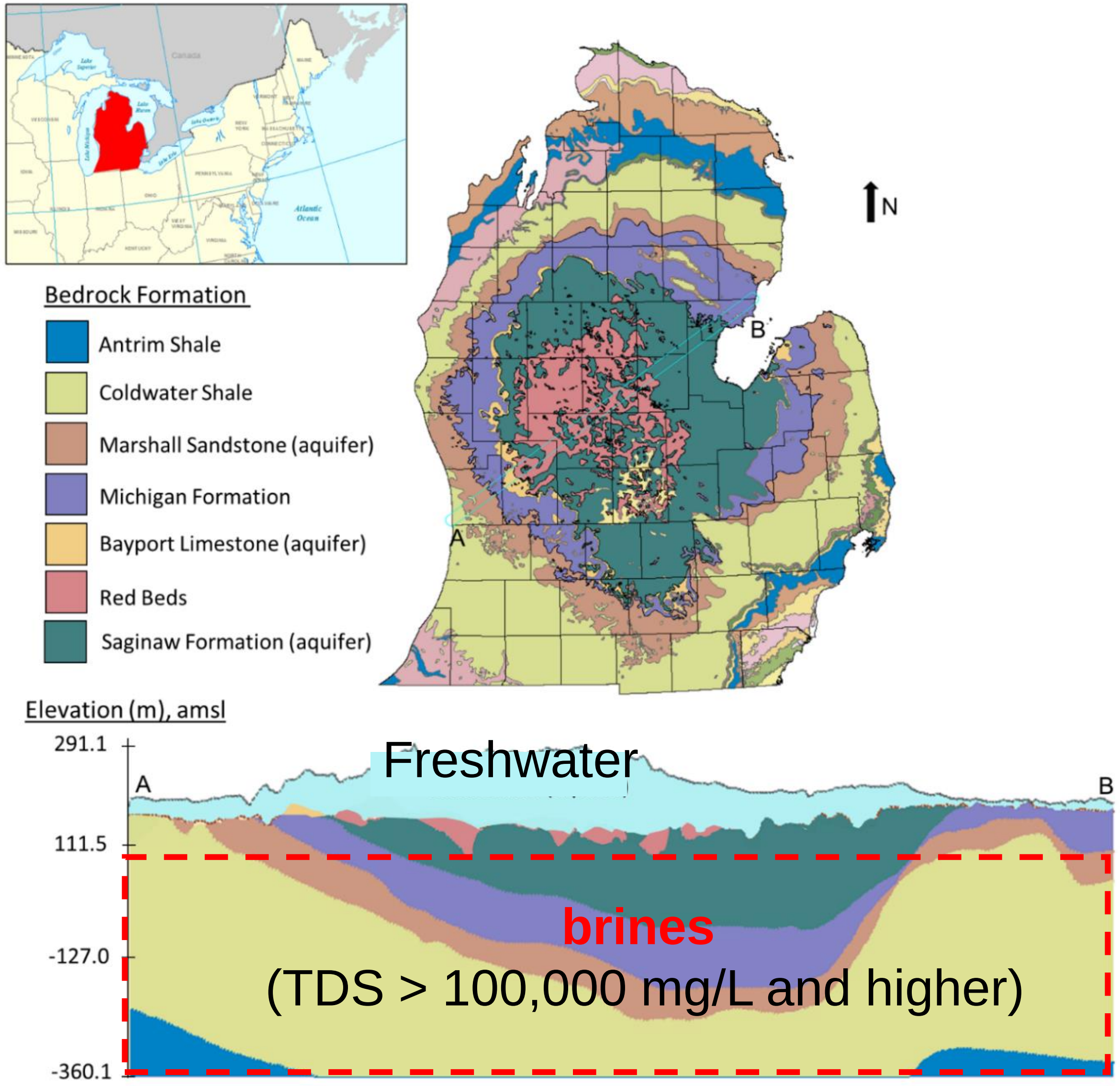
From: Curtis et al. (2017)



Natural Source Of Elevated Chloride Concentrations

There is an important natural source to consider. The Michigan Basin —an ovate, bowl-shaped accumulation of sedimentary rock – contains very high total dissolved solids concentrations (TDS>450,000 mg/L) in its deep bedrock formations (Wilson and Long 1993a, 1993b). Several studies published as part of the U.S. Geological Survey (USGS) Regional Aquifer-System Analysis (RASA) program documented high dissolved-solids and dissolved-chloride (Cl−) concentrations (TDS>100,000 mg/L) within the Mississippian and Pennsylvanian bedrock formations, with concentrations that increase towards the basin center (e.g., Ging et al. 1996; Meissner et al. 1996; Westjohn and Weaver 1996b; Lampe 2009). Lane (1899) and Long et al. (1988) documented saline near-surface (<100 m) groundwater in east-central Lower Peninsula of Michigan—the Saginaw Lowlands.

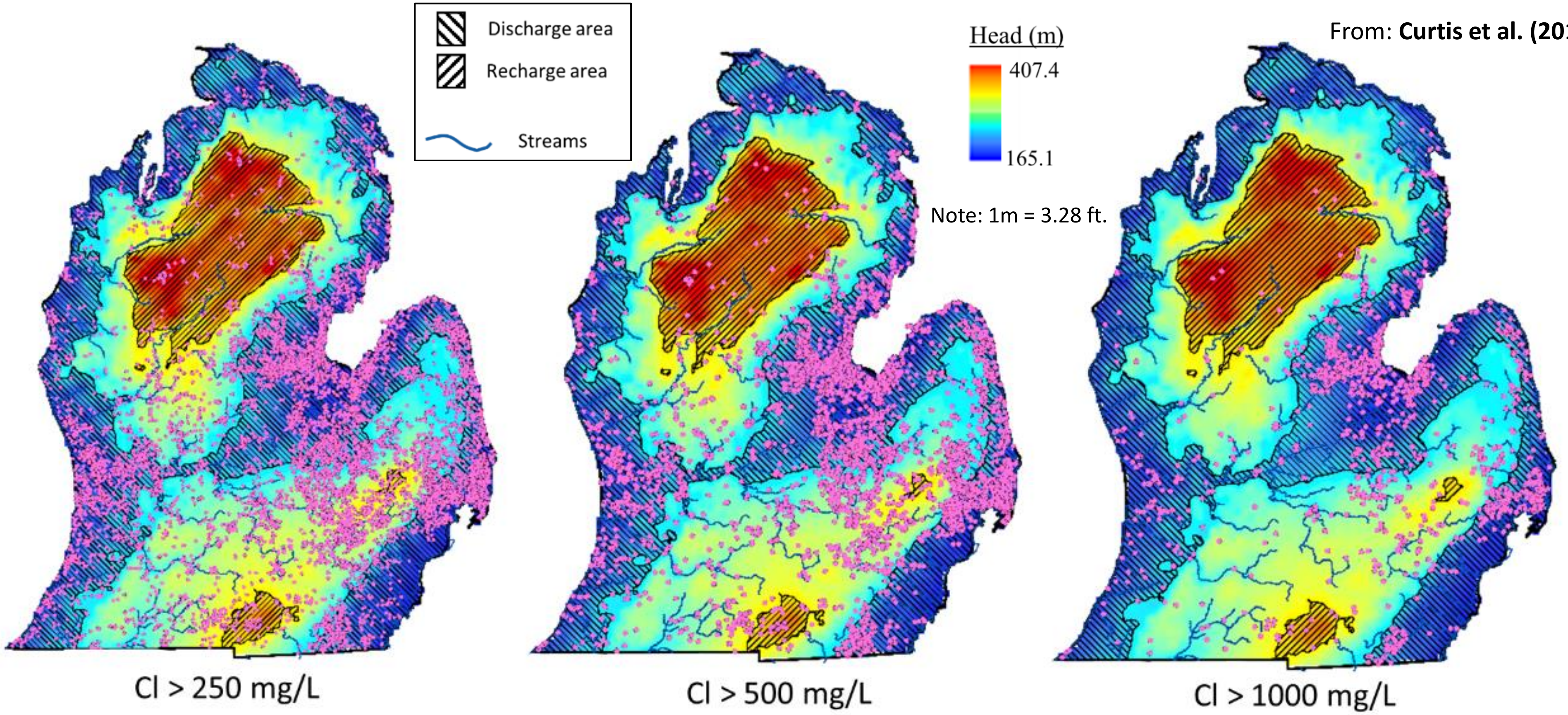
A *key question* that was considered: **are these deep brines upwelling and mixing with shallow freshwater, leading to the observed elevated chloride concentrations in shallow aquifer systems across the state?**



Elevated Chloride Concentrations and Basin-Scale Groundwater Flow Patterns

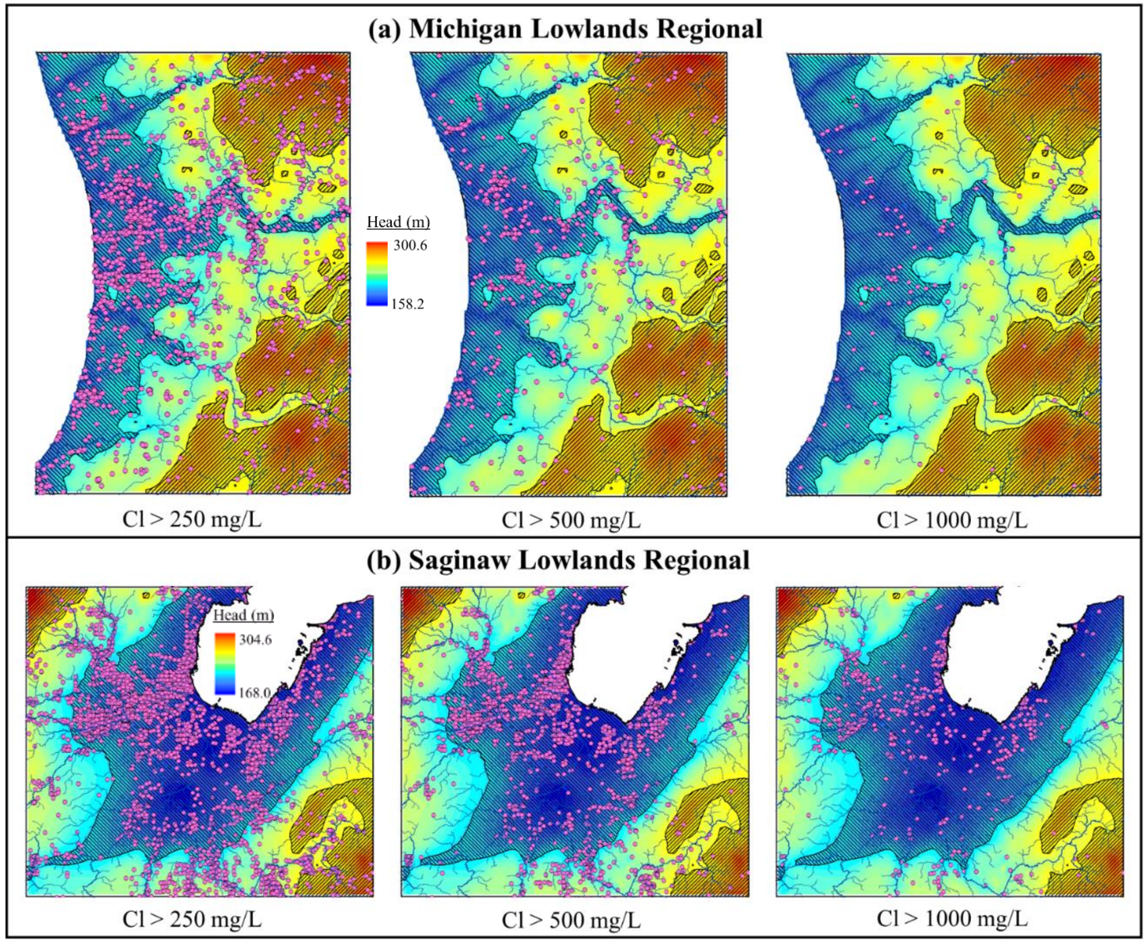
This slide shows a peninsula-wide delineation of groundwater recharge and discharge areas (groundwater "mounds" and "valleys", respectively) with elevated chloride concentrations (>250, >500, >1000 mg/L) overlaid. Clearly, **elevated chloride concentrations are focused to groundwater discharge** areas along the coast, in the Saginaw Lowlands, and in Michigan Lowlands (west-central southern Michigan). In discharge areas, groundwater is primarily moving upwards.

From: **Curtis et al. (2017)**

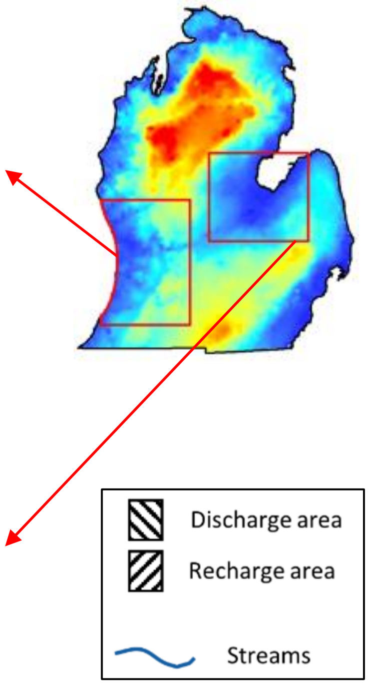


Elevated Chloride Concentrations and Regional-Scale Groundwater Flow Patterns

A similar analysis of groundwater recharge/discharge areas and the occurrence of the elevated chloride concentrations was performed at the regional scale for the Michigan and Saginaw Lowlands. As seen at the statewide scale, **clusters of elevated Cl^- concentrations occur primarily within local discharge zones**. The recharge zones and the interfluves between major streams are mostly devoid of elevated Cl– concentrations. Note that these patterns are seen for all subsets of Cl data (>250, >500, >1000 mg/L).



From: **Curtis et al. (2017)**

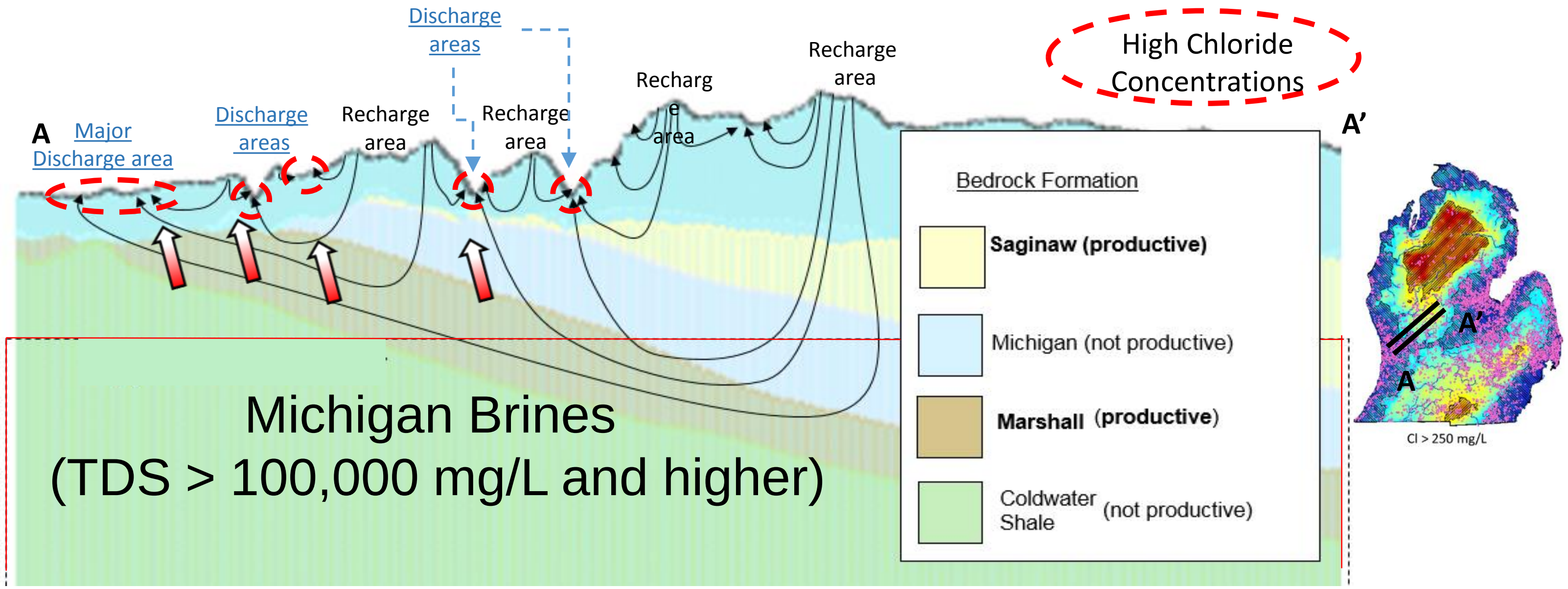


UPWELLING BRINES ARE THE DOMINANT SOURCE OF ELEVATED CHLORIDE CONCETRATIONS

The results of the multiscale Cl−-SWL analyses are interpreted as follows: deep flow patterns naturally deliver brackish water towards the statewide shallow groundwater discharge areas, and undulations in the regional topography and the major stream networks form regional flow patterns that act as 'natural pumps' of the brine-influenced groundwater, concentrating the Cl− contamination along large stream corridors. This interpretation is consistent with Heath's (1984) overview of the hydrogeology of the glaciated central region of the U.S., which included the entire Lower Peninsula of Michigan: " . . . the depth to saline water is less under valleys than under uplands, both because of lower altitudes and because of the upward movement of saline water to discharge."

The data-driven analysis and statewide and regional scales can be summarized as follows:

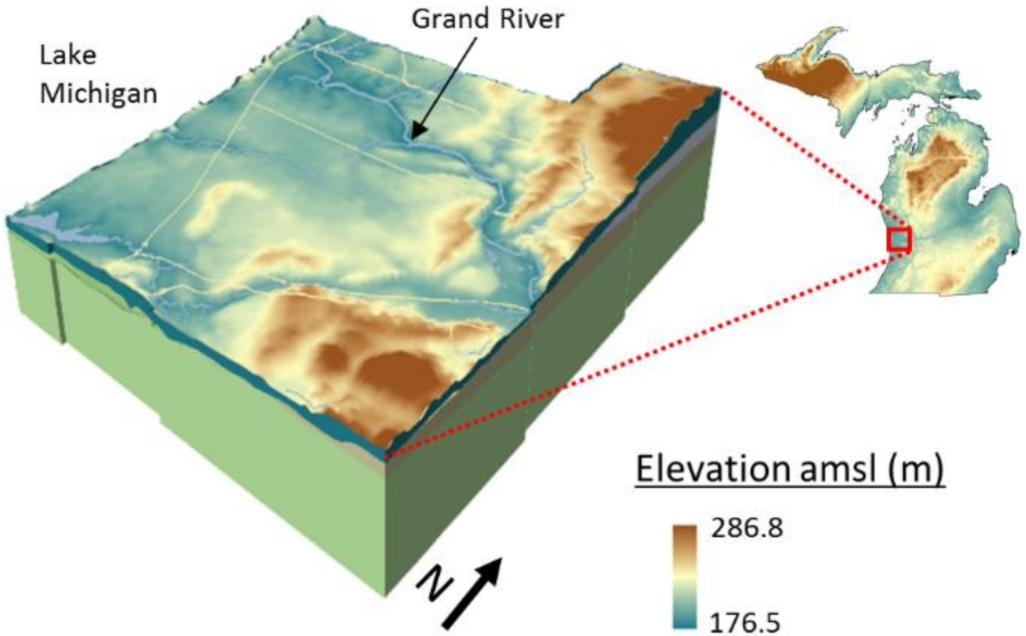
- **A natural process primarily controls the large-scale distribution of brine-influenced groundwater in southern Michigan**
- **The 'signal' from brines is most obvious at higher concentrations…at lower concentrations, contamination from anthropogenic sources may be embedded in the observations**



NATRUAL DISCHARGE AREAS, PUMPING, AND GEOLOGY CONTROL LOCAL DYNAMICS

The key finding s from county-level evaluations were as follows:

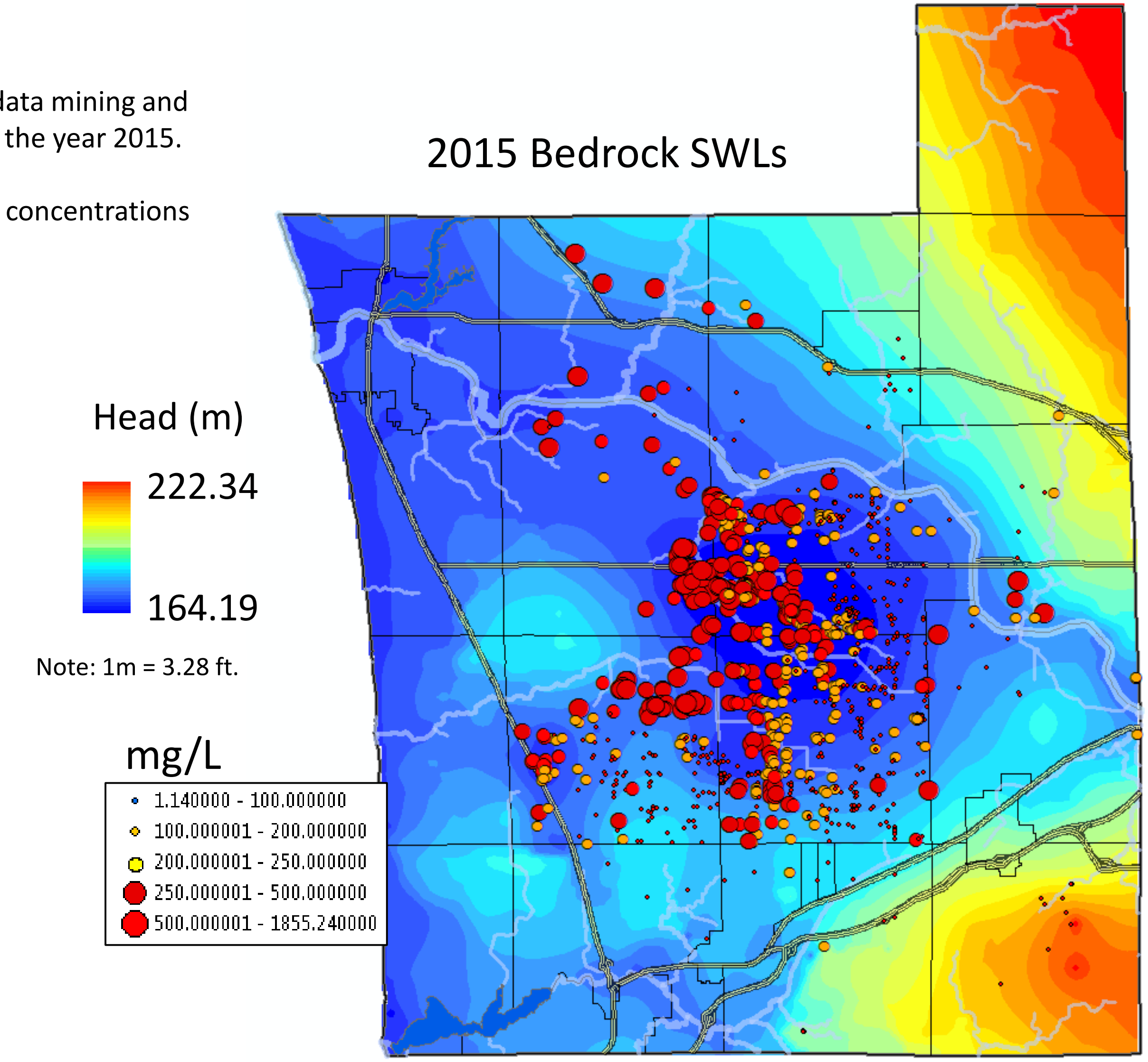
- **Similarly to the basin-scale and regional scale analyses … the contamination is worst where groundwater levels are low (both naturally and 'artificially'**
- **The contamination is focused to the deeper bedrock aquifer (Marshall aquifer)**
- **A thick, continuous layer of clay/silt prevents freshwater flushing from above**



Cl-SWL Relationship was also Identified for Ottawa County

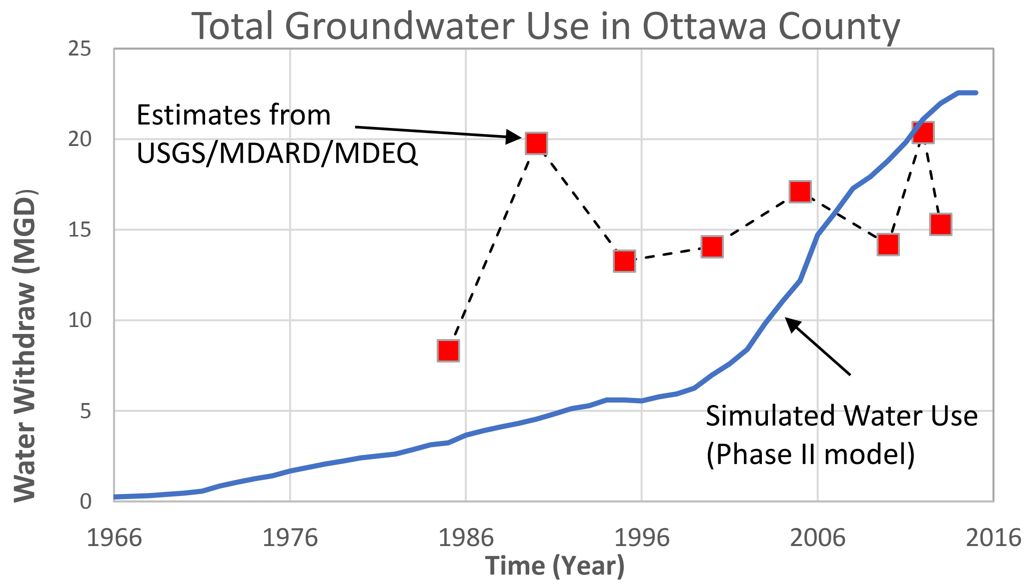
This slide shows chloride concentrations compiled from the historical data mining and field sampling overlaid on the simulated Static Water Levels (SWLs) for the year 2015.

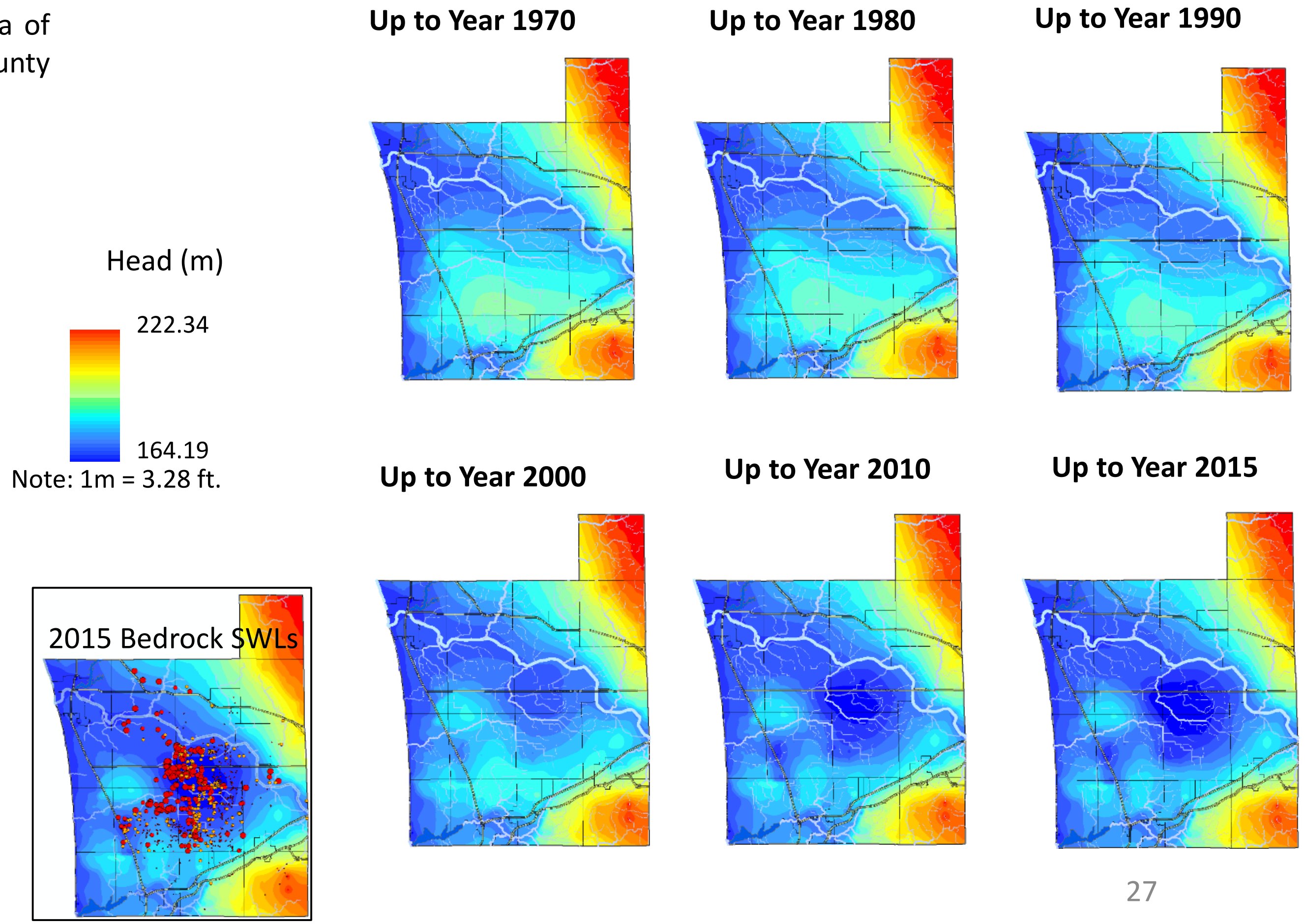
As seen in the peninsula-wide and regional-scale analyses, elevated Cl^- concentrations are focused in areas of **low** groundwater levels.



Pumping Seems to Have Made the Problem Worse

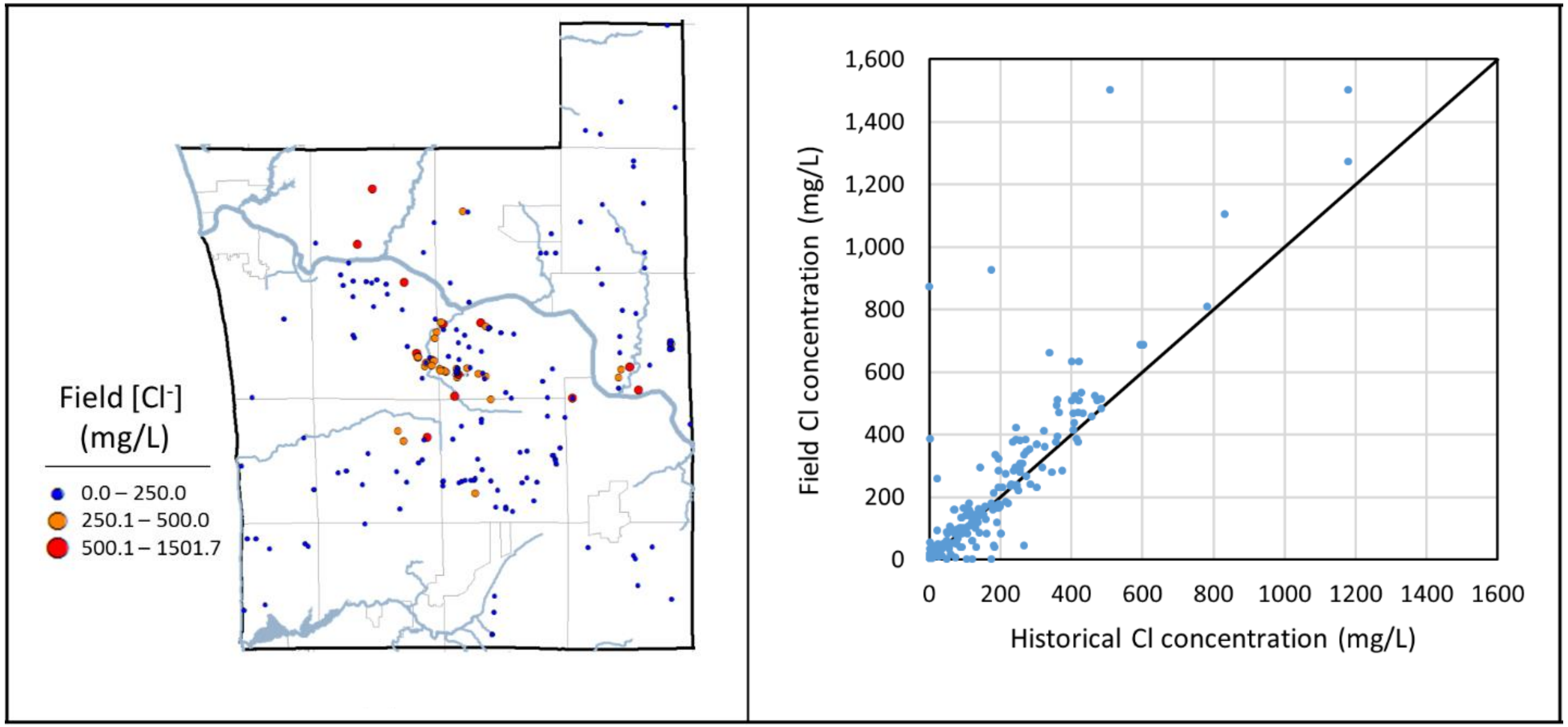
While areas of low groundwater levels are natural (e.g., along major stream corridors and in the northwest part of the county), others are due to human activity. In particular, the cumulative impact of increased groundwater withdrawals over the past 50 years has created ‘artificially’ low groundwater levels in parts of the county. Extensive area of groundwater drawdown has occurred in the central and west-central parts of the county as a result of groundwater pumping.





Decline in SWL due to Pumping …. Has Aggravated the Cl problem Over Time

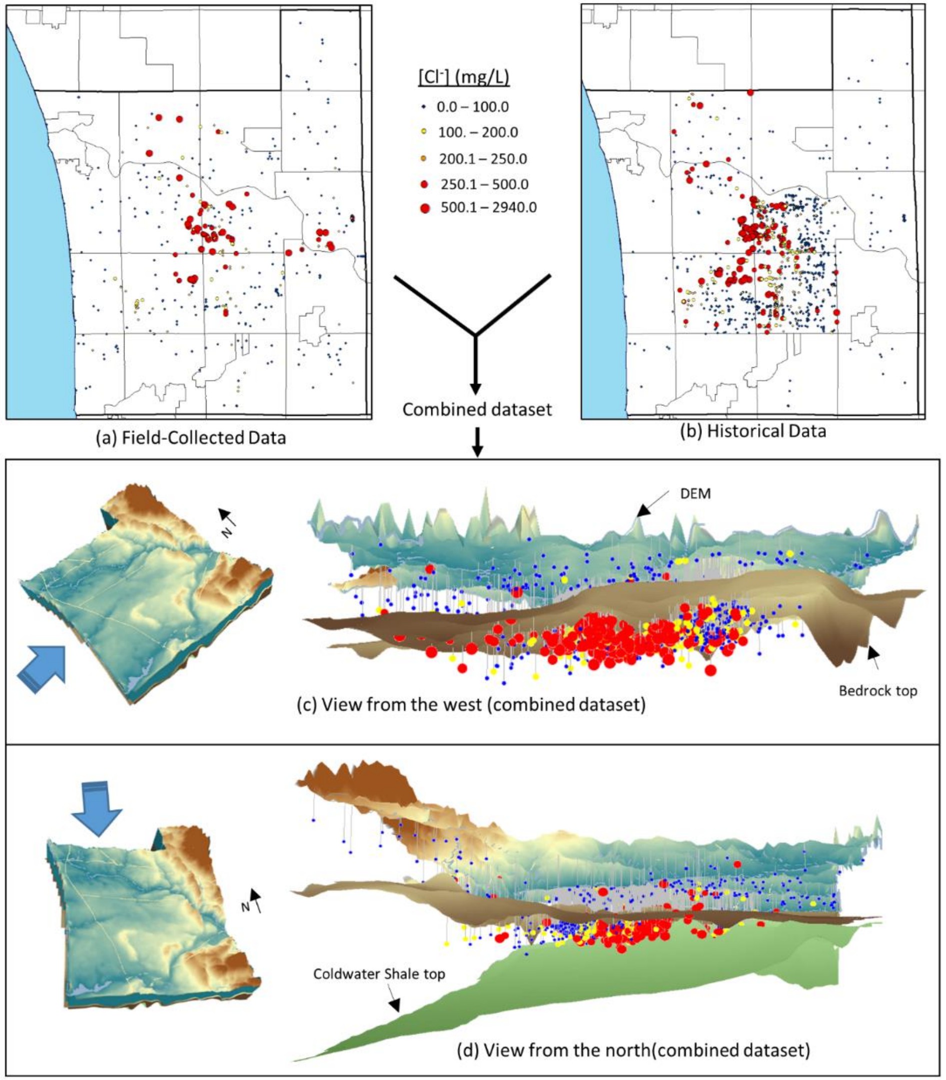
An analysis was completed using samples from locations yielding historical data and where field data were collected. This allowed for comparing samples taken at different times from the same wells. **Comparing the field-collected Cl- concentration versus the historical Cl- concentration for 248 of the visited during the field sampling shows a general increase in Cl- concentrations** (i.e., most of the data points fall above the 45 degree line of perfect agreement). This is especially the case for locations with a field-collected concentration of 250 mg/L or more, with 62 of 75 (83%) such locations showing an increase in time. As below, most of these locations occur in the area where significant drawdown has occurred (central Ottawa County).



Analysis of the 3D structure of Cl Concentrations in Ottawa County

This slide presented a three-dimensional visualizations of the Cl− concentrations and the bedrock top elevation surface. Clearly, **elevated Cl− concentrations are focused in the Marshall bedrock aquifer, and all but a few of the glacial wells with elevated Cl− concentrations are screened at or near the bedrock surface**.

The results are consistent with the "brine upwelling hypothesis" for the elevated groundwater salinity in the Michigan Lowlands, notably that **Cl− concentrations increase with depth (consistent with a deep source),** and that almost all samples yielding high Cl− concentrations, i.e., above 250 mg/L, came from wells completed in the Marshall bedrock aquifer (which is known to contain brines down-dip of the subcrop area in the Michigan Lowlands—see Ging et al. 1996).



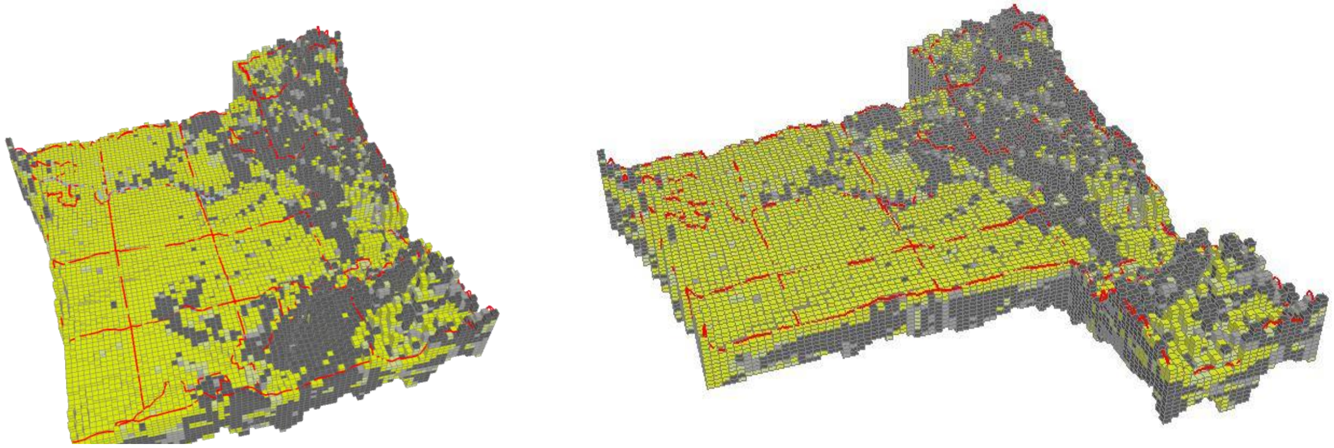
Chloride mg/L

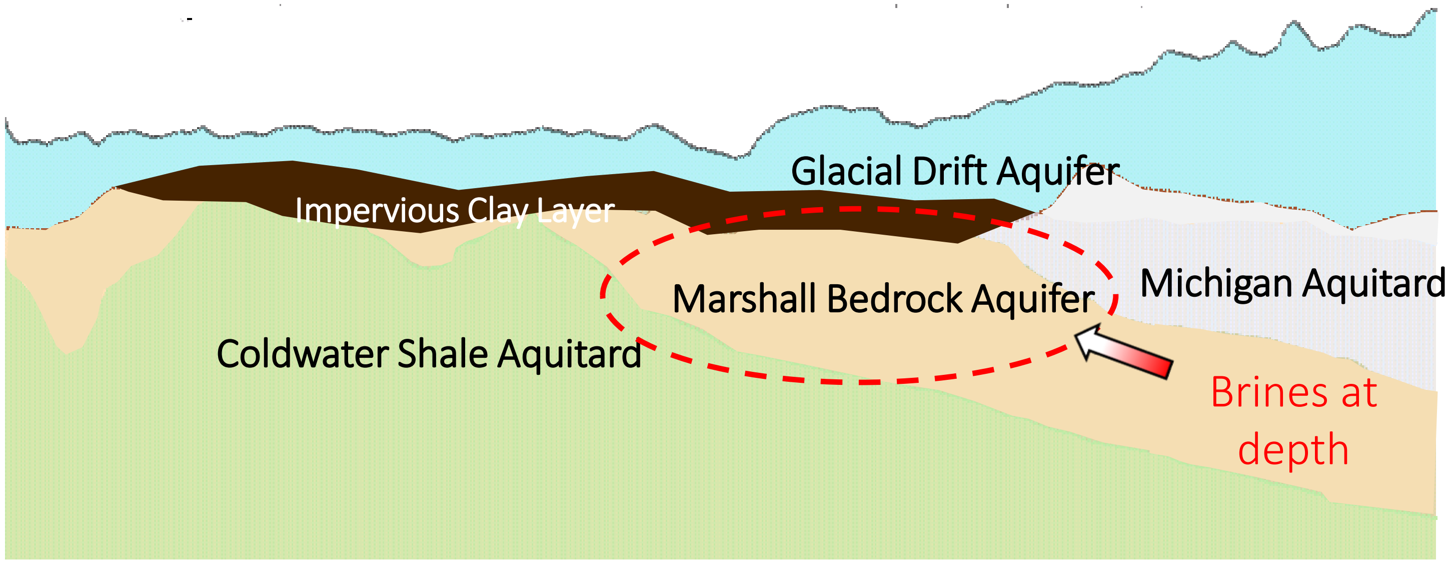
2.19 - 100	
100 - 200	
200 - 250	
250 - 500	
500 - 1,855	

Surficial Glacial Geology in Ottawa County

A geostatistical simulation of the aquifer material distribution revealed that **a continuous clay layer spans across central Ottawa County and restricts freshwater recharge to the bedrock aquifer lying below. This slow-flushing of deeper groundwater is partially responsible for elevated chloride concentrations in parts of the county's aquifer system.**

- AQ (aquifer
- MAQ (marginal aquifer)
- PCM (partially confining)
- PCM (confining material)





Screening-level Evaluations For Counties Potentially At Risk

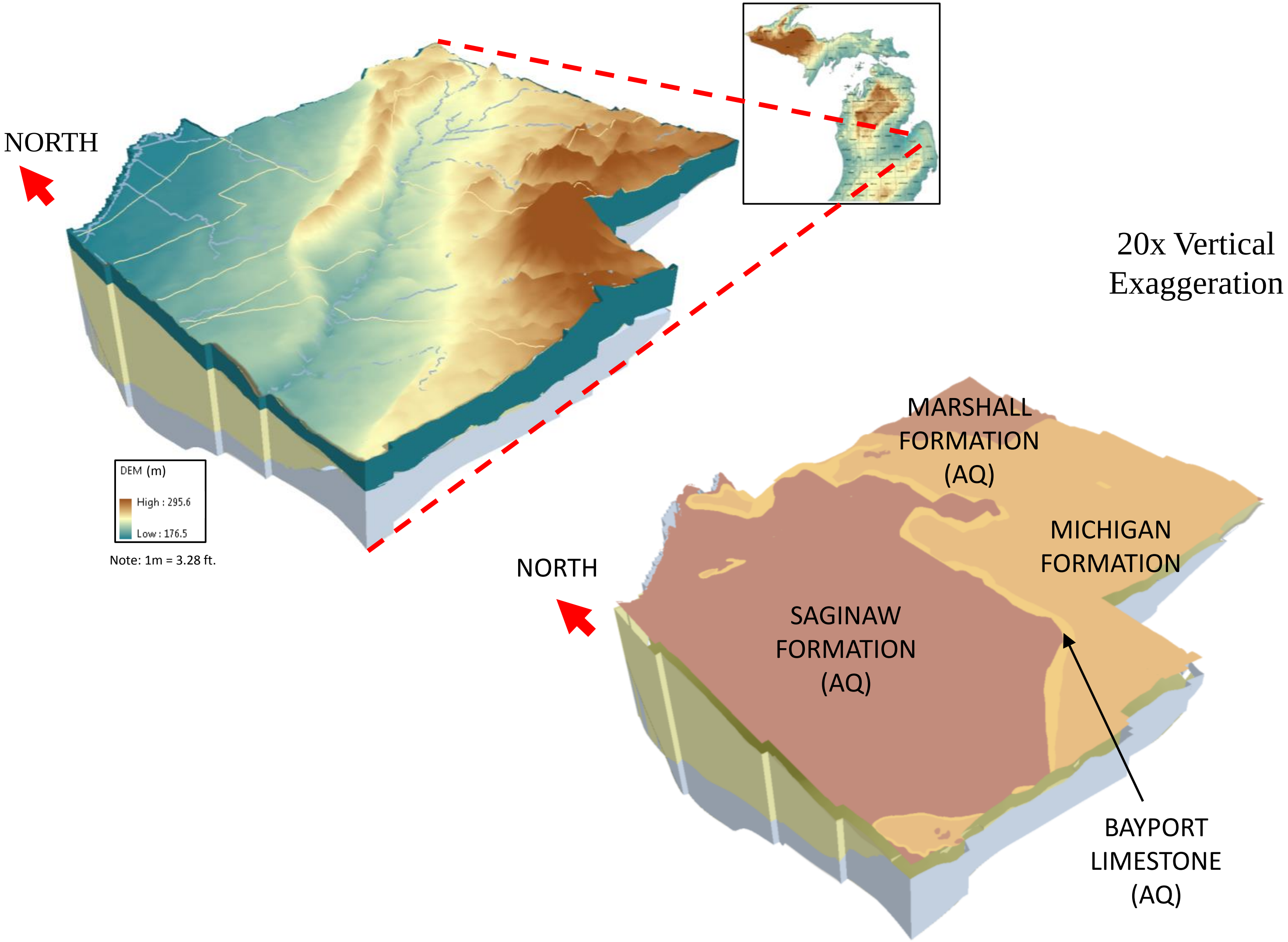
Thirty-six counties in low-lying areas of southern Michigan were identified as ‘potential at risk. For each of these counties, we used pre-existing data from Wellogic and Waterchem to map/analyze:

- Distribution of elevated chloride concentrations
- Static Water Level maps (groundwater levels)
- Subsurface occurrence of clays/silts and extent of bedrock aquifers
- Temporal trends in Static Water Levels (SWLs

Illustrative examples are shown on the following slides.

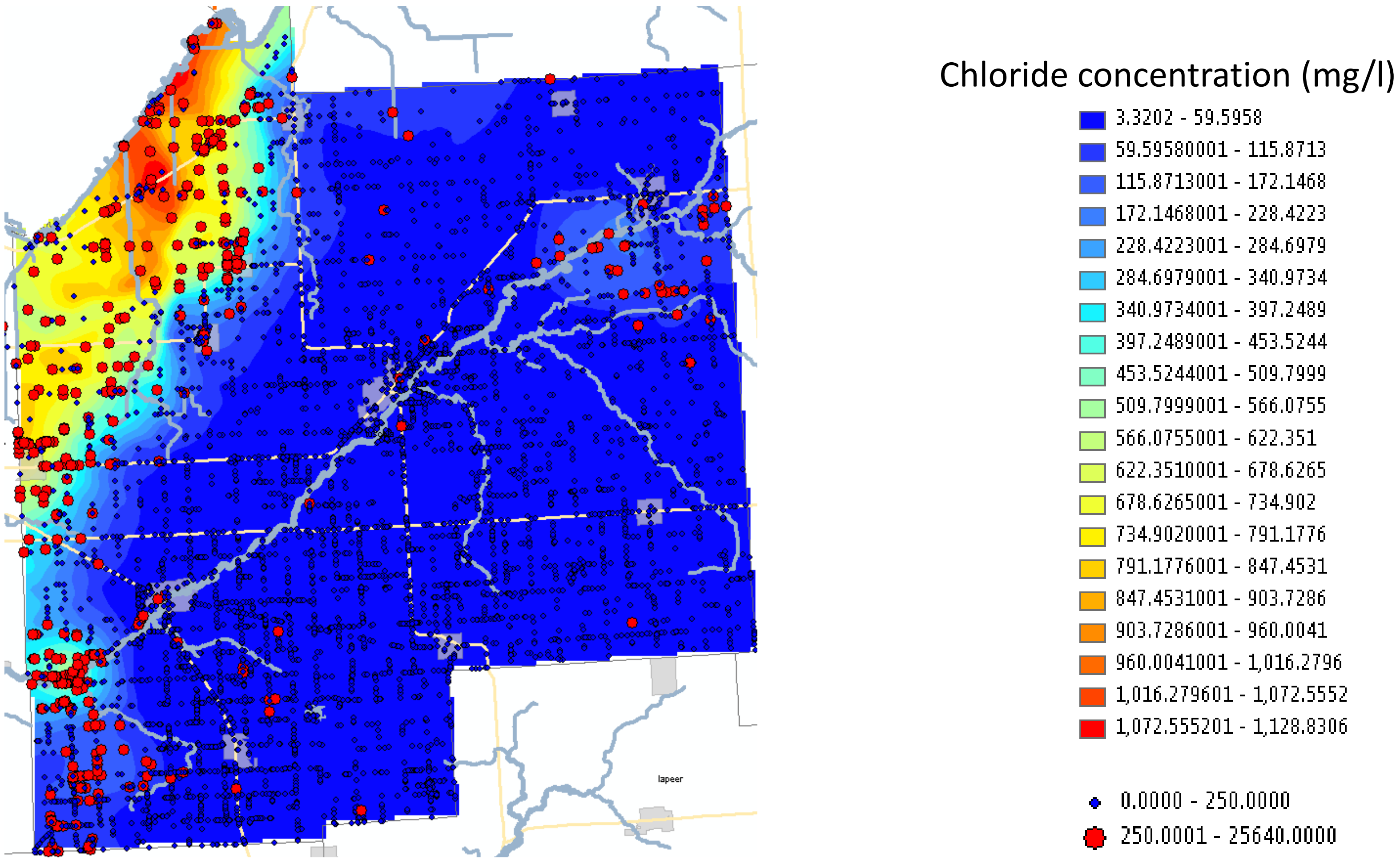
Illustrative Example # 1 – Tuscola County

The western half of Tuscola County is underlain by the Saginaw Aquifer. Most of the eastern half of the county is underlain by the Michigan confining unit, although the NE corner of the county is underlain by the Marshall Aquifer.



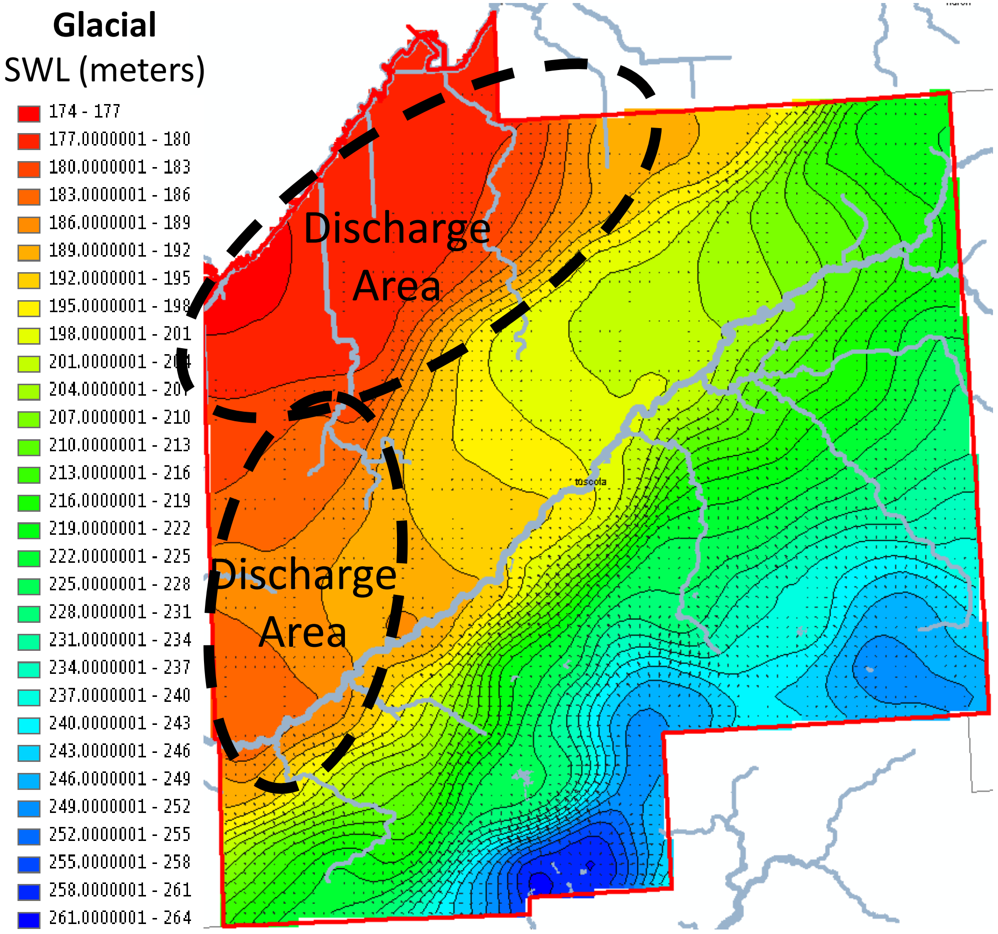
Chloride Concentrations – Tuscola County

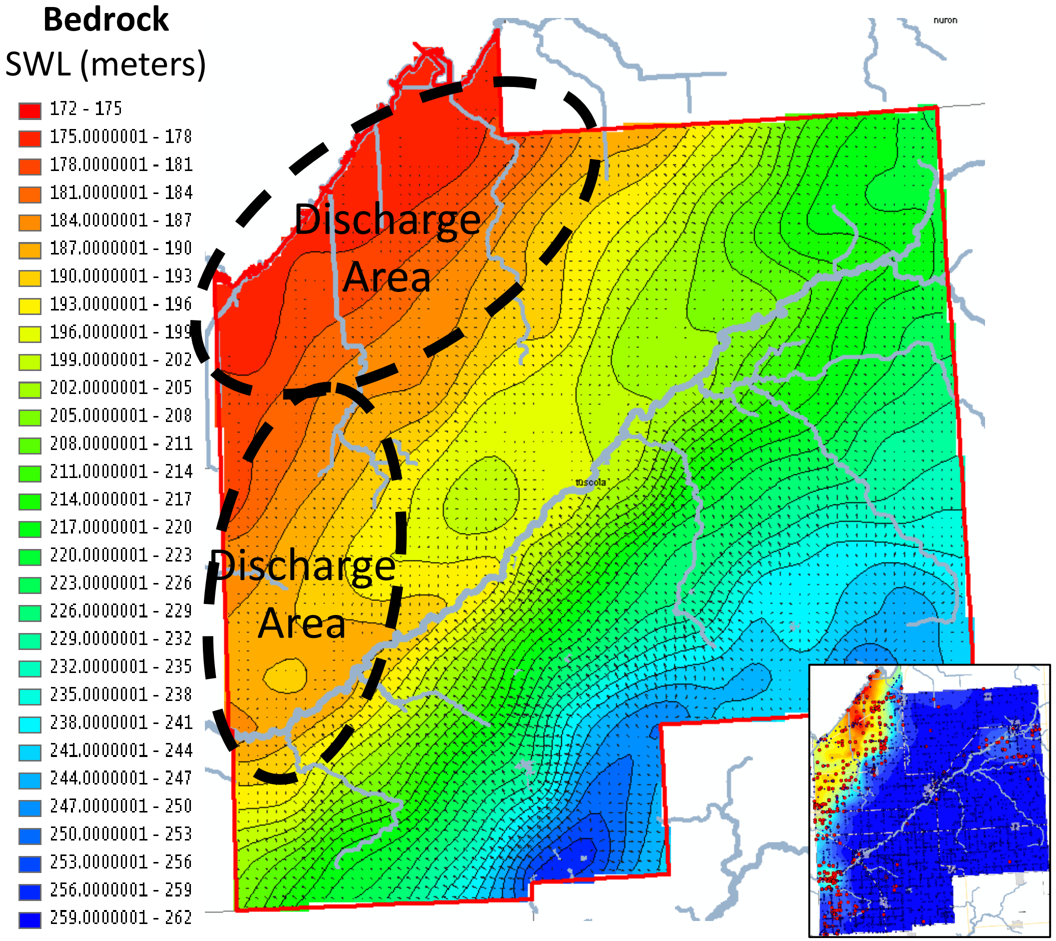
The major elevated chloride zone in Tuscola County is in the major discharge area along the coastal zone. A smaller chloride hotspot occurs in the lower Cass River valley in the vicinity of the border with Saginaw County.



Groundwater levels – Tuscola County

The static water elevations (SWE) in the glacial aquifers of Tuscola County generally mimic the surface topography. The SWE are highest in the hilly terrain in the southcentral and SE parts of the county the regional recharge area) and lowest in the coastal zone of Saginaw Bay (the regional discharge zone). The static water elevations (SWE) in the Saginaw Aquifer beneath Tuscola County generally mimic those of the overlying glacial sediments. The SWE are highest in the southcentral and SE parts of the county (the county-scale recharge area) and lowest in the coastal zone of Saginaw Bay (the regional discharge zone). **Note that the areas where groundwater is low correspond with the areas where chloride concentrations are high.**



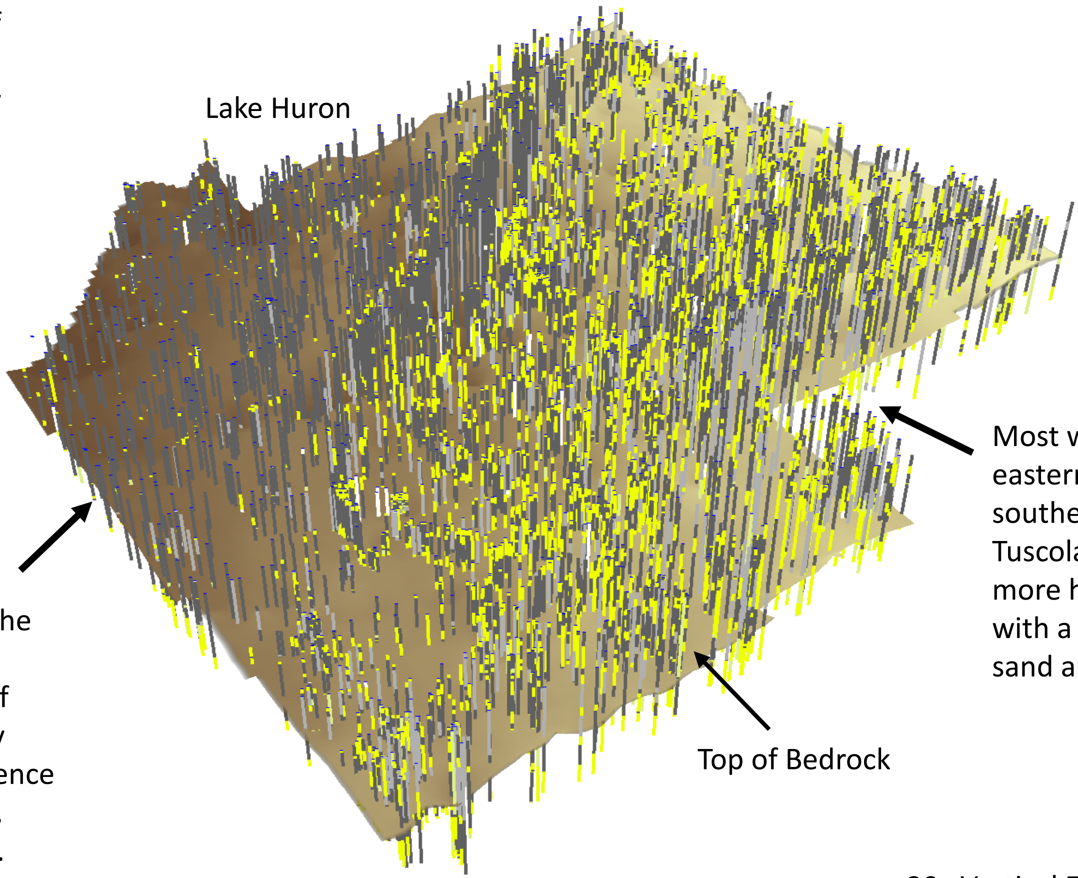


Note: 1m = 3.28 ft.

Visualization of Lithology – Tuscola County

Most water well records from the NW one-third of Tuscola County, including the Port Huron Moraine, show **the presence of a continuous, thick, clay layer. Note that this area corresponds with the areas where chloride concentrations are high.**

NORTH

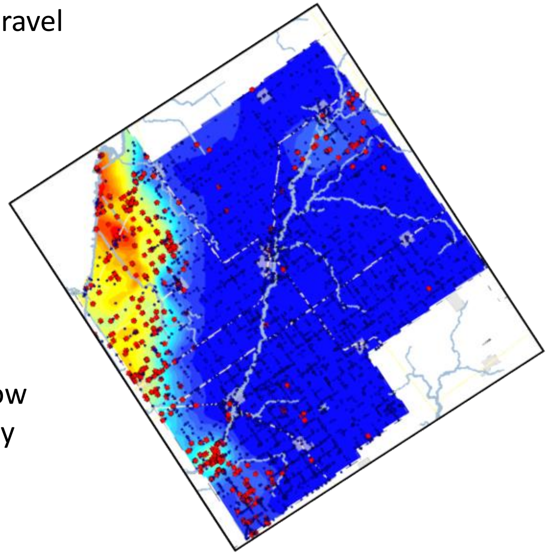


Clay, Silt

Sand, Gravel

Most wells in the northern and western part of Tuscola County show the presence of a persistent, thick clay layer.

Most wells in the eastern and southern part of Tuscola County show more heterogeneity with a mixture of sand and clay.

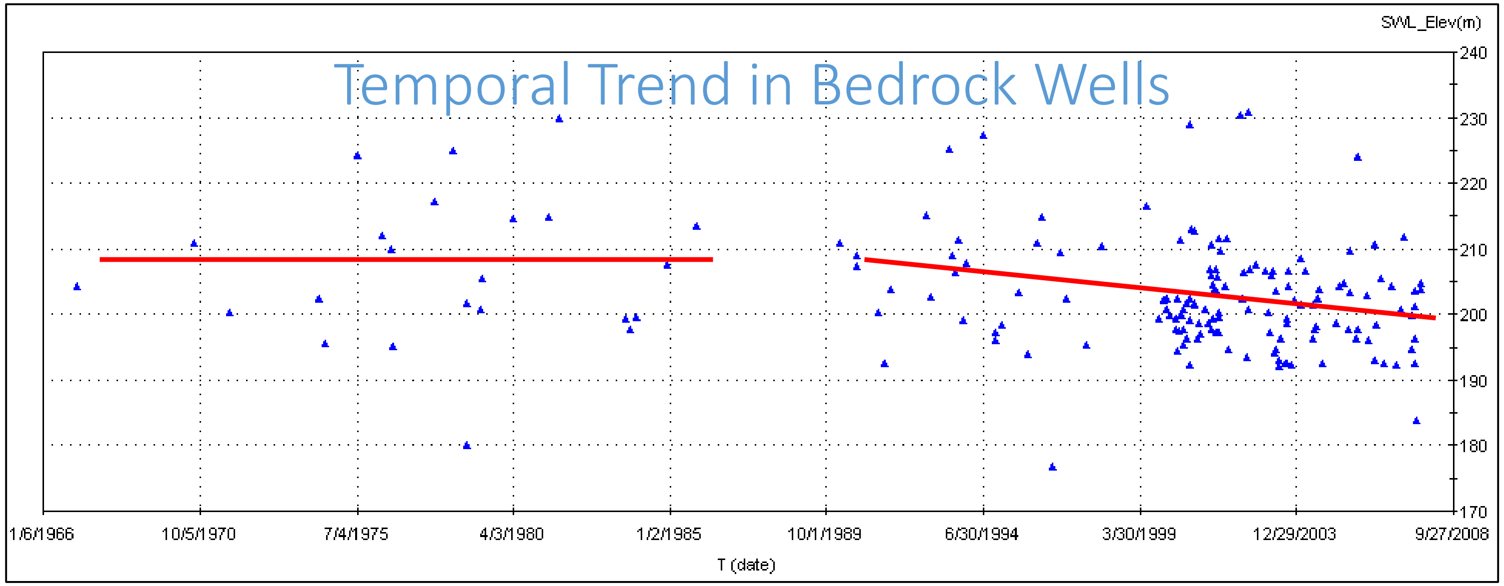


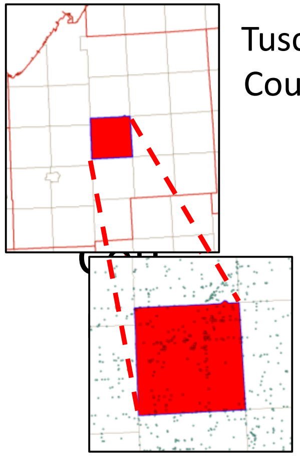
30x Vertical Exaggeration

Temporal Trends of SWLs – Tuscola County

A fairly strong trend of declining SWE is obvious in the period 1990 – 2008, when SWE may have dropped by as much as 9 meters (29.5 ft.).

Note: 1m = 3.28 ft.





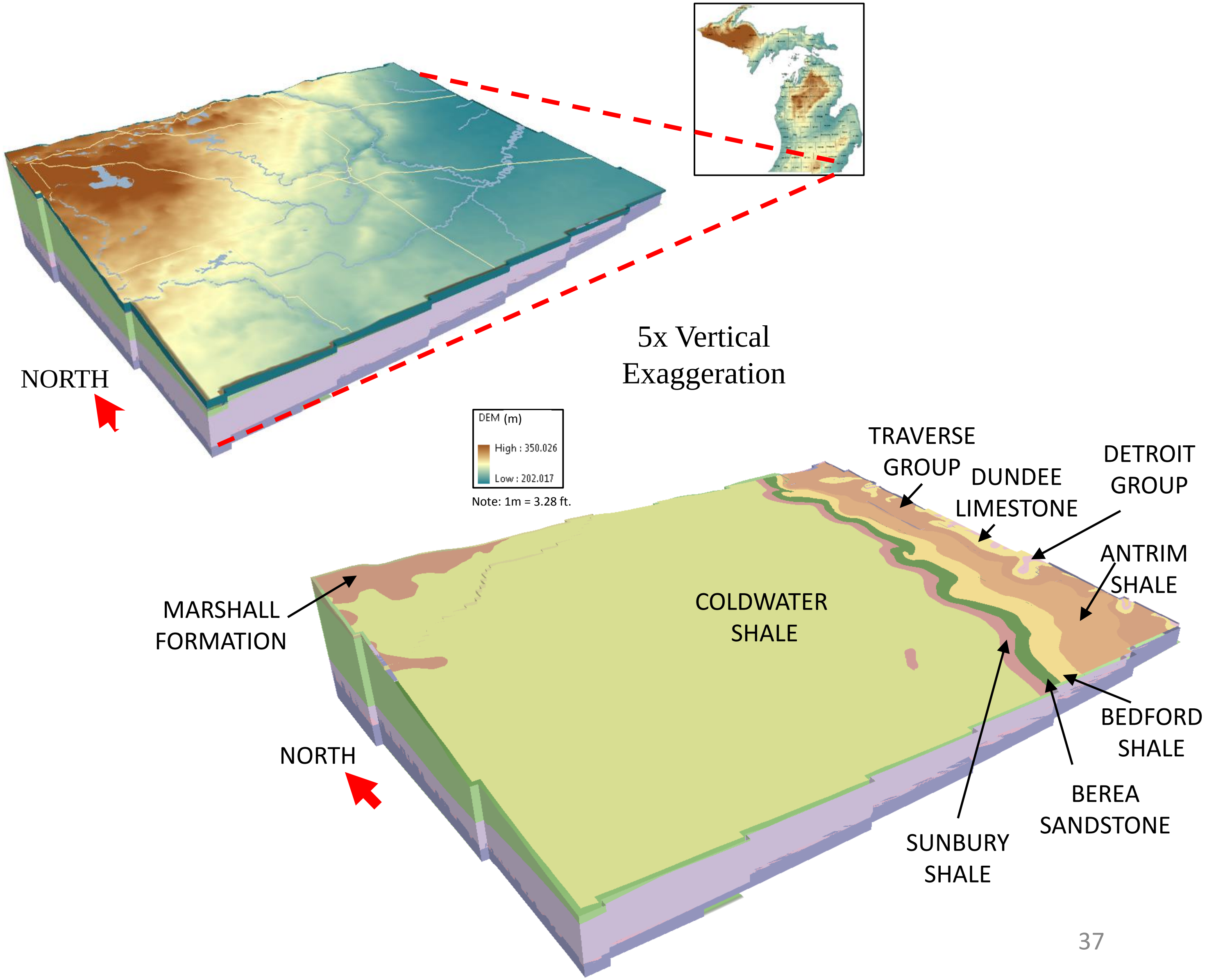
Tuscola County

Indian Fields Township

SWL change: - 30 ft.

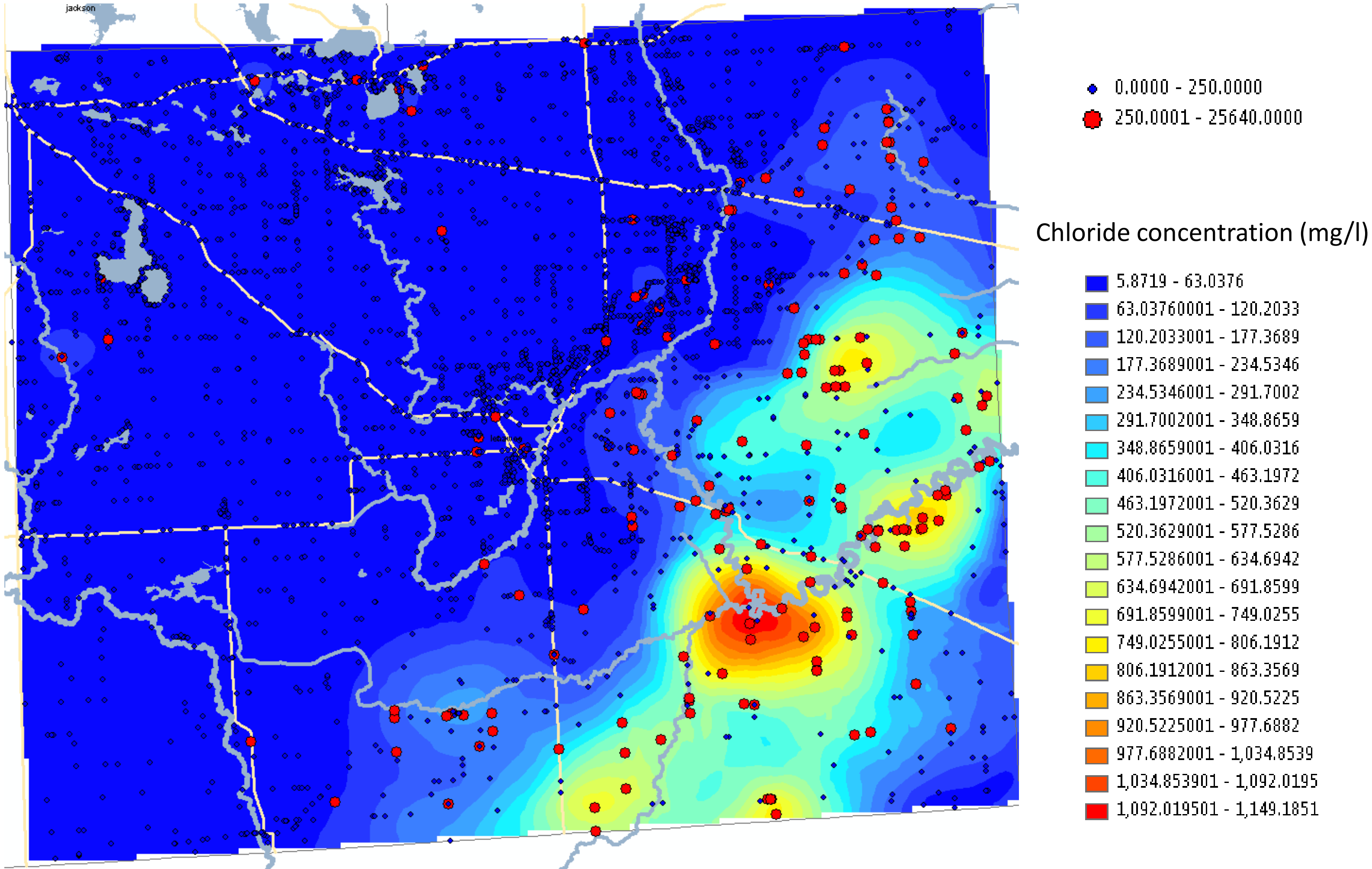
Illustrative Example # 2 – Lenawee County

The bedrock beneath Lenawee County is dominated by shale units. The Marshall sandstone subcrops in the extreme NW corner of the county and two limestone units subcrop along the easternmost edge of the county.



Chloride Concentrations – Lenawee County

This slide presents chloride concentrations in Lenawee County. Note the hotspot in the SE portion of the county.



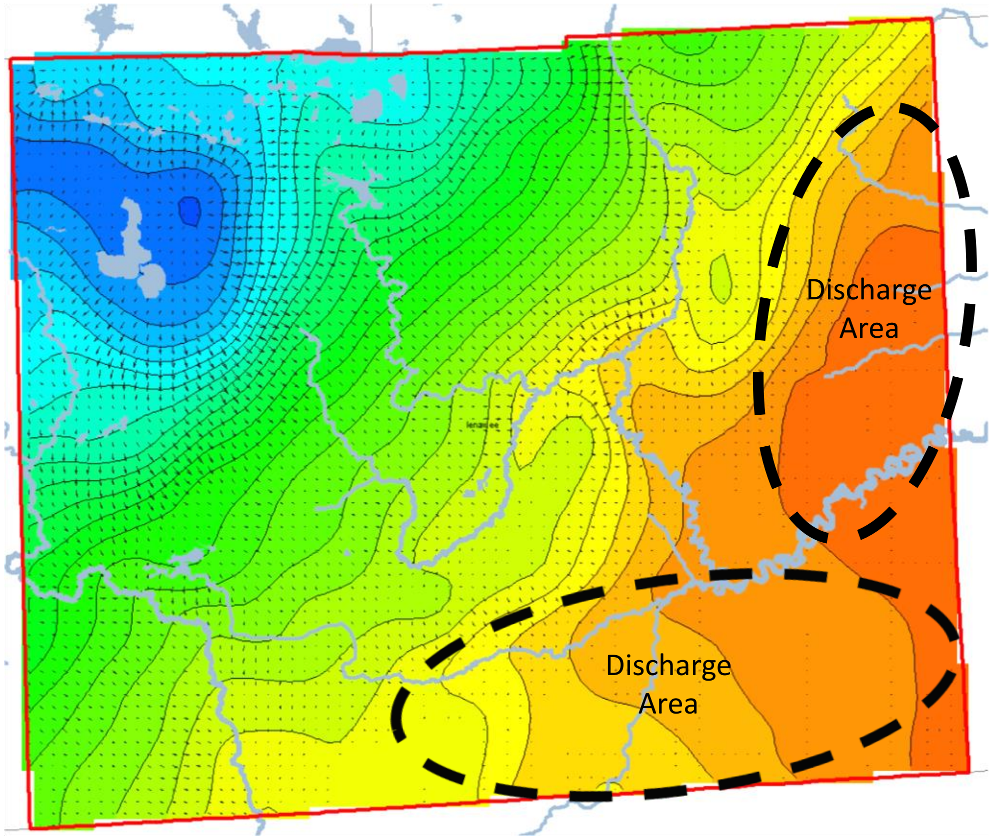
Groundwater levels – Lenawee County

This slide shows SWLs in the glacial and bedrock aquifers of Lenawee County. **Note the single discharge area in the E and SE part of the county, which coincides with the portion of the aquifer system where the chloride hotspot is found.**

Glacial

SWL (meters)

- 186 - 191
- 191.0000001 - 196
- 196.0000001 - 201
- 201.0000001 - 206
- 206.0000001 - 211
- 211.0000001 - 216
- 216.0000001 - 221
- 221.0000001 - 226
- 226.0000001 - 231
- 231.0000001 - 236
- 236.0000001 - 241
- 241.0000001 - 246
- 246.0000001 - 251
- 251.0000001 - 256
- 256.0000001 - 261
- 261.0000001 - 266
- 266.0000001 - 271
- 271.0000001 - 276
- 276.0000001 - 281
- 281.0000001 - 286
- 286.0000001 - 291
- 291.0000001 - 296
- 296.0000001 - 301
- 301.0000001 - 306
- 306.0000001 - 311
- 311.0000001 - 316
- 316.0000001 - 321
- 321.0000001 - 326
- 326.0000001 - 331
- 331.0000001 - 336

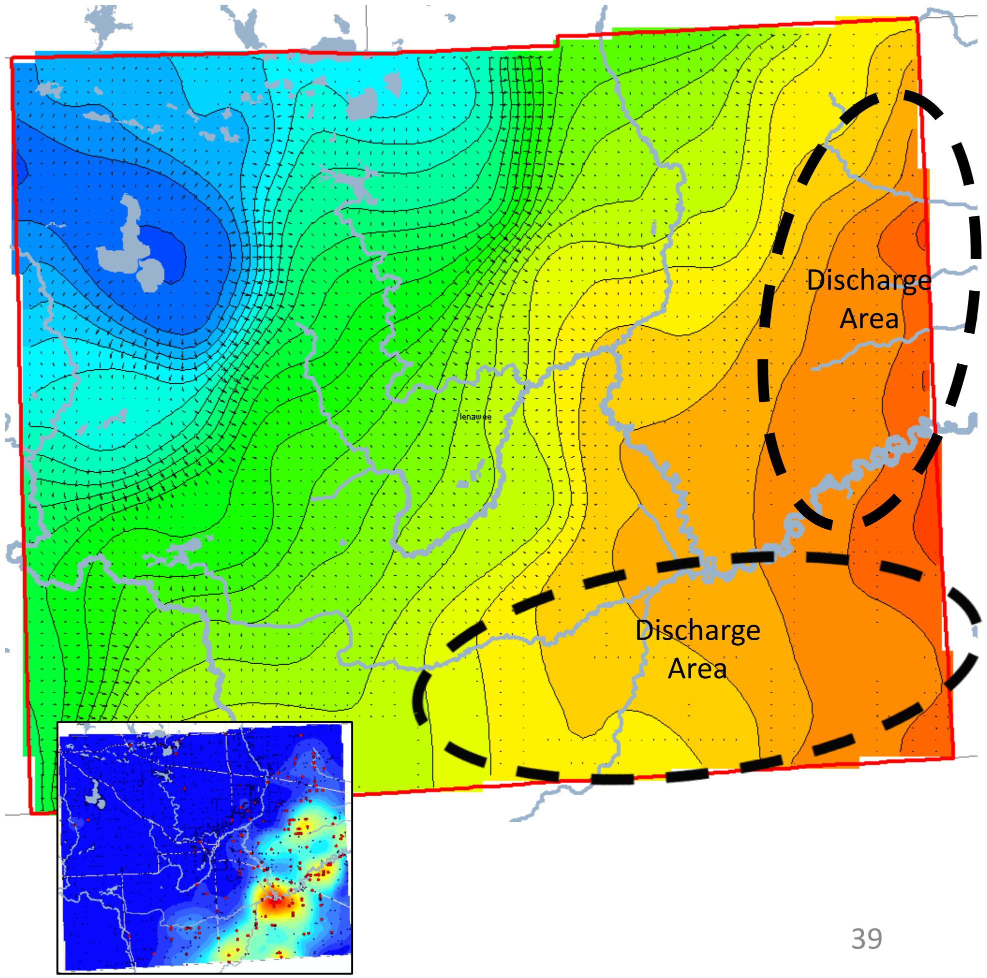


Note: 1m = 3.28 ft.

Bedrock

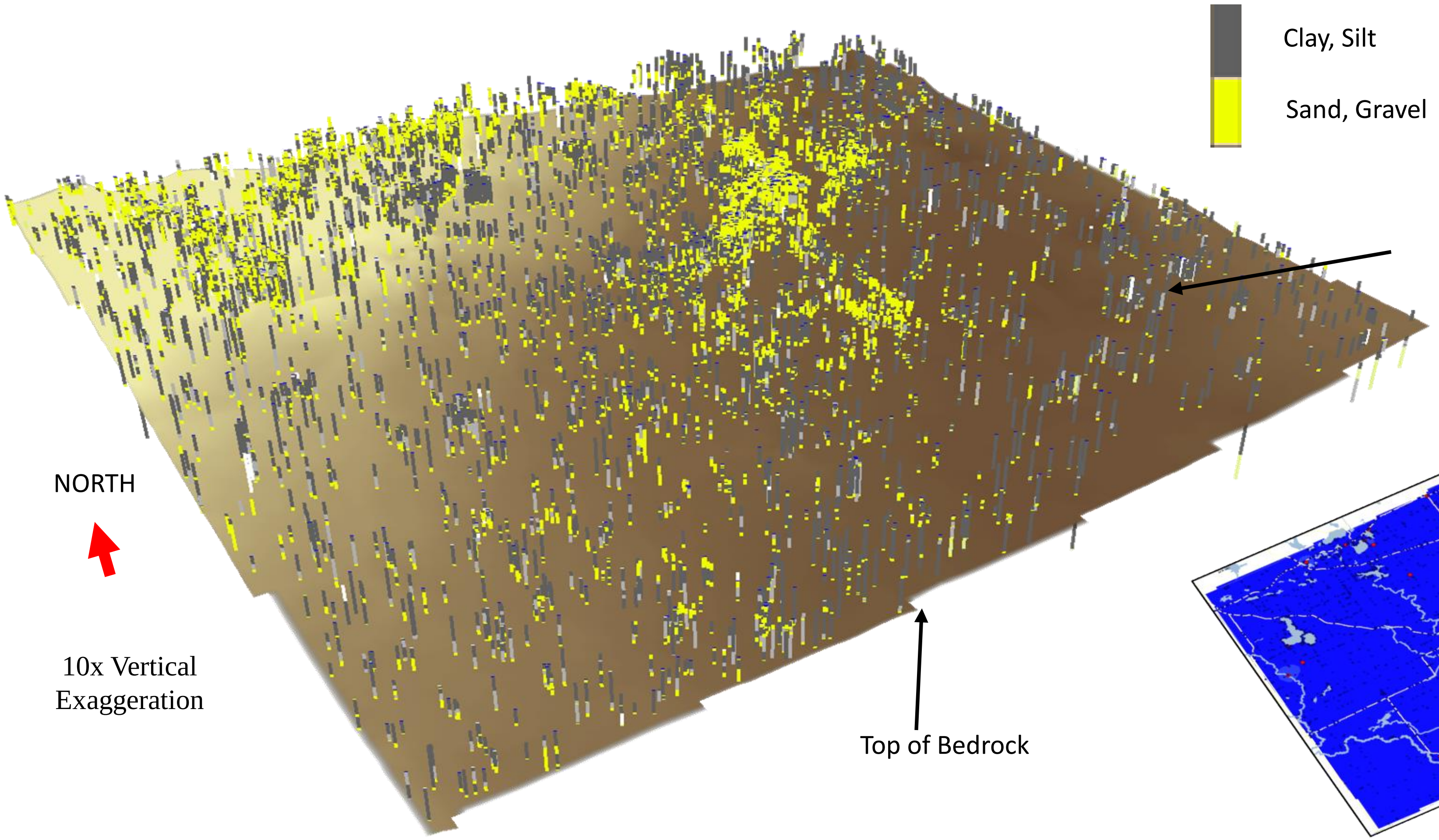
SWL (meters)

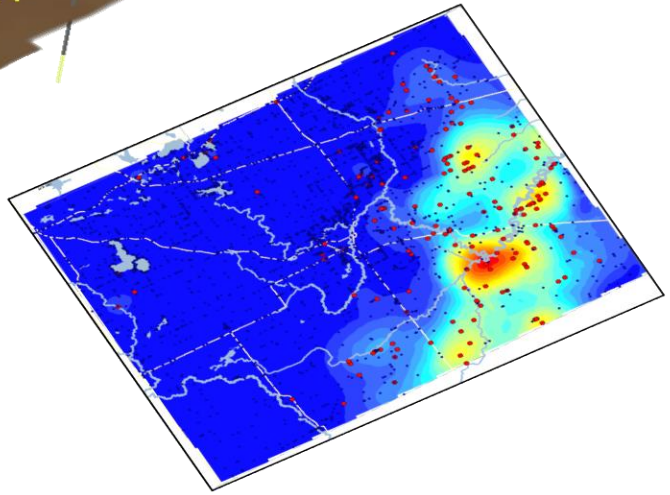
- 182 - 187
- 187.0000001 - 192
- 192.0000001 - 197
- 197.0000001 - 202
- 202.0000001 - 207
- 207.0000001 - 212
- 212.0000001 - 217
- 217.0000001 - 222
- 222.0000001 - 227
- 227.0000001 - 232
- 232.0000001 - 237
- 237.0000001 - 242
- 242.0000001 - 247
- 247.0000001 - 252
- 252.0000001 - 257
- 257.0000001 - 262
- 262.0000001 - 267
- 267.0000001 - 272
- 272.0000001 - 277
- 277.0000001 - 282
- 282.0000001 - 287
- 287.0000001 - 292
- 292.0000001 - 297
- 297.0000001 - 302
- 302.0000001 - 307
- 307.0000001 - 312
- 312.0000001 - 317
- 317.0000001 - 322
- 322.0000001 - 327
- 327.0000001 - 332



3D Visualization of Lithology – Lenawee County

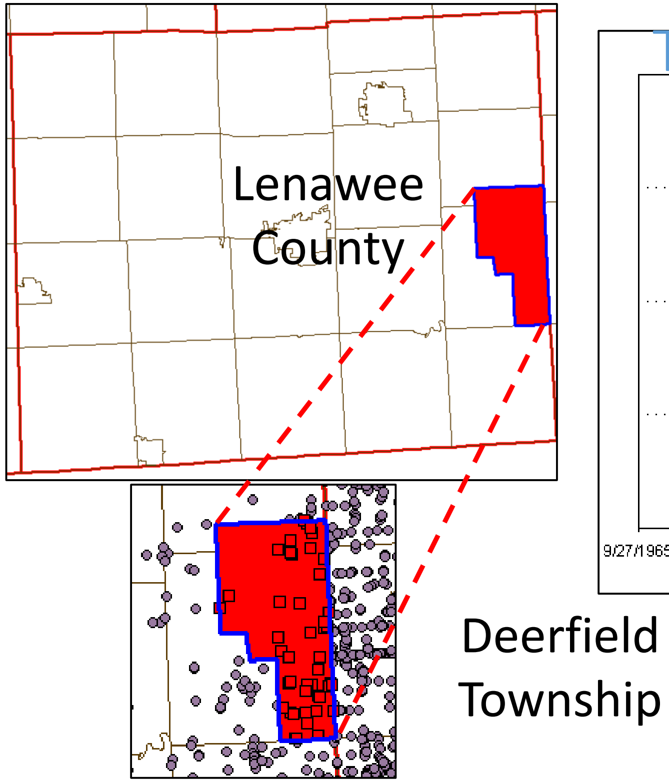
Southeastern Lenawee County is underlain by **nearly-continuous, thick, clayey glacial deposits. Note that this area corresponds with the areas where chloride concentrations are high.**



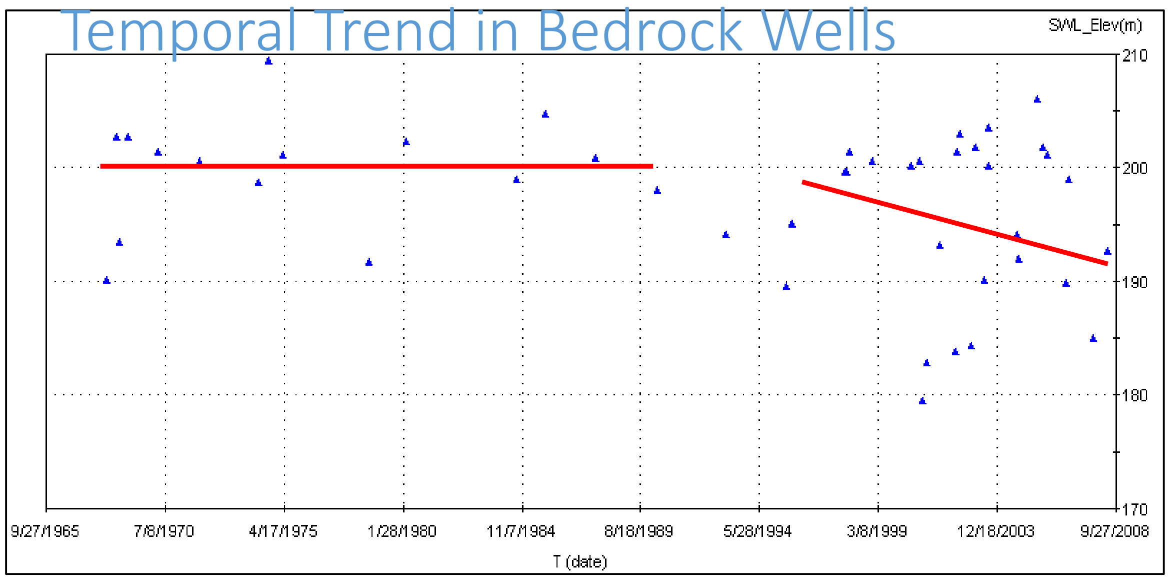


Temporal Trends of SWLs – Lenawee County

There is a **moderate downward trend in the bedrock static water elevations** (SWE) commencing about 1996.



Note: 1m = 3.28 ft.



SWL change: - 24 ft.

SUMMARY OF KEY FINDINGS

The issues facing Ottawa County are related to larger statewide problem:

- Brines are systematically impacting low-lying areas where groundwater is discharging (moving upwards)
- Pumping is lowering groundwater levels and aggravating the Cl problem
- Areas typically associated with occurrence of continuous clay/silt layers and bedrock aquifers yield the highest Cl concentrations

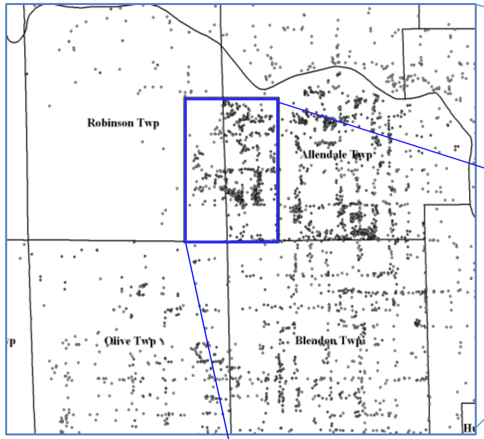
OTTAWA COUNTY GROUNDWATER QUANITY

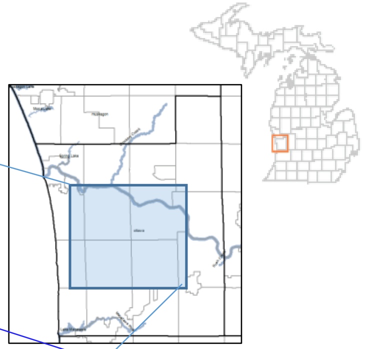
TEMPORAL ANALYSIS OF STATIC WATER LEVELS

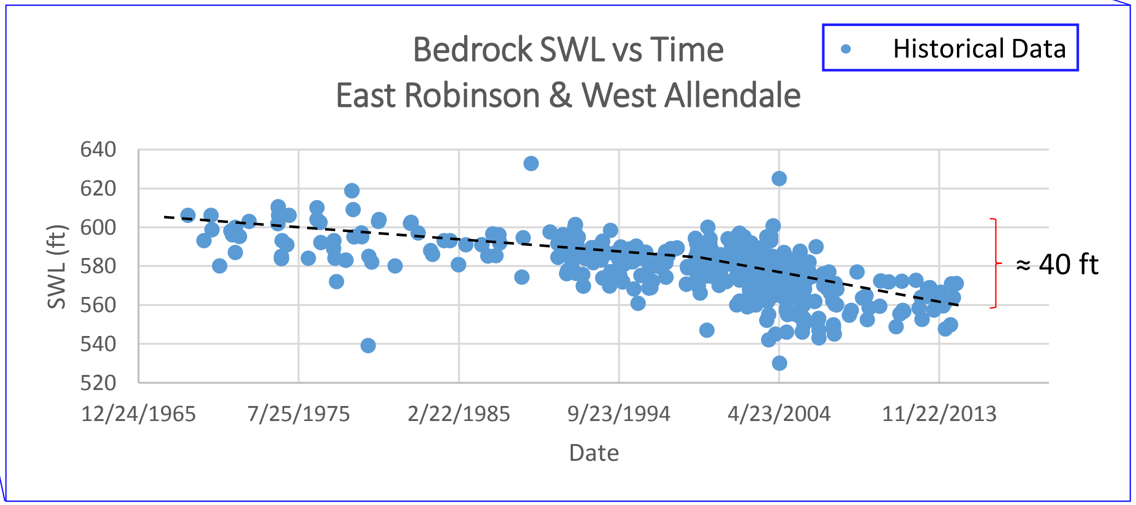
To quantify the sustainability of Ottawa County's groundwater resources, it was necessary to understand how the current conditions compare to past conditions. Ideally, numerous monitoring wells distributed relatively evenly throughout the aquifer would be used to collect time-series of groundwater levels for flow model calibration. In Ottawa County, however, monitoring wells were not available in locations (and for time periods) needed for this study, and given the budget constraints and the fact that the modeling and analysis was to be completed in a few years, it was not feasible to establish a new monitoring network for the purposes of the study.

It is for these reasons that thousands of SWL measurements – made at single points in time but distributed throughout the aquifer system – were used to calibrate the county-wide groundwater model. By aggregating many SWL taken at different times within a relatively small area (e.g., for an entire township), it was possible to detect systematic changes in groundwater levels that would be observed with a single monitoring well.

Bedrock wells in central Ottawa County

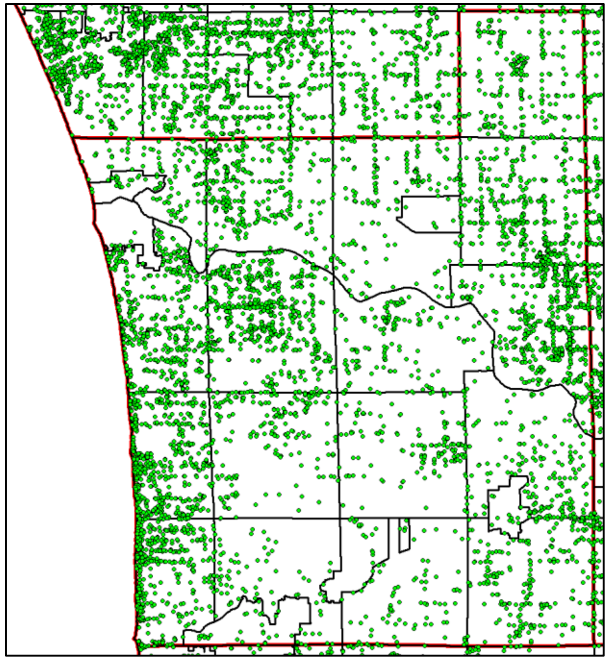




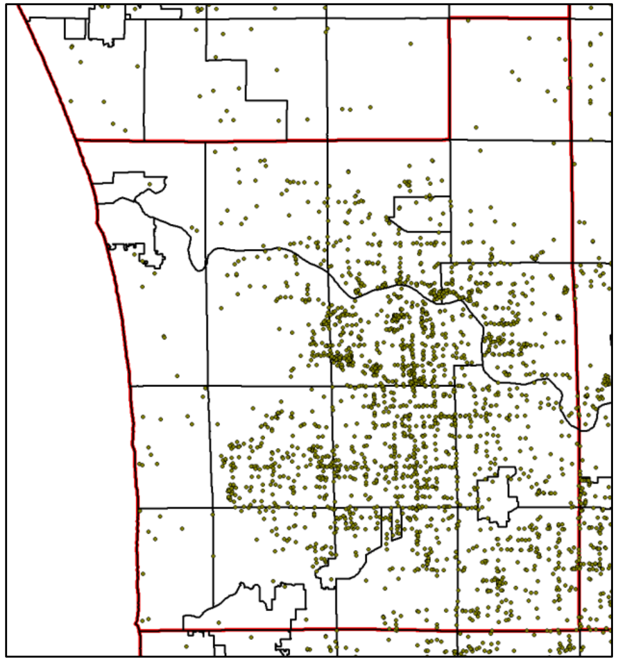


Static Water Level Data Sources

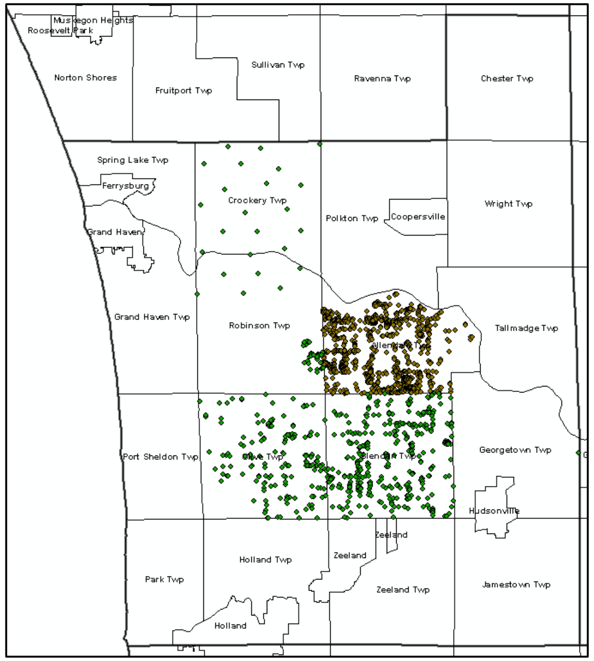
Static water levels were obtained from two sources: Wellogic – the statewide water well database maintained by the Michigan Department of Environmental Quality (MDEQ 2014); and the Ottawa County Department of Public Health (Environmental Health) - which maintains a system that organizes, on a property-by-property basis, borehole records and well logs from *Wellogic* or local government agencies (or even directly from the drillers themselves, especially in the case of older wells) with documentation from water quality testing (i.e., sodium, fluoride, hardness, iron, nitrate, nitrite, and sulfate). The graphics below show the distribution of wells used in the analysis of SWLs.



Glacial wells in Wellogic



Bedrock Wells in Wellogic



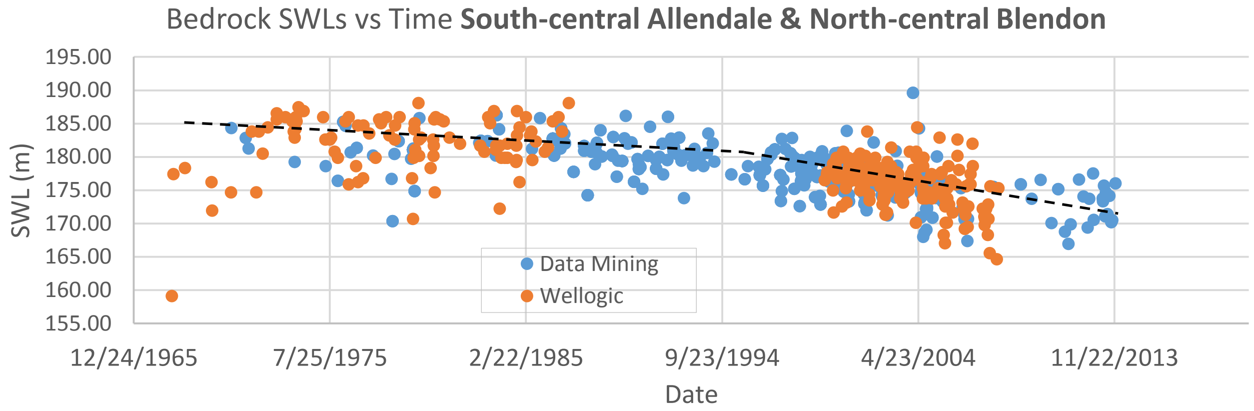
Wells mined from Ottawa Env. Health

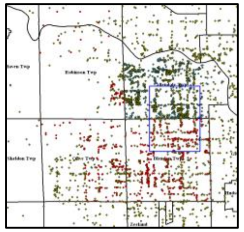
Bedrock SWL Trends – Central Ottawa County

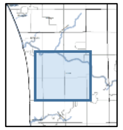
These charts show SWLs trends detected in the bedrock aquifer in the central part of Ottawa County. Note how the SWLs obtained from data mining compliments the Wellogic dataset by “filling in the gap” of the 1990s.

Importantly, for parts of the aquifer system the decreases in groundwater levels that have occurred over the past 50 years are larger than the SWL variability caused by spatial aggregation of observation data and noise in the measurements themselves. Thus, this approach was not only effective for the purposes of quantifying SWL changes controlling the sustainability of the county-wide aquifer system, but necessary given limited resources available for new data collection.

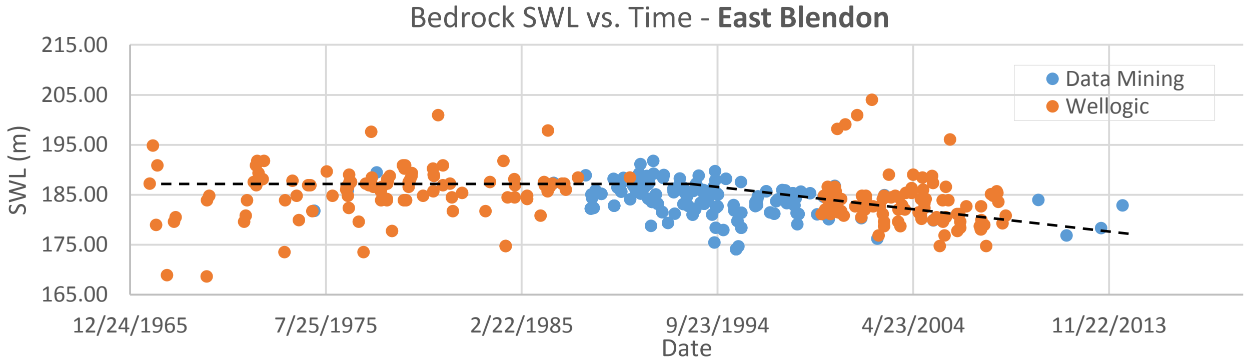
The groundwater flow simulator discussed in the following slides was calibrated so that it could reproduce the SWL trends observed in the compiled SWL dataset.

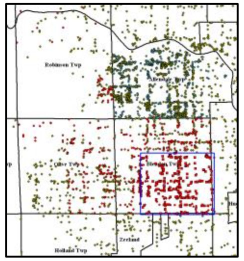


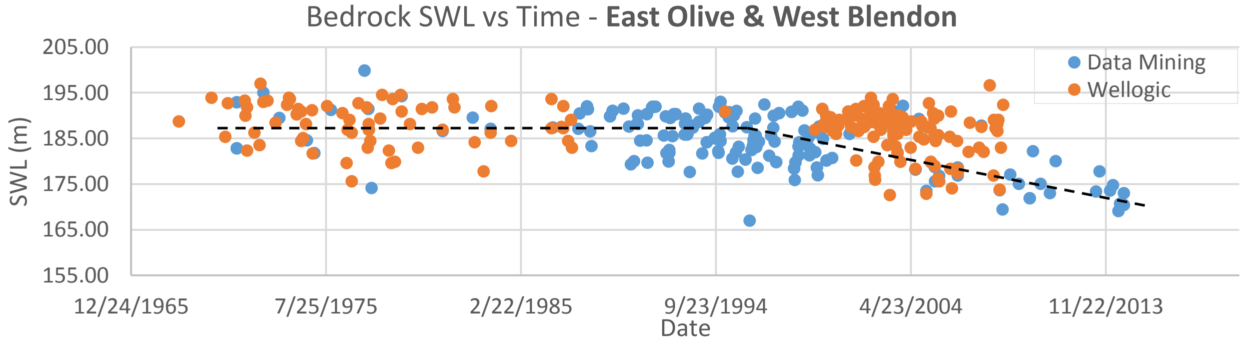


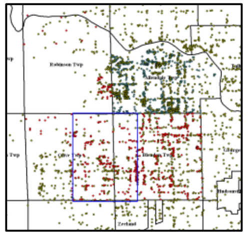


Note: 1m = 3.28 ft.



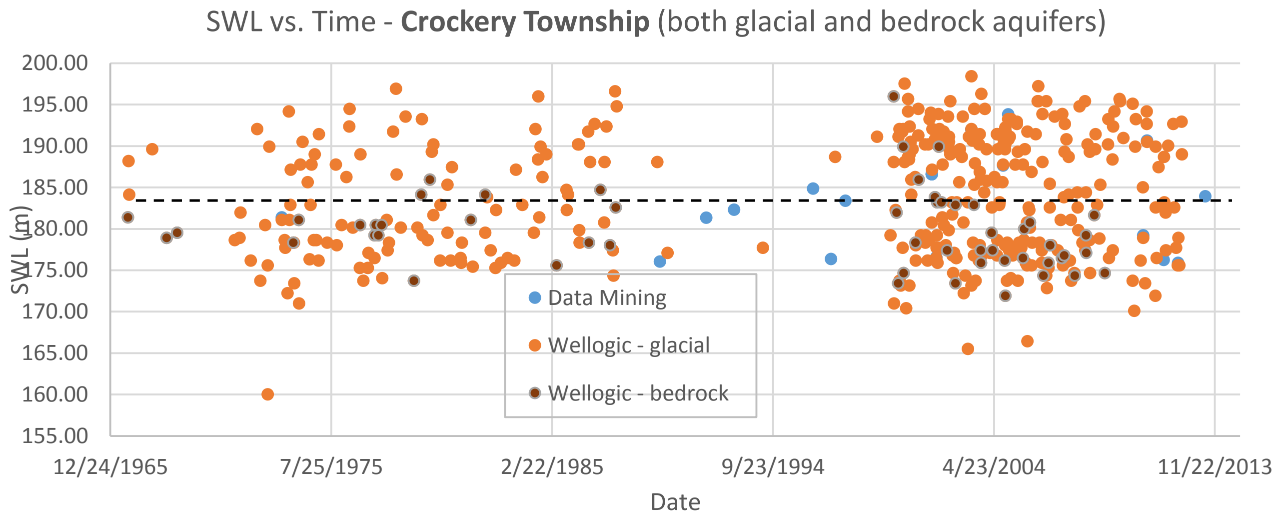


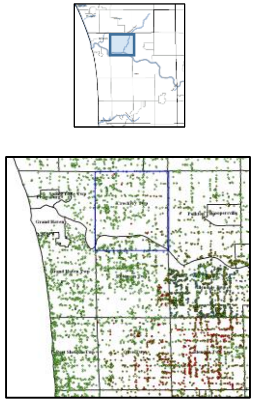


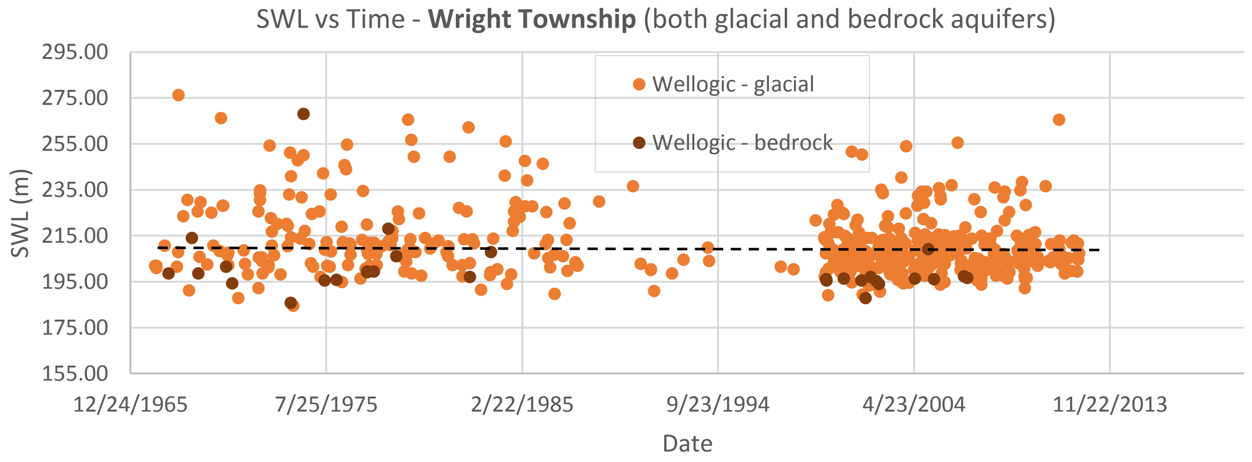


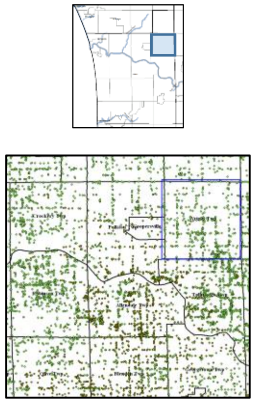
SWL Trends – 'Outer' Townships

In some parts of the county, a SWL temporal trend could not be identified because a) the decreases in groundwater levels are smaller than the SWL variability; or b) a trend was not present. This slide presents two examples of areas in Ottawa County where a SWL temporal trend could not be identified.





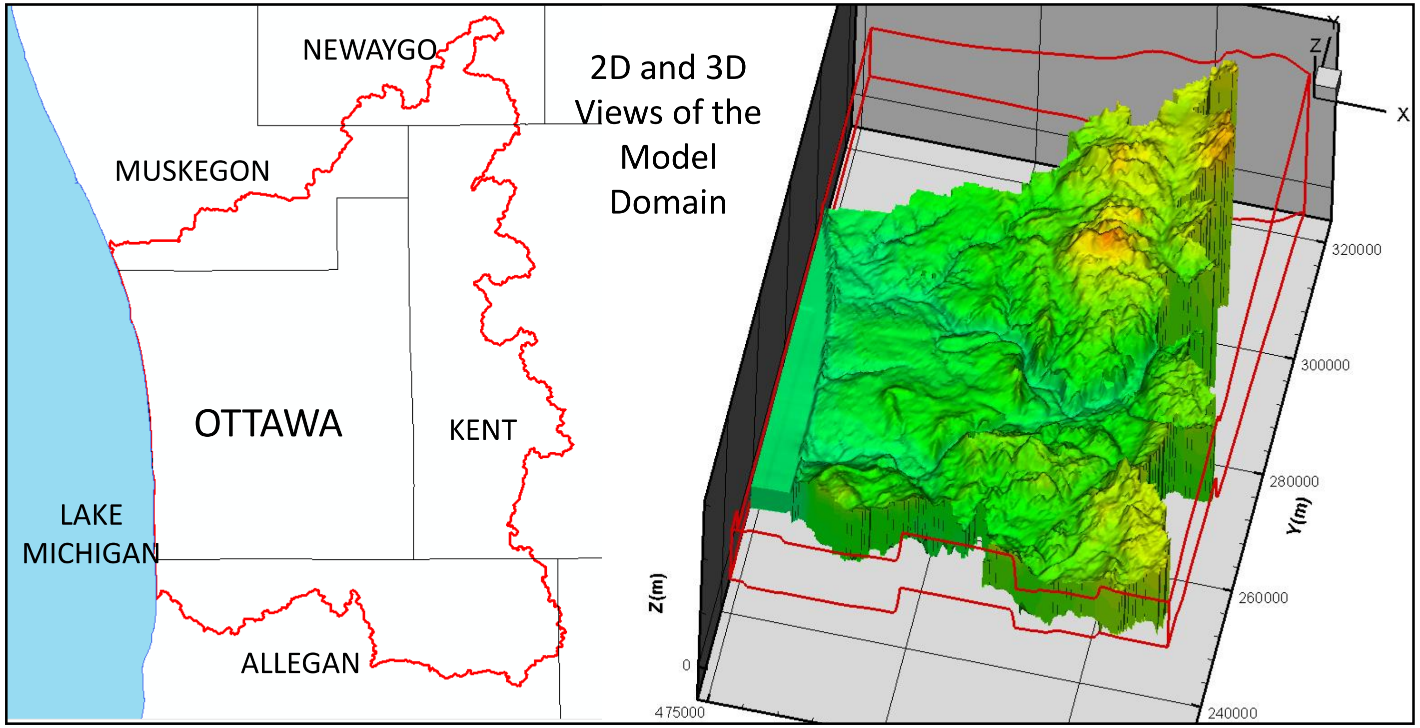




NUMERICAL GROUNDWATER FLOW SIMULATIONS

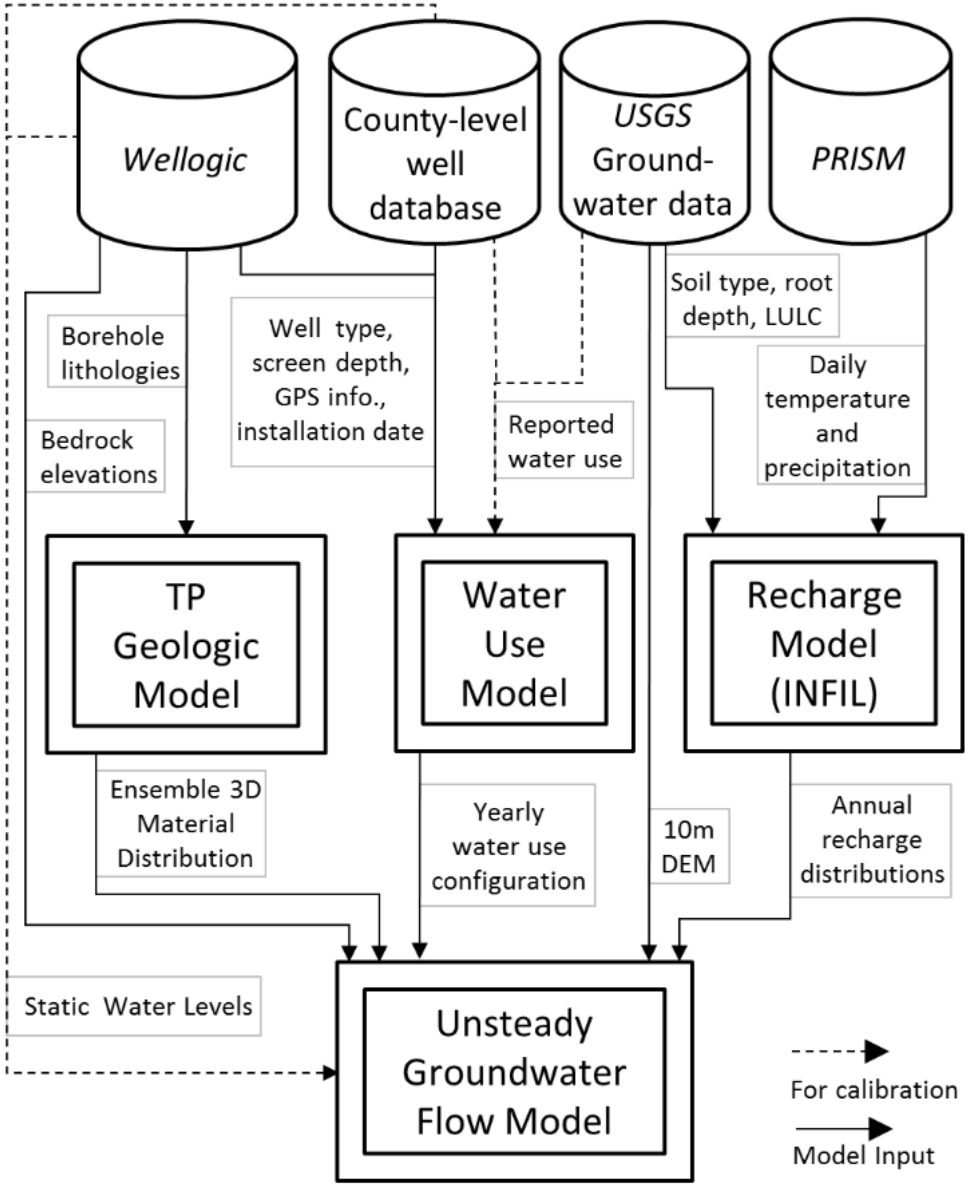
Computer software was used to simulate groundwater levels in the Ottawa County aquifer system for the past 50 years, which represents the time period over which a vast majority of the water wells were installed for groundwater use.

The model spans all of Ottawa County and its immediate surroundings. The northern, eastern, and southern lateral boundaries were constructed using 12-digit (small) watershed boundaries from USGS NHD (2010). The model is three-dimensional, including both the glacial sediments and underlying bedrock formations.



Overview of Modeling Process

The workflow integrating the databases used for model inputs and calibration and the models needed to develop the numerical flow model is shown in the figure. Well information from *Wellogic* and local water well records compiled by the Ottawa County Environmental Health Department (Ottawa County 2014) were used to develop a water use model providing yearly water use configurations, and to calibrate the groundwater model using Static Water Levels (SWLs) measured at the time of well installation. Lithologic information from *Wellogic* borehole records was used to develop a Transition Probability (TP) geostatistical model to characterize the glacial aquifer heterogeneity. Spatially-explicit annual recharge distributions were simulated using *PRISM Climate Group* precipitation and temperature data and land surface data from USGS and the United State Department of Agriculture (USDA), e.g., soil type, root zone depth, etc. *Interactive Groundwater* (IGW), a modeling software introduced by Li and Liu (2006) but being periodically updated (see, e.g., Li and Liu, 2006; Li et al 2006; Liao et al. 2015), was used for all of the modeling.

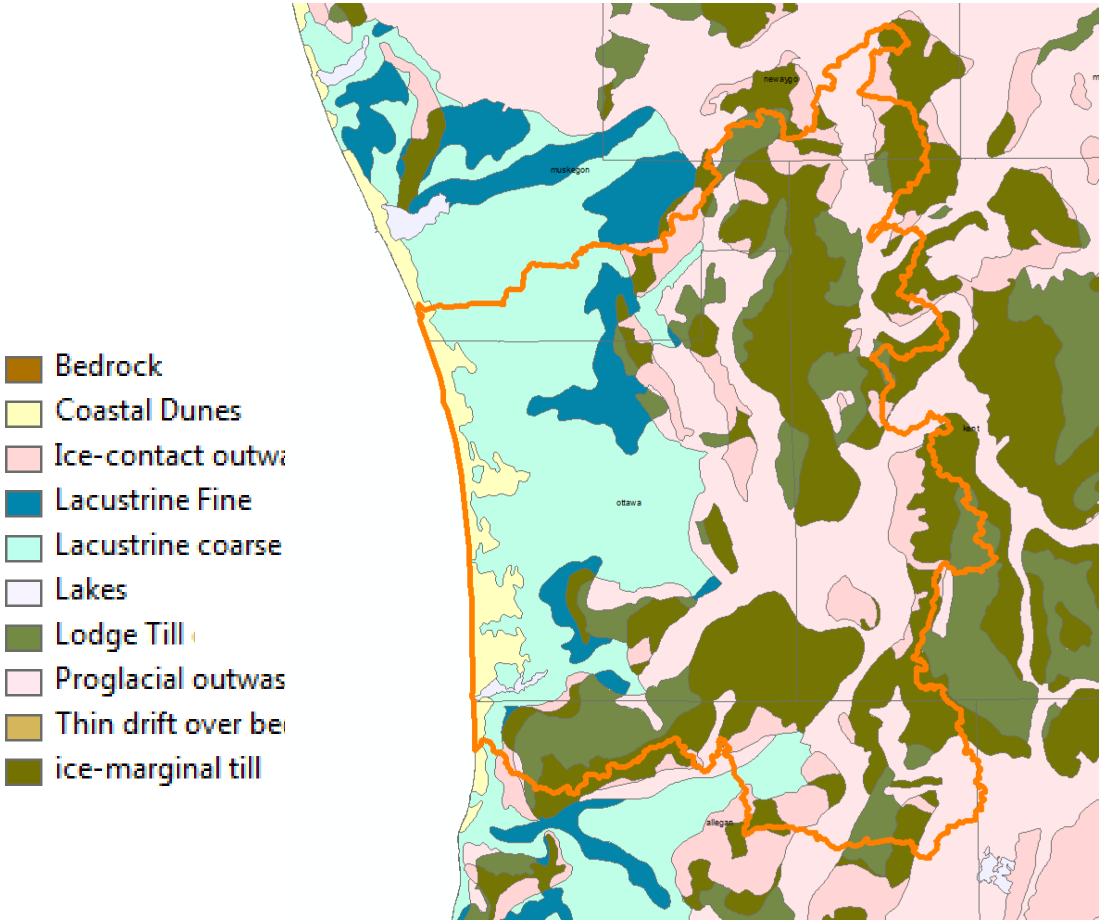


GEOLOGIC MODELING

Western and central Ottawa County is dominated by eolian and lacustrine sediments, most of which are sandy. A few small areas exhibit clays at the surface. The eastern edge of the county is dominated by moraines composed of till. A continuous swath of outwash sands and gravels were deposited along the western flanks of these moraines.

The map shown here represents the surface geology (i.e., the types of sediments closest to the land surface) within the study area.

Part of the aquifer system was represented in the deterministic, layer-based approach (bedrock), while a critical portion required a better representation of small-scale heterogeneity (glacial aquifer).

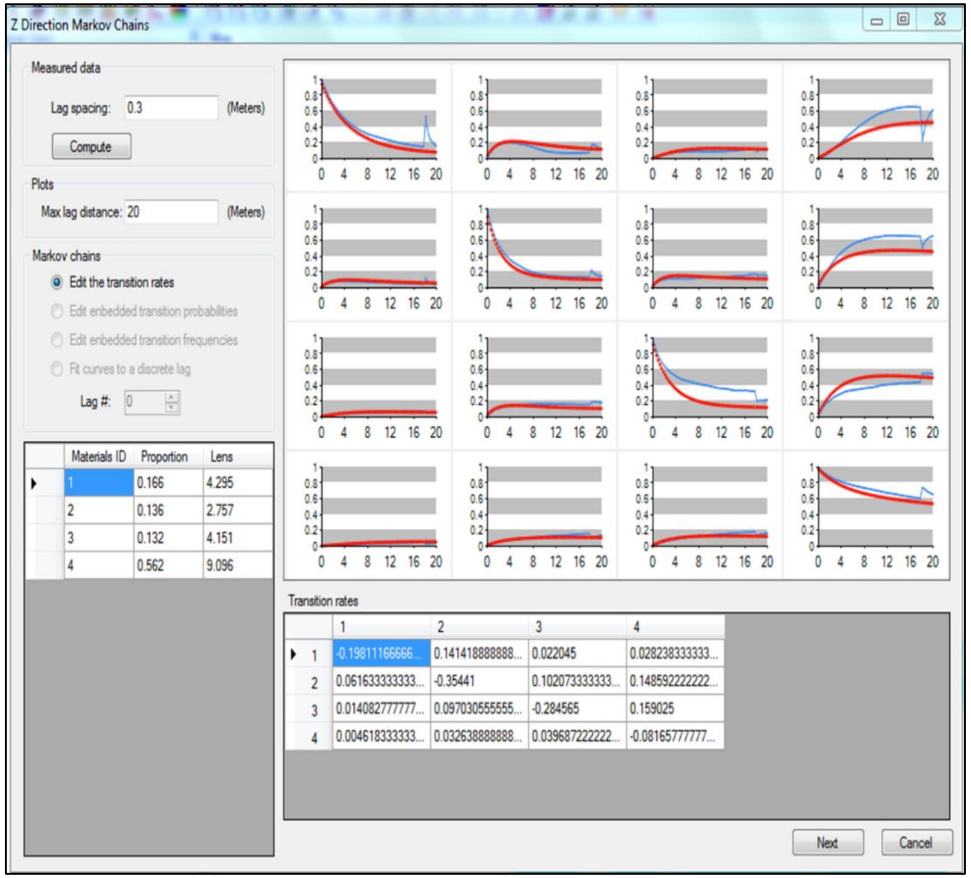


3D-Geostatical Simulation of the Glacial Aquifer

A key aspect of the model conceptualization is the extension of the Transition Proability (TP) geostatistical approach for mapping the glacial aquifer heterogeneity. This approach is based on the premise that the probability of 'k' occurring at location 'x+h' depends only upon what happens at location 'x', or in the case of geologic spatial analysis, the probability that a given material type is present at another location depends only upon the material type at the current location. The Transition Probability Geo-statistical Software (T-PROGS) was used to apply the TP approach (Carle, 1999).

Roughly 19,000 *Wellogic* borehole records were available for analysis. First, lithologic descriptions for given depth intervals were classified into four different geologic material types:'Sand', 'Gravel', 'Coarse stones' or similar descriptions were classified as aquifer material (AQ); 'Silt', 'Clay' or similar descriptions were classified as confining material (CM); and descriptions that were a mix of AQ and CM materials, such as 'Gravel & Silt' or 'Clay and fine sand', were classified as marginal aquifer (MAQ) or partially confining material (PCM), respectively. Each of the re-classified boreholes were analyzed to create a transition probability matrix of auto- and cross- correlations between the material types as a function of vertical lag spacing. Graphical depictions of the spatial correlations versus vertical lag distance were generated and geostatistical models were fit to the data using Markov chain analysis (see Carle and Fogg 1996; 1997 for more details on Transition Probability geostatistics).

The vertical ('Z-direction') analysis is used to create a 3-dimensional realization of glacial aquifer material distribution that extends from the 10m DEM top boundary to the top of the bedrock surface (500m resolution) delineated by Oztan (2007). The was done by assuming a ratio of the horizontal extent of a material to its vertical extent – or an anisotropy ratio – and applying the geostatistical models derived from Z-direction Markov chain analysis. The anisotropy ratios for AQ, MAQ, PCM and CM were chosen as 10, 10, 10, and 8.4, respectively. The geologic model cells had a vertical length of 4m and a horizontal length of 500m, and each cell is assigned as one of the four material types for each model realization. One thousand realizations were executed to produce an ensemble mean geologic model by assigning the most frequently occurring geologic material at each grid cell.

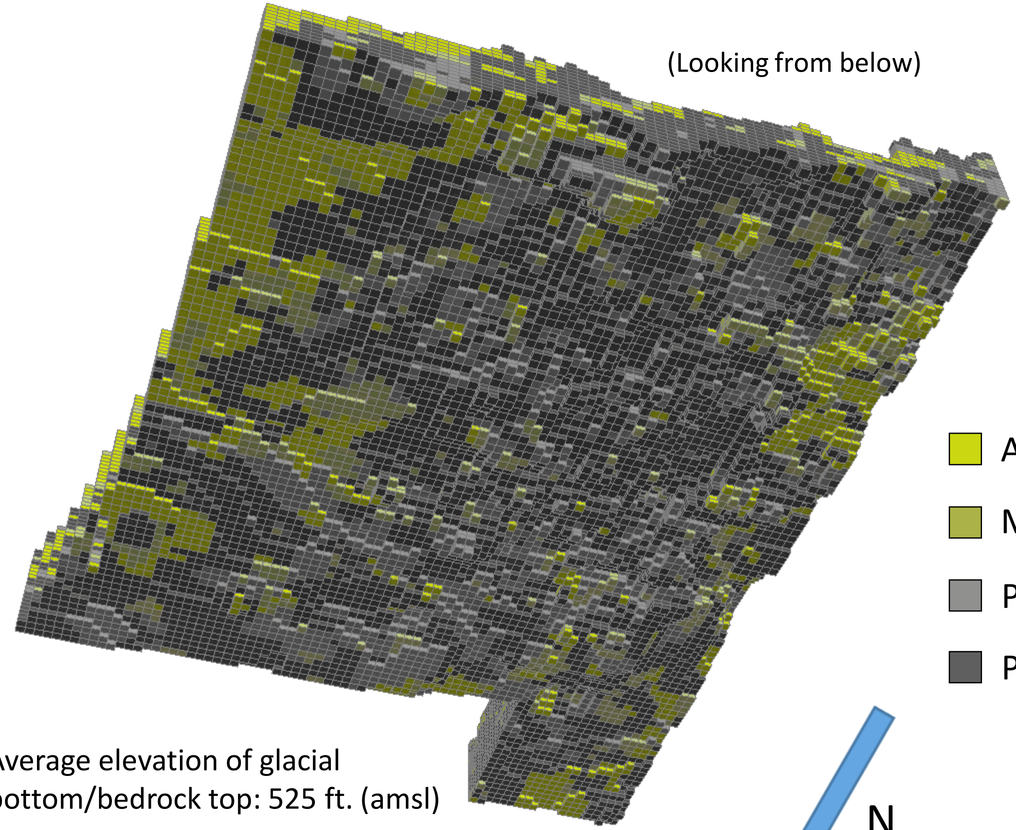


Example Markov Chain analysis (z-direction) used for creating the 3D geostatistical model of aquifer material type distribution. Materials IDs: 1=AQ; 2=MAQ; 3=PCM; 4=CM. 'Proportion' represents the fractional amount of a given material from the analysis of all boreholes; 'Lens' represents the average vertical thickness (m) of the material type.

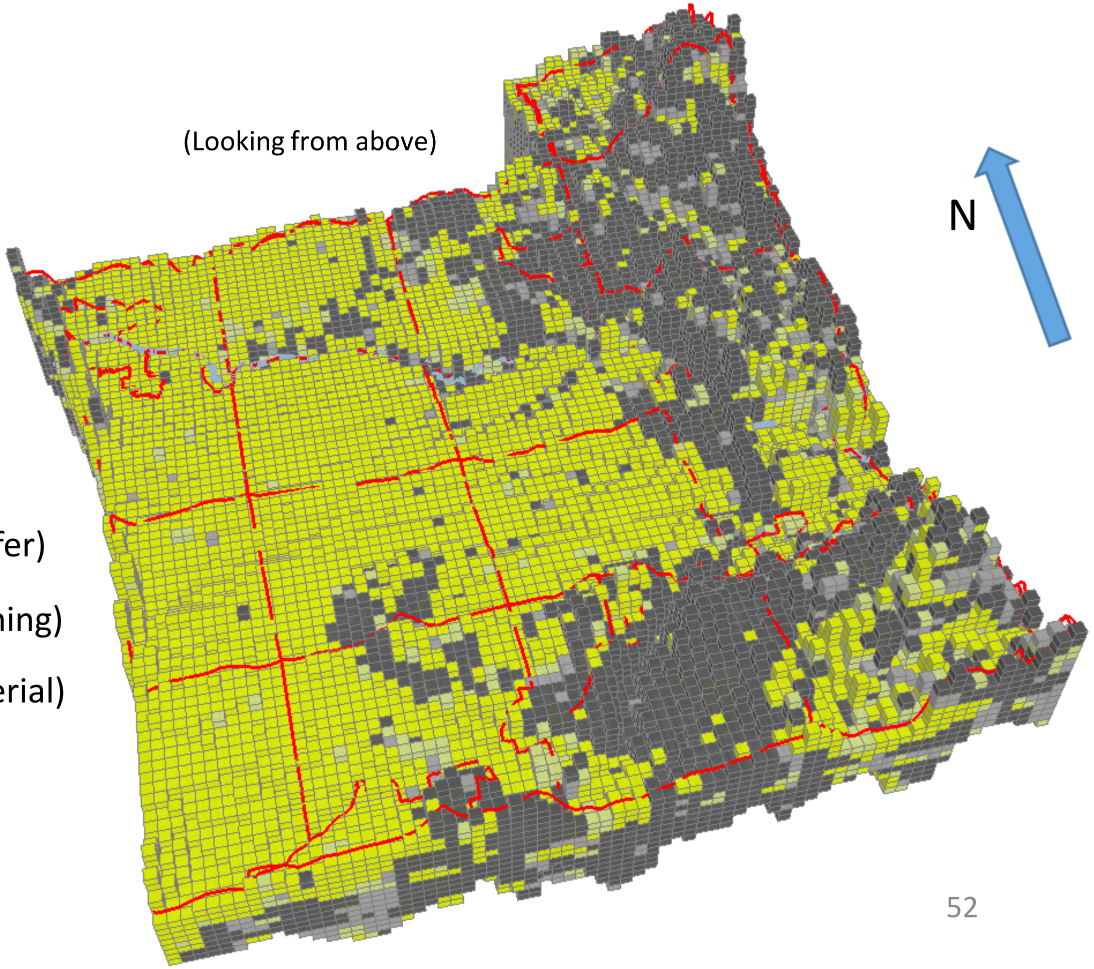
3D-Geostatical Model

This slide presents the ensemble mean geologic model. Note the strong 3D variability, especially in the eastern portions of the county (see the Phase 1 report for more details on the geologic variability of the glacial aquifer system in Ottawa County).

(Looking from below)



(Looking from above)



N

N

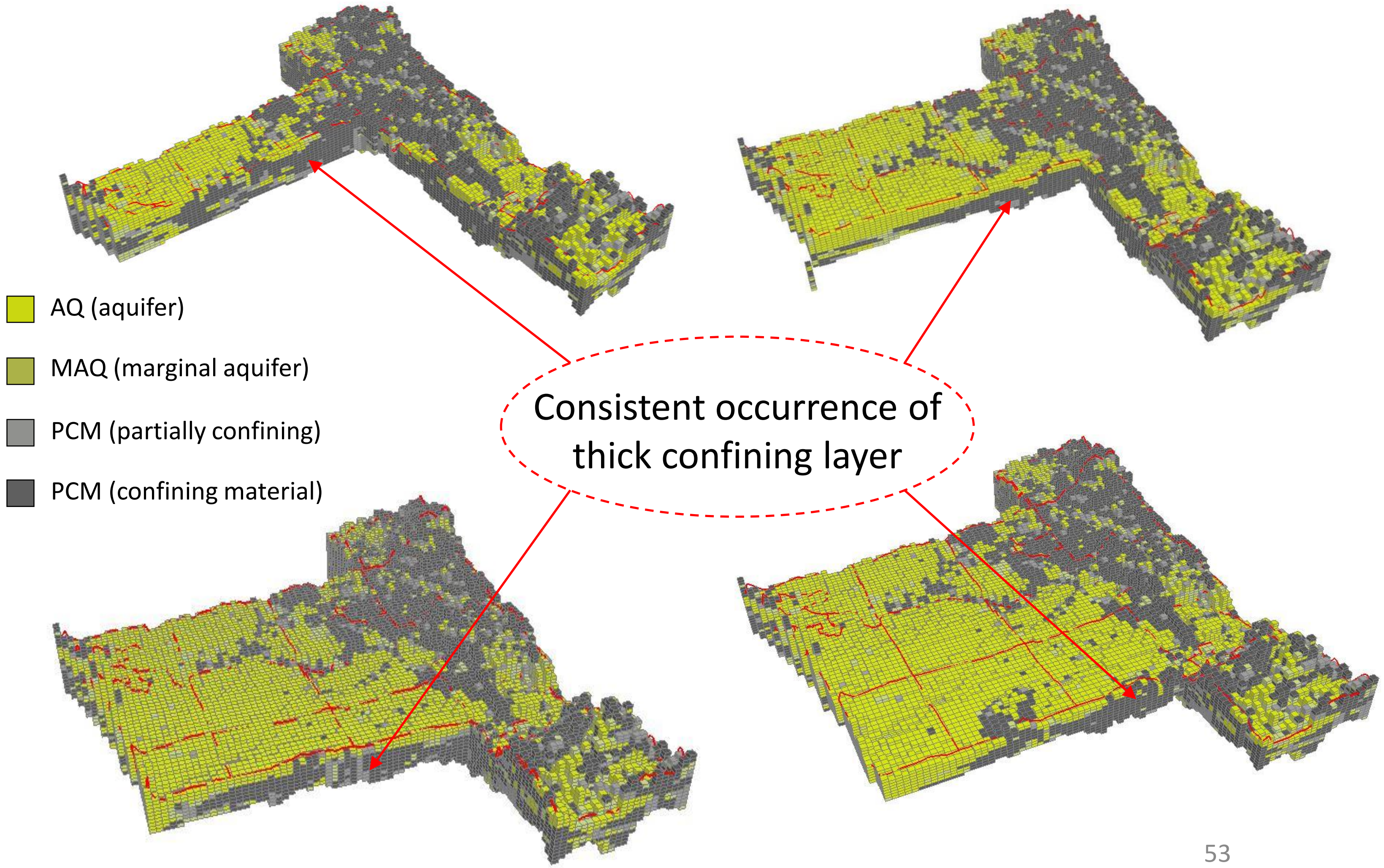
- AQ (aquifer
- MAQ (marginal aquifer)
- PCM (partially confining)
- PCM (confining material)

Average elevation of glacial bottom/bedrock top: 525 ft. (amsl)

(Churches and Wampler, 2013)

A Large, Continuous Clay Layer Exists in Central Ottawa County

Shown here are "cutouts" from the geologic model of the glacial aquifer. These help to visualize the extensive confining layer occurring throughout the central portion of the county. This layer – composed primarily of silts and clay – restricts localized recharge of freshwater to the bedrock below.



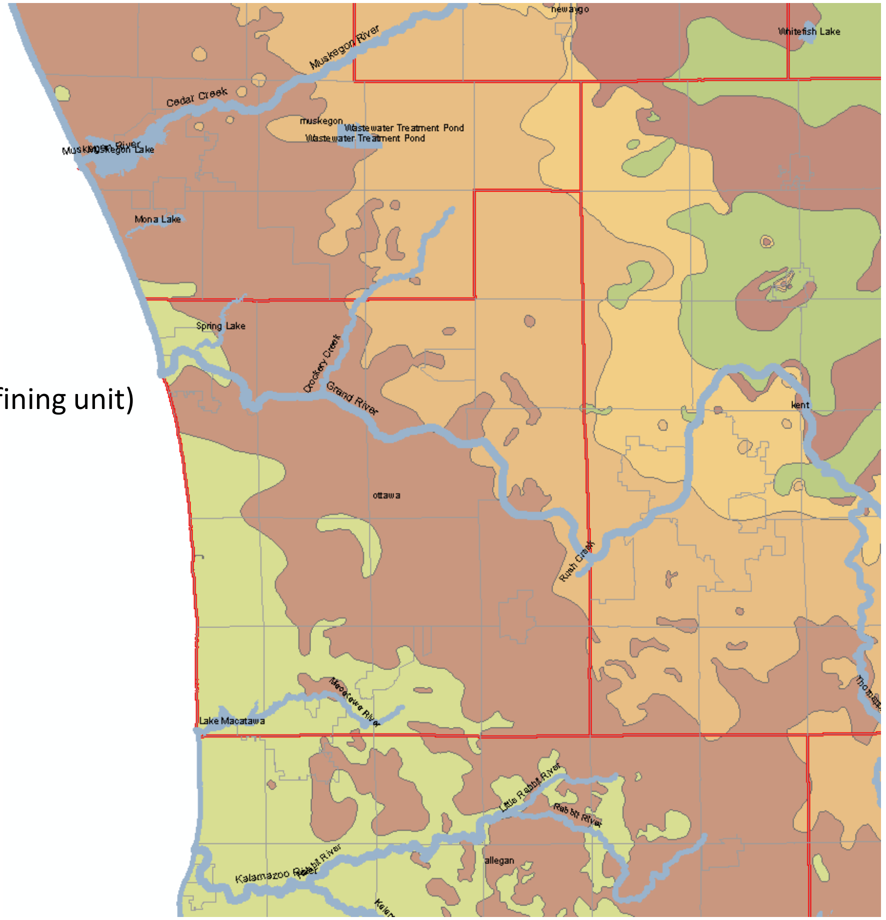
Bedrock Units Underlying Ottawa County

Ottawa County is located on the WSW margin of the Michigan structural basin, so the bedrock formations underlying the county strike NW – SE. Only three sedimentary formations subcrop beneath Ottawa County: the Michigan Formation (partially confining material, the Marshall Formation (aquifer), and the Coldwater Shale (confining material).

Michigan Formation (partially confining unit)

Marshall Sandstone (aquifer)

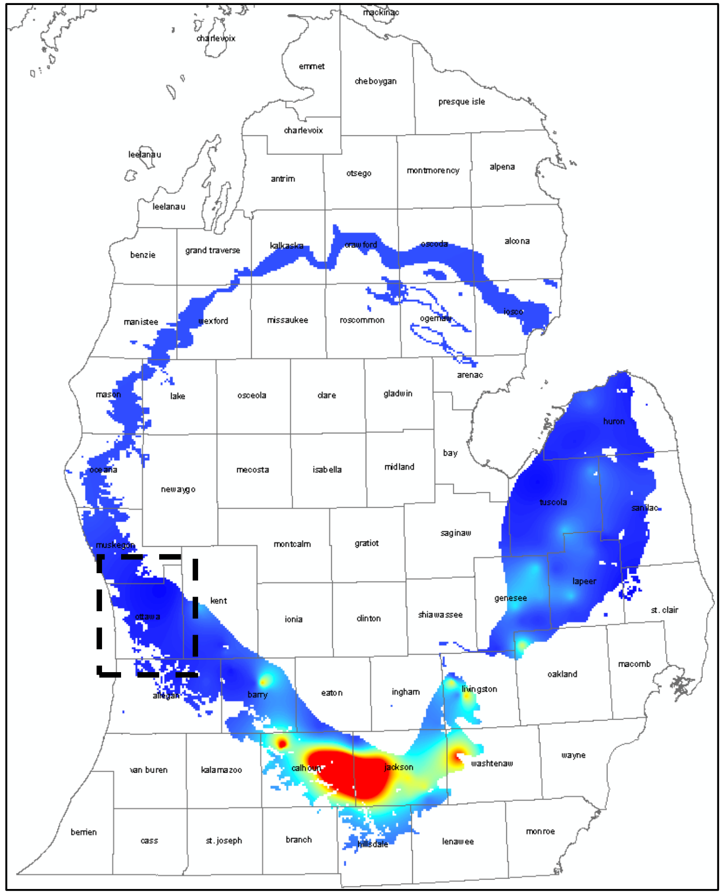
Coldwater Shale (confining unit)

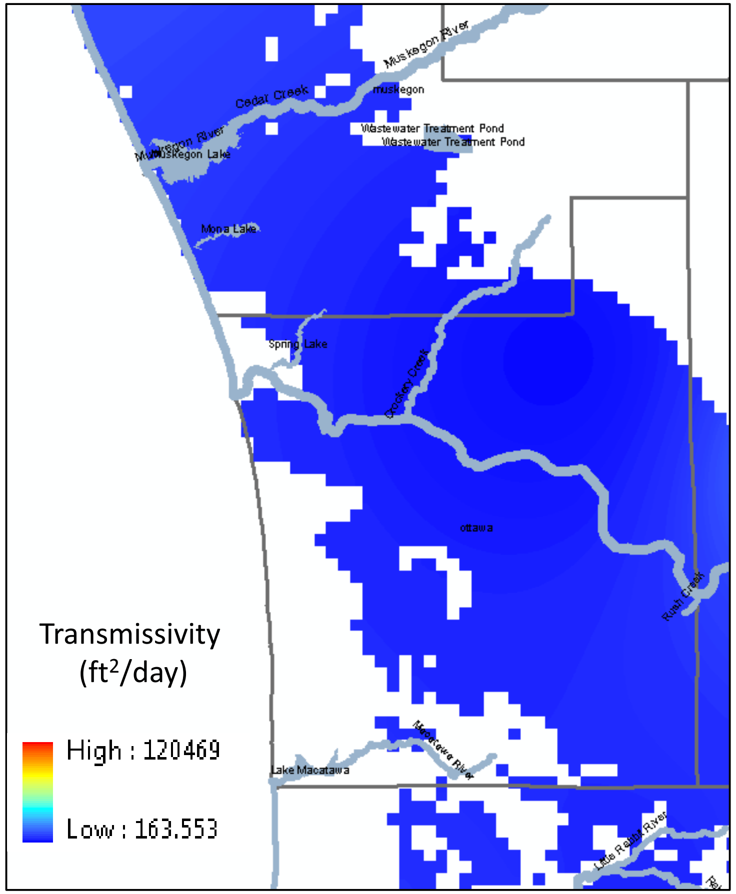


Modeling Marshall Aquifer Transmissivity

Using aquifer test data provided by MDEQ, the transmissivity of the Marshall aquifer subcrop was estimated for the entire Lower Peninsula of Michigan. Ottawa County happens to overlie a portion of the Marshall aquifer where the transmissivity is very low.

The low transmissivity of the Marshall below Ottawa County means that the impacts of pumping are more localized than in other parts of the state (i.e., the drawdown is deeper and focused to a relatively localized area).





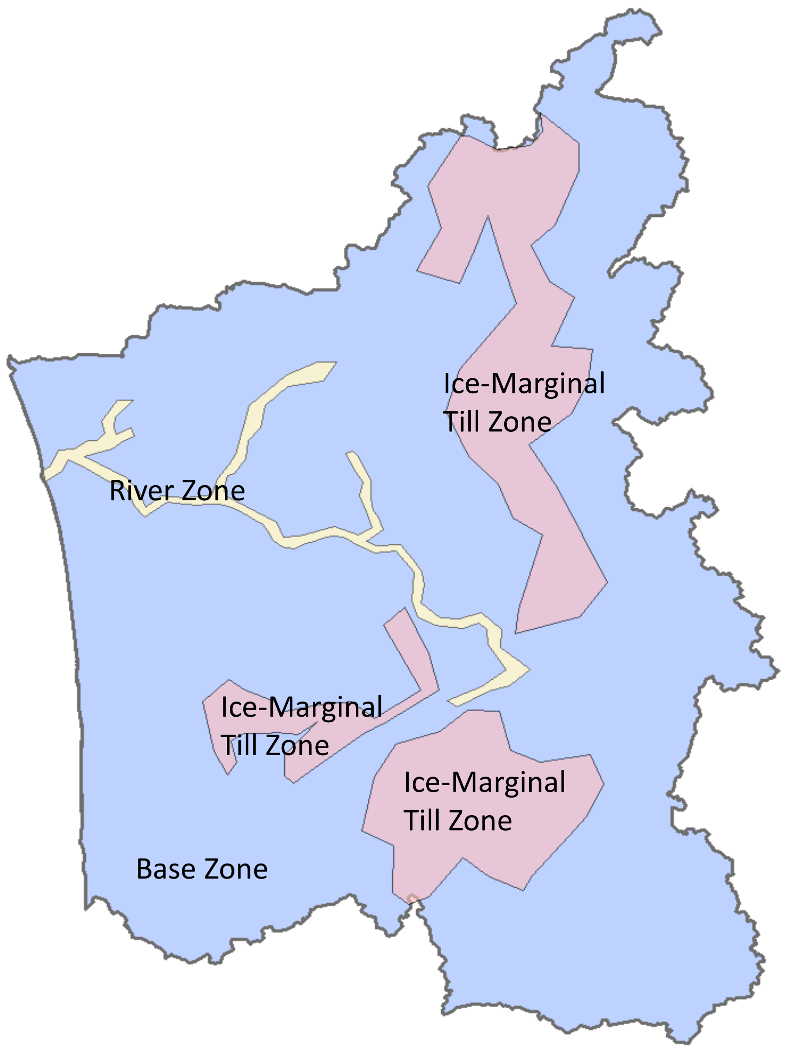
TP Zones

Using the large-scale glacial land system delineations as a guide, three distinct zones were created to account for different geomorphologies that may alter the hydraulic properties for similar material. In other words, this zonation allows for AQ to take on three different K values that are all orders of magnitude greater than those used for CM, but different enough to account for differences in large-scale depositional history across different areas of the model domain. The three zones created were:

River zone - a narrow region following the Grand River and it largest local tributaries with a relatively high hydraulic conductivity and a strong connection to the bedrock

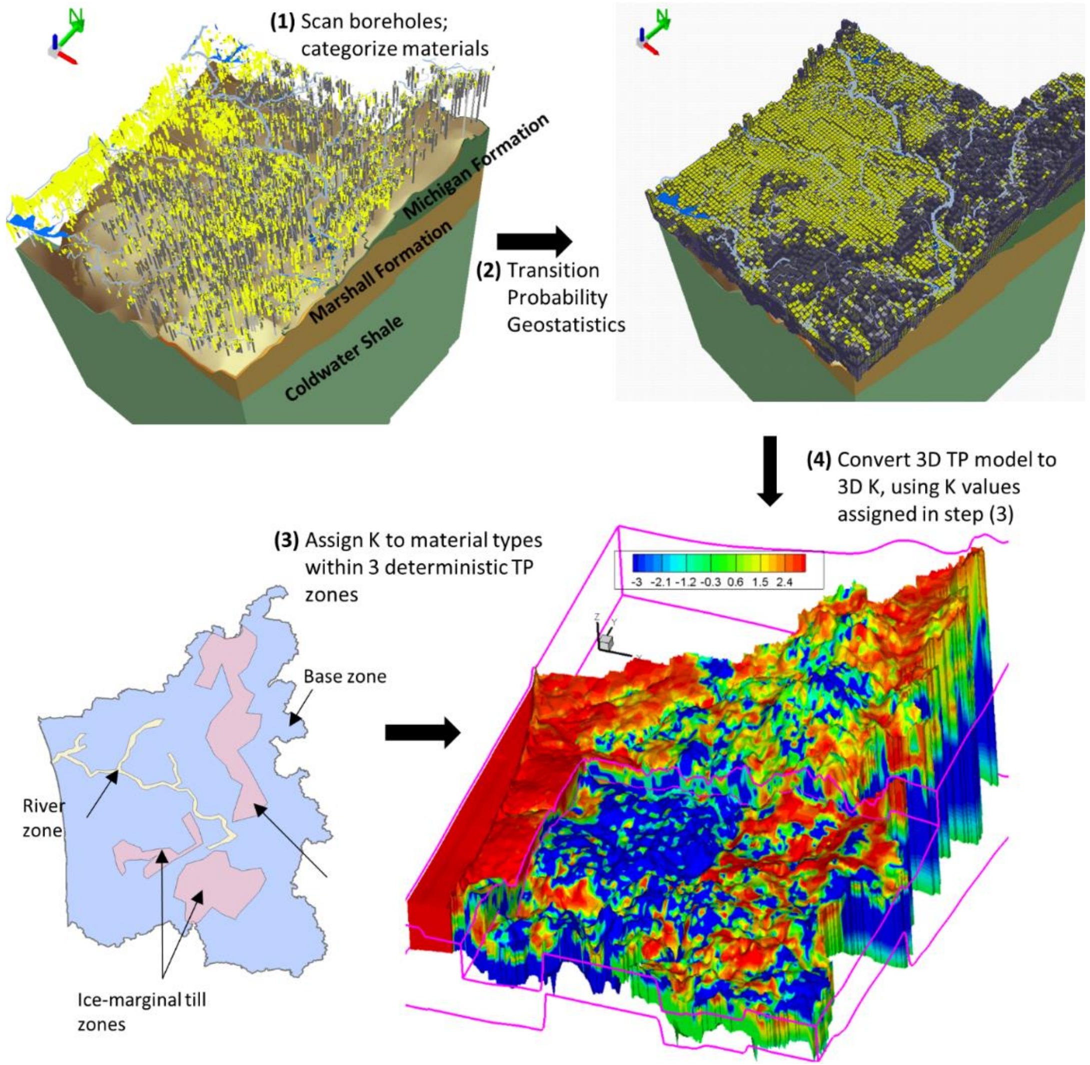
Ice-Marginal Till Zone - areas of relatively high elevation, strong heterogeneity (especially in the vertical direction) and composed primarily of ice-marginal till zones.

Base Zone - all remaining areas of the model domain with a relatively more 'restrained' depositional history and more continuity of geologic materials (e.g., a continuous clay layer across the west-central portion of the study domain)



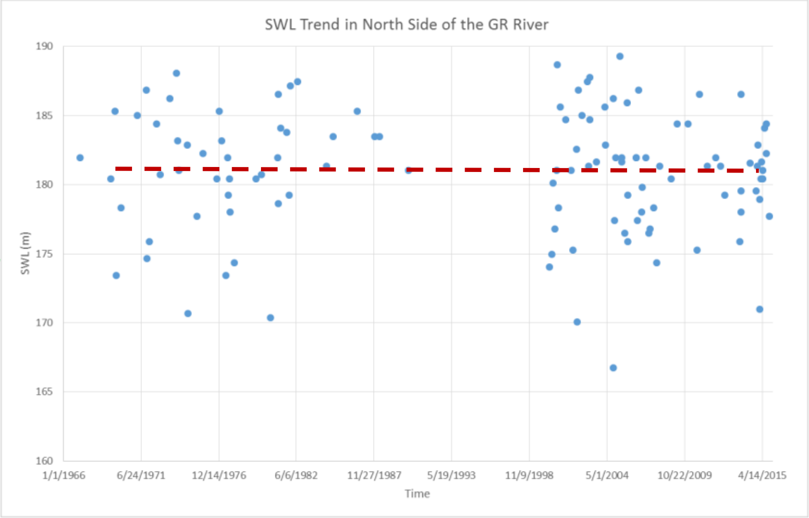
Converting the 3D Geologic Model to a 3D Hydraulic Conductivity (K) Field

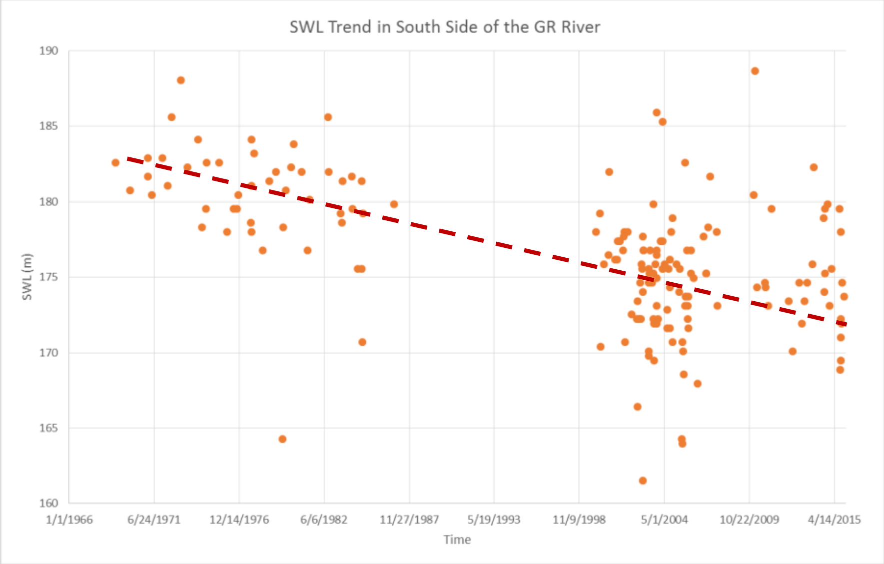
To incorporate the TP model into IGW, a K_x, K_x/K_y and K_x/K_z value for each material type must be assigned. For all material types, 2D isotropic conditions were assumed (K_x/K_y=1), and K_x and K_x/K_z were assigned reasonable estimates based on typical aquifer and confining unit properties from Fetter (2001), and were then fine-tuned during calibration. These values were used to calculate the hydraulic conductivity in each groundwater model grid cell. If one groundwater model cell contained two or more geologic model cells in the horizontal direction, the resulting K_x of the groundwater cell was the arithmetic average of the K values from the geologic model cells. If the groundwater cell contained two or more geologic model cells in the vertical direction, a harmonic average was utilized to calculate K_x for the groundwater cell. If two or more geologic cells were within one groundwater cell in both the horizontal and vertical directions, first the arithmetic average was calculated for geologic model cells in the same vertical layer, then the harmonic average was calculated using the calculated arithmetic averages. The result is a complex 3-dimensional K_x field to be used in groundwater flow modeling.

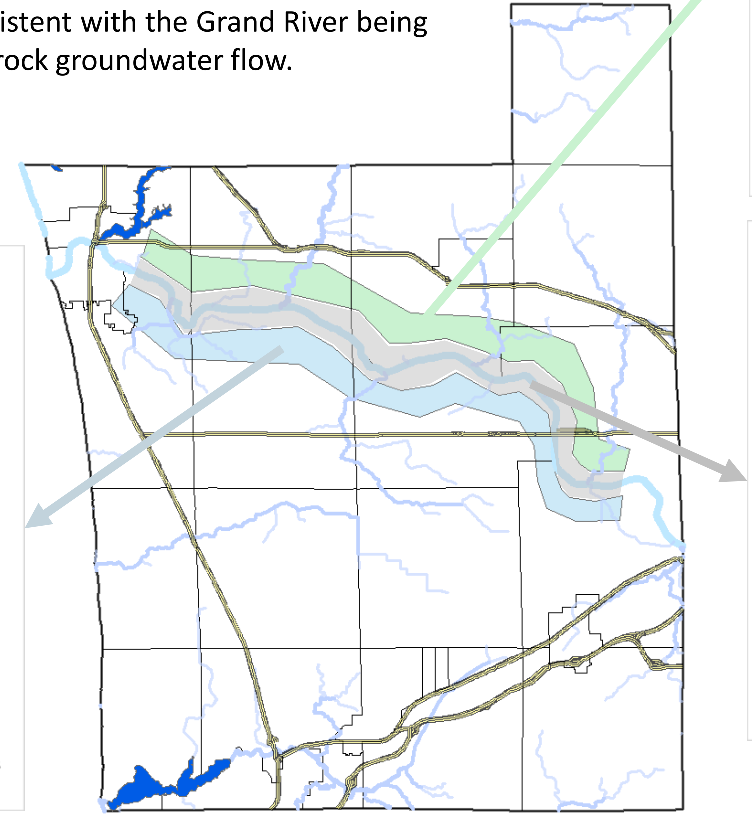


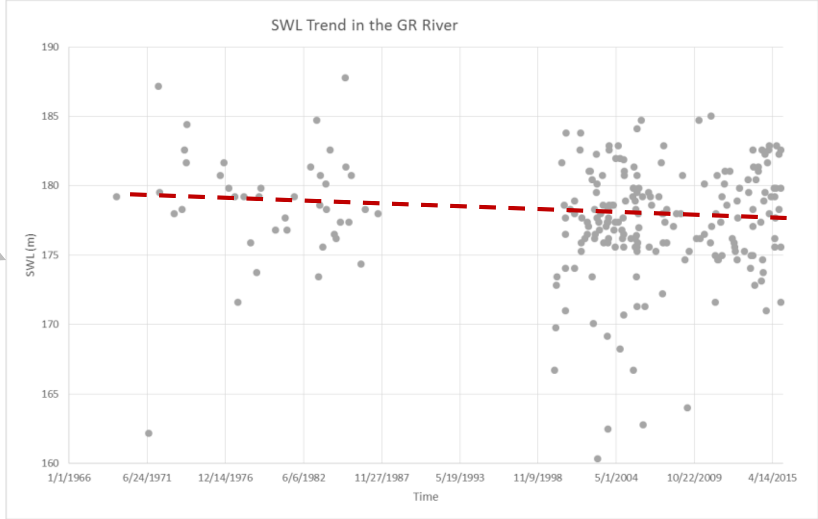
Basis for a Connection Between the Bedrock and the River Zone

The connection between the bedrock and the "River Zone" was an important but necessary conceptualization, given the relatively thin alluvium deposits (<40m) over the bedrock surface and localized occurrences of boulder-rich alluvial deposits along the Grand River throughout the study domain (Churches and Wampler 2013). Temporal analysis of bedrock SWLs along the river and narrow bands north and south of the river confirms the natural hydraulic connection to the bedrock (see graphics below and on right). If the Grand River were not well connected to the bedrock, the trend along the Grand River would be similar to the trend south of the river (where significant pumping has occurred). However, a relatively flat trend is observed along the river and north of the river, which is consistent with the Grand River being connected to the bedrock and acting as a natural sink of bedrock groundwater flow.





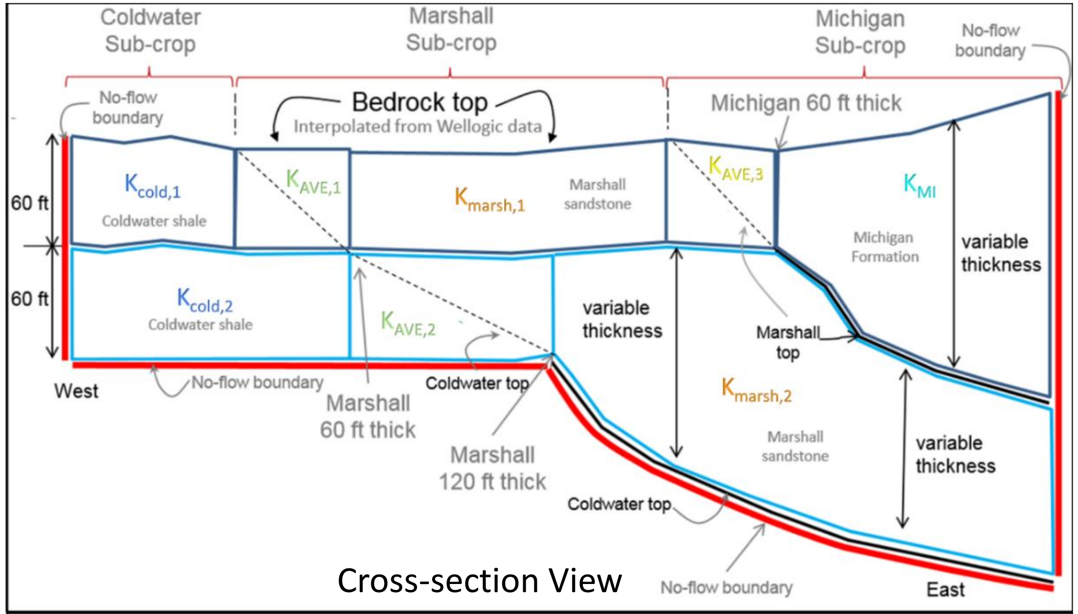


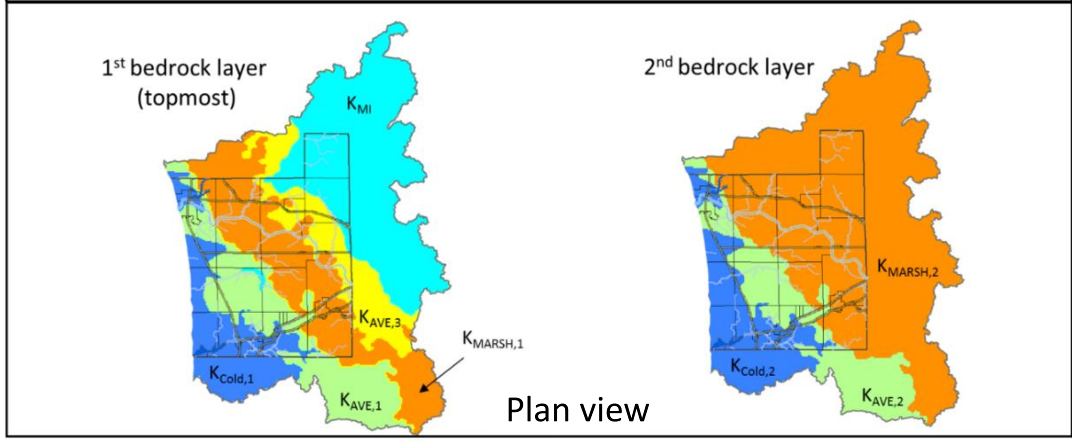


Bedrock Conceptualization

The Marshall Formation was represented using two layers: a shallow 'fractured' portion extending 60 ft. into the bedrock aquifer, and a deeper 'unfractured' portion that varied in thickness according to the geometry of the confining layers above and below. As illustrated on slides 16 and 27 , the Marshall dips toward the center of the basin as the Michigan formation becomes the top interface to the Marshall in place of the glacial sediments, creating confining conditions. Directly beneath the Marshall is the Coldwater Shale, which also acts as a confining unit and was therefore assumed to be a 'no-flow' lower boundary condition for the model domain. Because IGW is a layer-based modeling platform such that polygon features will extend across the entire thickness of the layer for all cells that the polygon occupies, a conceptual simplification of the down-dip geometry of the bedrock formations was utilized: each interface between bedrock formations was vertical, but the areal extent of the Michigan and Marshall Formations were mapped at distinct depths (60 ft and 120 ft. from the bedrock top surface) to approximate the relationship between depth and the position of the Michigan/Marshall interface or the Marshall/Coldwater Shale interface. 'Transition zones' (e.g. Kave,1) are used to represent portions of a bedrock layer where Marshall or Michigan Formation are less than 60 ft. thick and include a different bedrock unit (Coldwater Shale or Marshall Formation, respectively) within the layer-based zone. All zones in both bedrock layers are assigned an effective hydraulic conductivity, which is later calibrated.

The choice of using a separate layer to represent the "fractured zone" of the Marshall Formation is based on the standard geologic rule that fracturing decreases with depth, so that the effective transmissivity of the aquifer changes by roughly an order of magnitude when going from fractured to non-fractured. The depth of the fractured zone was estimated by examining the penetration depth of water wells extracted from Wellogic into the bedrock, assuming that the wells would not be drilled into non-fractured (and thus, non-productive) depths of the Marshall. Note that a minimum thickness of 60 ft. was assigned for both bedrock layers, even in eastern portions of the model domain where the only unit present is the Coldwater Shale – which is not an effective transmitter of water – and calibration data are lacking. This was done to alleviate issues related to numerical stability when trying to solve hydraulic head across a computational layer with significant variability in thickness.

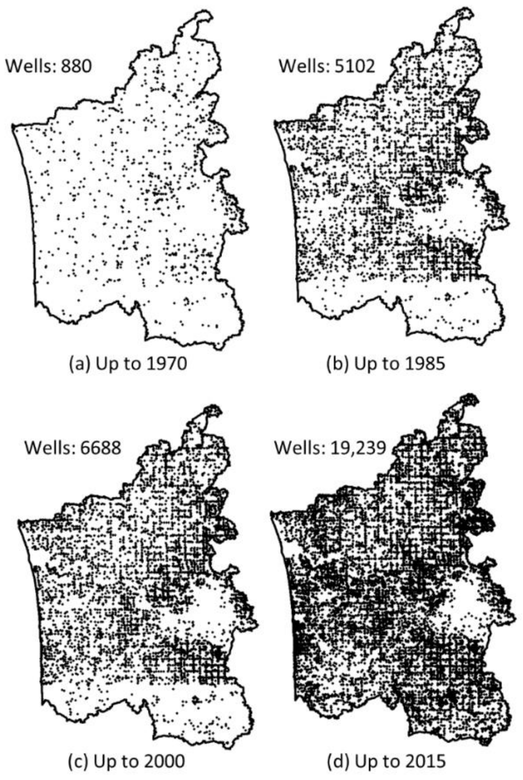




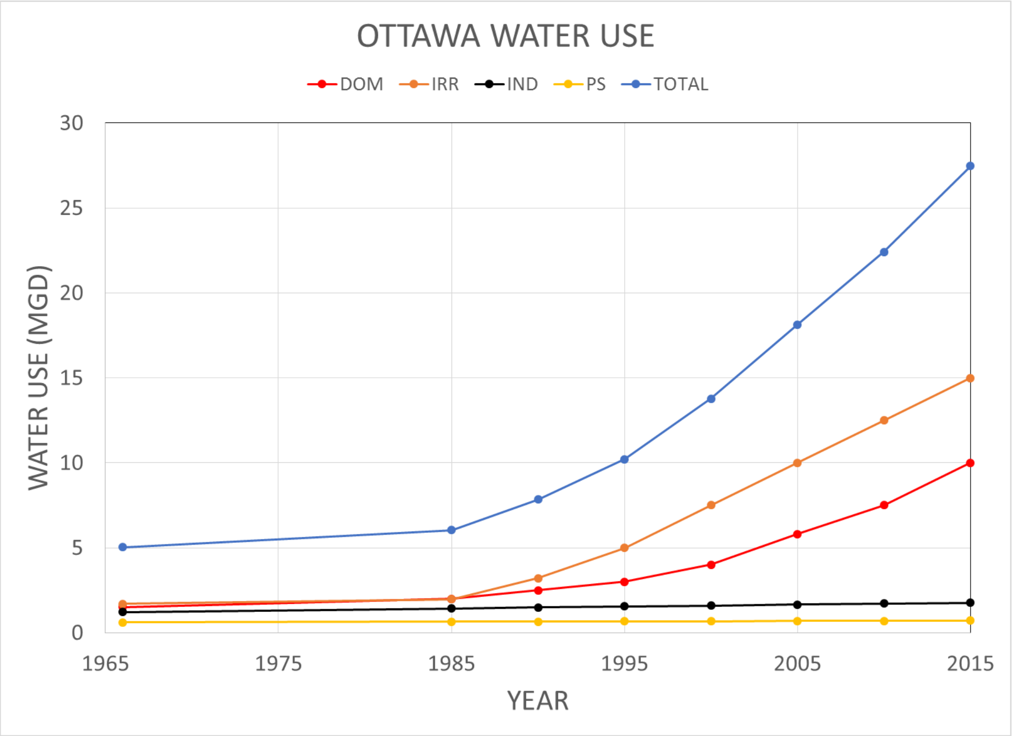
WATER USE MODELING

Knowledge of the well type (domestic use, public supply, etc.), location, screen depth interval, and construction date was available from records in the Wellogic database. This allowed for populating the groundwater model with extraction wells at the correct time and location, and assigning the pumping rate based on the well type. All wells in Wellogic were classified as 'domestic', 'irrigation', 'public supply', or 'industrial/commercial', and the pumping rates of different well types was adjusted during calibration and constrained by sector-specific water use data from recent years as well as countywide estimates from U.S. Geological Society (USGS).

Because this study is concerned with long-term groundwater flow dynamics, seasonal fluctuations were ignored, and wells were assumed to pump at a continuous rate throughout the remainder of the simulation once they were installed (i.e., pumping rates were based on 24-hours-a-day, 365-days-a-year pumping to simplify the simulations while still being able to asses long-term changes). In this way, the increase in groundwater use within the model is due to the increase in the number of wells through time, although it is possible that water use for a given sector may change across years or decades as new technologies become available. This was ignored as the data required to potentially identify such trends was not available, although the impact is likely to be relatively weak compared to that of aggressive increases in the number of water well that are operating.



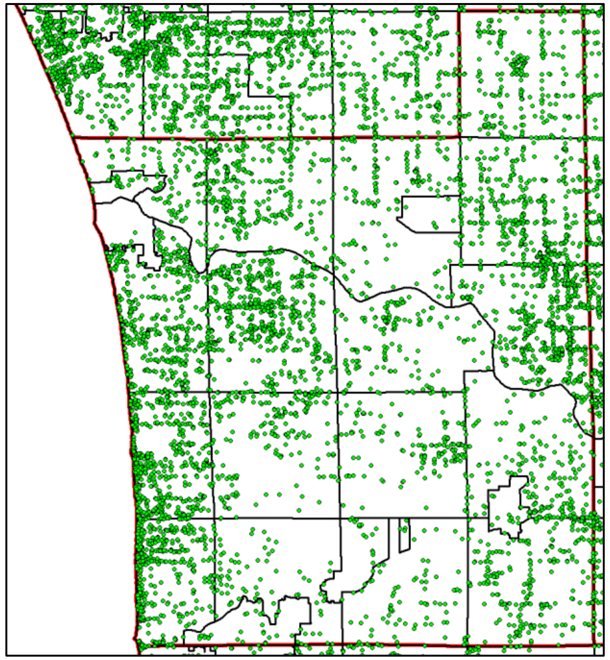
Growth of the Wellogic well network over time



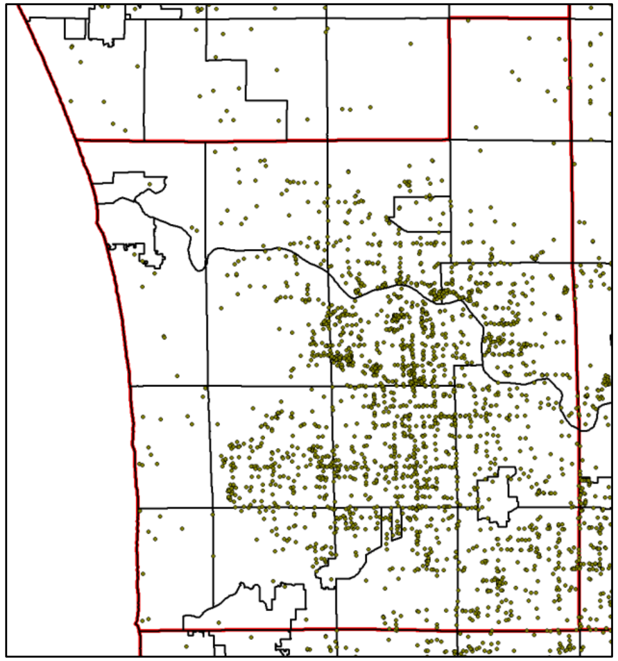
Example countywide water use curves, which could be compared to USGS countywide estimates.

Supplementing Wellogic data with Information from Environmental Health Well Records

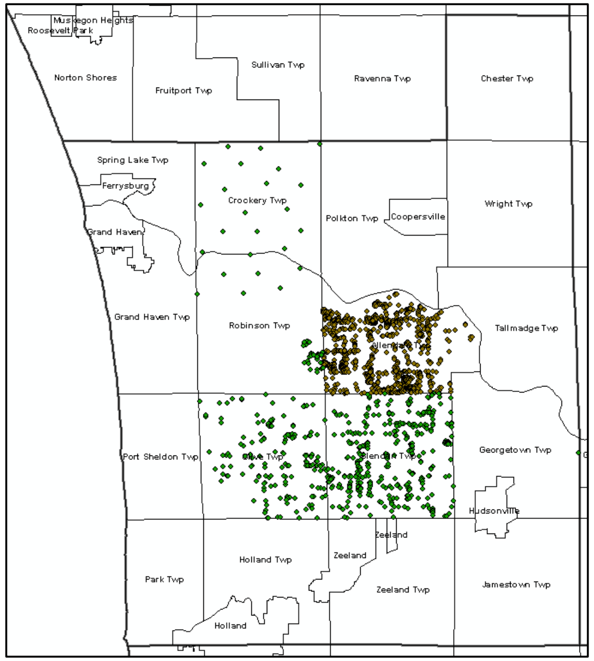
One issue with using the *Wellogic* to develop the water use model is that many wells installed during the 1990s have not been added to database. To ‘fill in the gap’, information was extracted from digitized water well records made available from Ottawa County Environmental Health Department (Ottawa County 2014), including latitude and longitude, well depth, and date of well installation for the water use model as well as SWLs for model calibration (see slides 69-71).



Glacial wells in Wellogic



Bedrock Wells in Wellogic

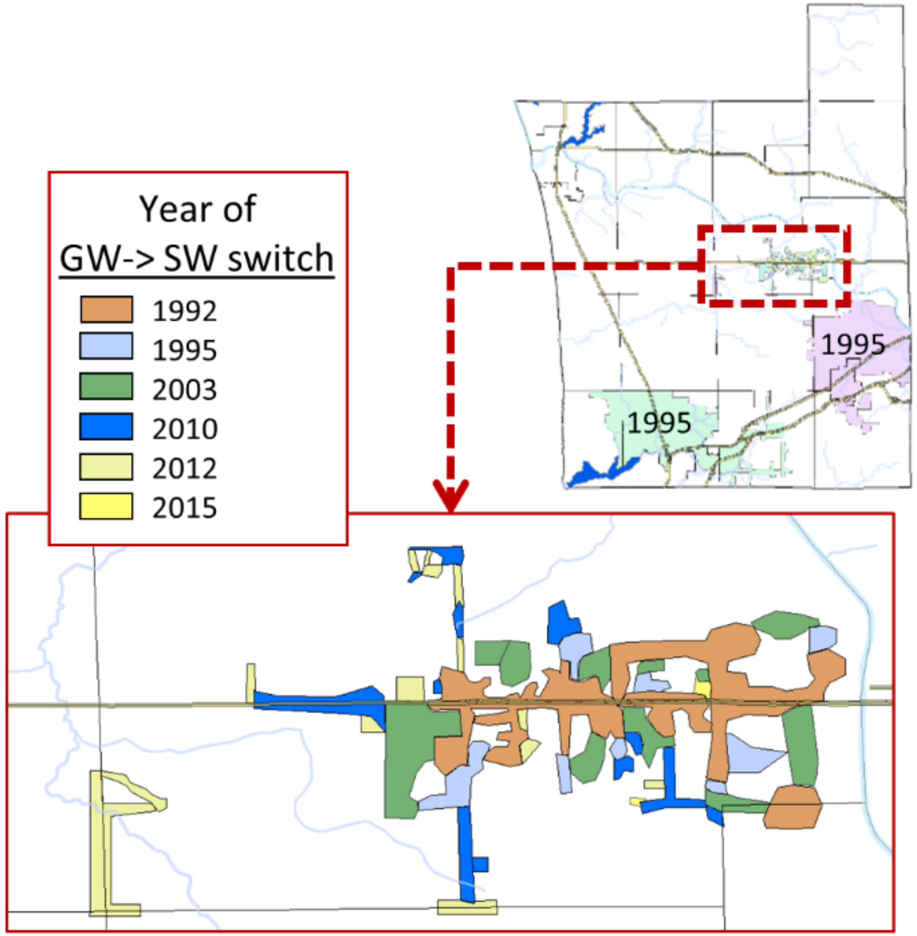


Wells mined from Ottawa Env. Health

Accounting for Switches Away from Well Water

During groundwater model development it became clear that the assumption of all wells pumping ad infinitum once installed was problematic in some areas of the county where municipal surface water supply became available in recent years. In these areas, many older wells were abandoned as properties tapped in to nearby water distribution systems. Therefore, we carefully examined the evolution of the water distribution system for a key area in the central portion of the study area to terminate pumping at the appropriate times and locations.

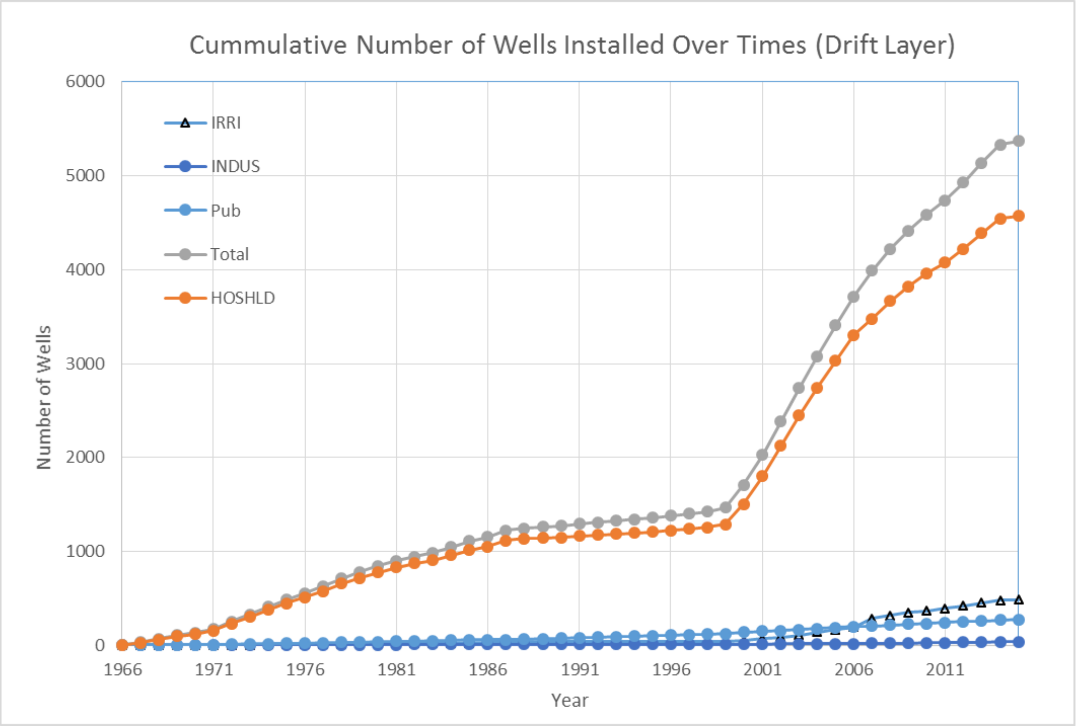
Scanned drawings and PDFs made available from the Ottawa County Public Utilities Department were converted into shapefiles, and wells constructed in polygons with installation dates *prior* to the year assigned to the polygons were terminated (i.e., turned off) in the year indicated by the polygon. If a well was installed within a polygon *after* the year assigned to polygon, it was assumed that the property was choosing to use groundwater over municipal surface water supply, and the pumping would continue throughout the groundwater simulation, with the pumping rate determined by the well type. In two areas of the study domain, detailed maps of the water system distribution were not available, but municipal water supply was first provided in 1995, and thus, the simplest treatment was to terminate wells installed prior to 1995 in these areas (see the smaller map in the graphic) once the simulation proceeded through 1995.

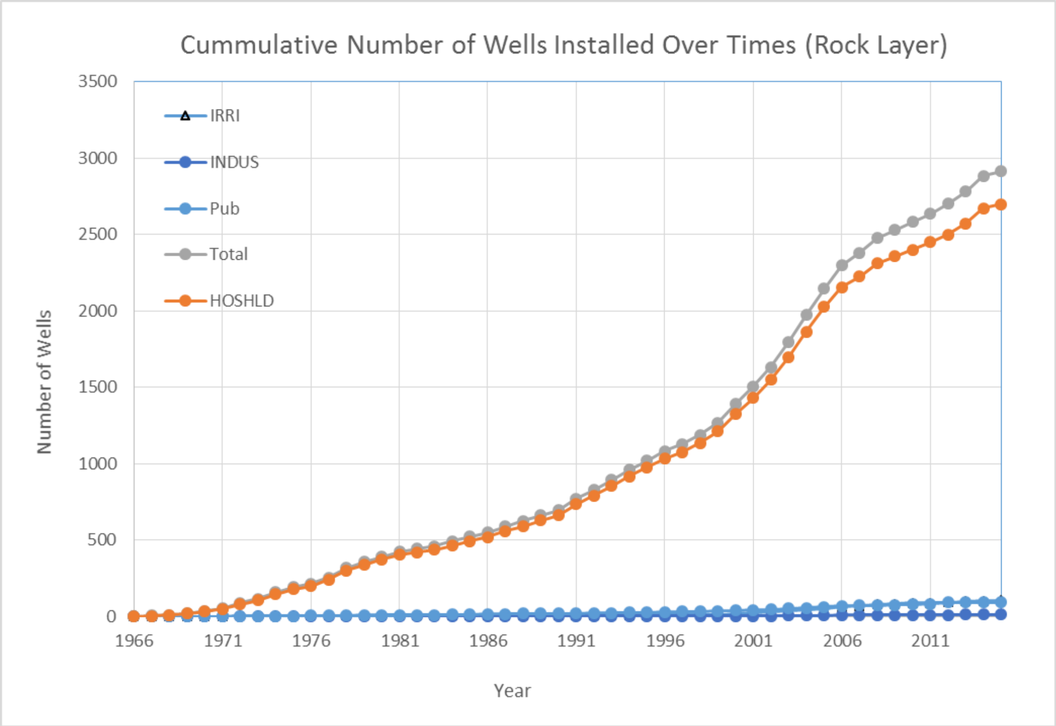


Modeled Cumulative Well Installations Over Time

This slide presents the cumulative number of wells represented in the flow model, including in the glacial aquifer (left-most graphic) and the bedrock aquifer (right-most graphic), Data series for wells used for irrigation (IRRI), industrial/commercial purposes (INDUS), public water supply (Pub), and private domestic use (HOSHLD) are included.

Note that the relatively "flat" portion of the curve representing total wells for the glacial aquifer is due to the low number of wells installed during 1990 included the Wellogic database. This is not seen in the plot associated with the bedrock aquifer because data mining was focused to that part of the aquifer system, where SWL trends were most significant and could be identified (see slide 46).

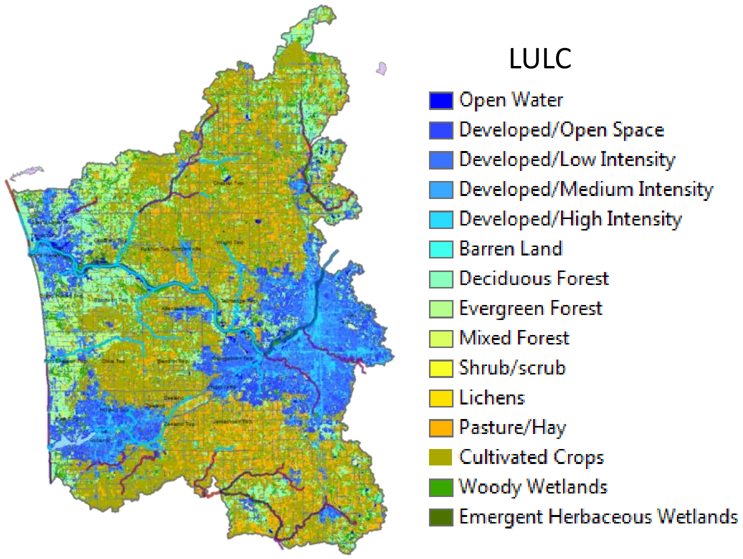




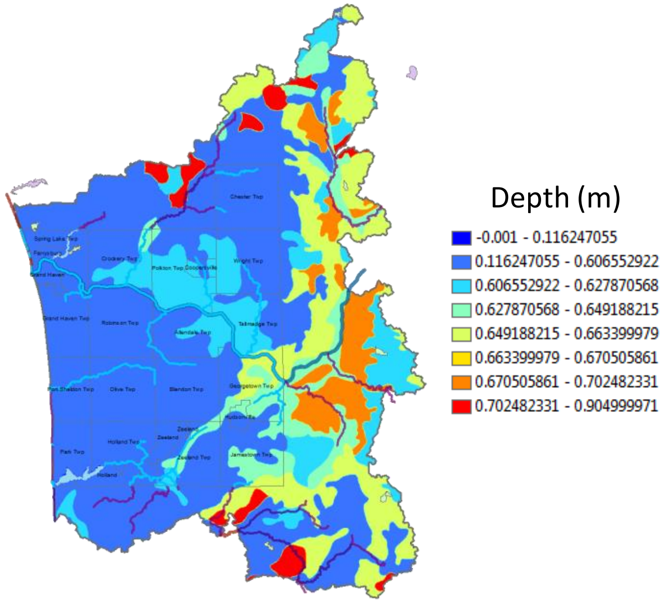
RECHARGE MODELING

Natural recharge to the aquifer system was simulated following the procedure used in the USGS model INFIL 3.0 – a grid-based, distributed-parameter, deterministic watershed model used to estimate net infiltration below the root zone (USGS, 2008). Drainage basin characteristics and daily climate records of precipitation and air temperature are used to simulate the near-surface water balance, including precipitation as either rain or snow; snowfall accumulation, sublimation, and snowmelt; infiltration into the root zone; evapotranspiration from the root zone; drainage and water-content redistribution within the root-zone profile; surface-water runoff from/to adjacent grid cells; and net infiltration across the bottom of the root zone.

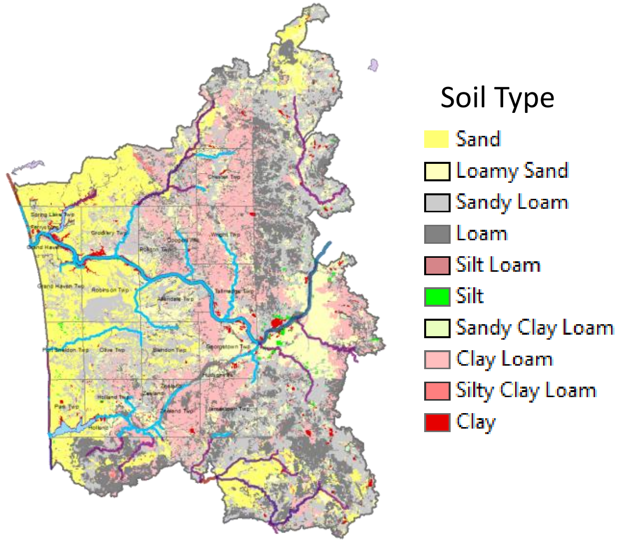
For this study, daily precipitation and air temperature data were obtained from the PRISM Climate Group, which offers nationwide coverage at 4km spatial resolution for all years since 1981 (PRISM 2004). Surface topography was modeled using 10m DEM from USGS NED (2006), and land use and land cover (LULC) was represented using a modified version of the 16-class land cover classification scheme from the USGS National Land Cover 2006 Dataset (Fry et al. 2011). The modification was a greatly reduced hydraulic conductivity for 'Developed' LULC types due to the large extent of impervious surfaces present within such areas of the model domain (e.g., Grand Rapids in the eastern subregion). Soil type distribution and root zone depth across the model domain was obtained from United States Department of Agriculture (USDA)



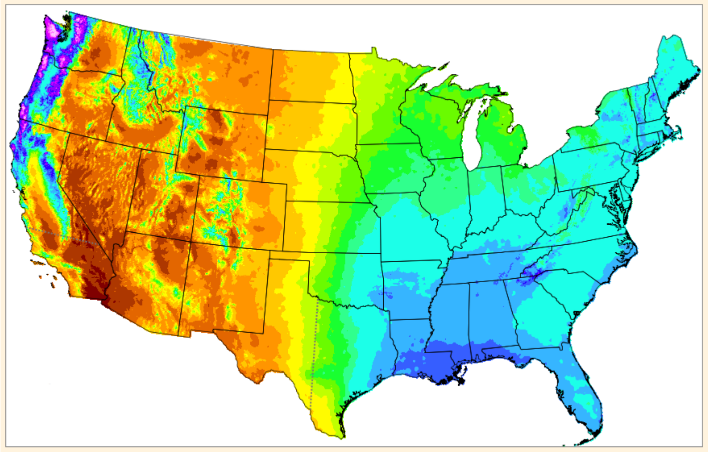
Land Use/Land Cover(USGS, 2006)



Root Zone Depth (USDA)



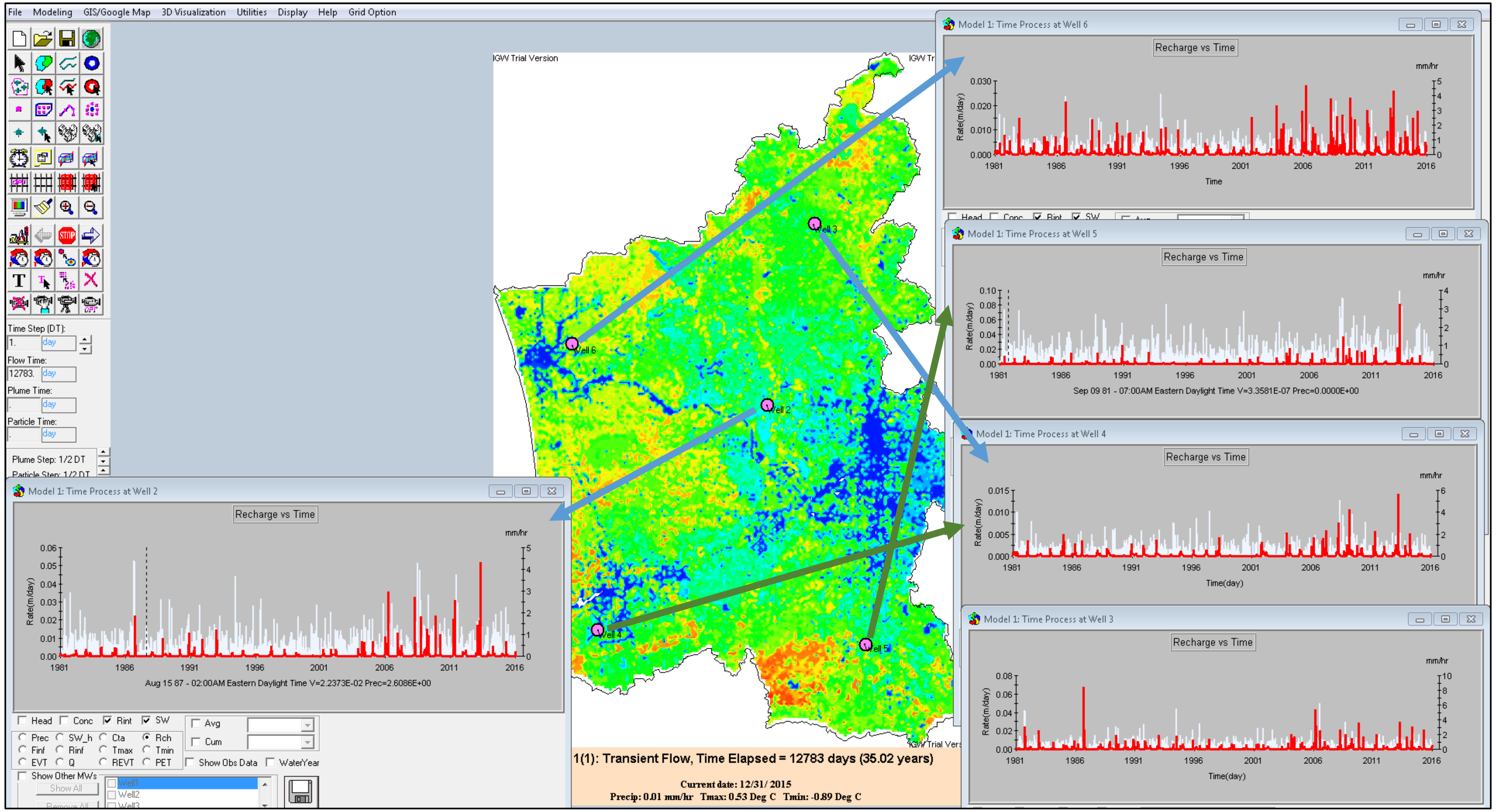
Soil Type (USDA)



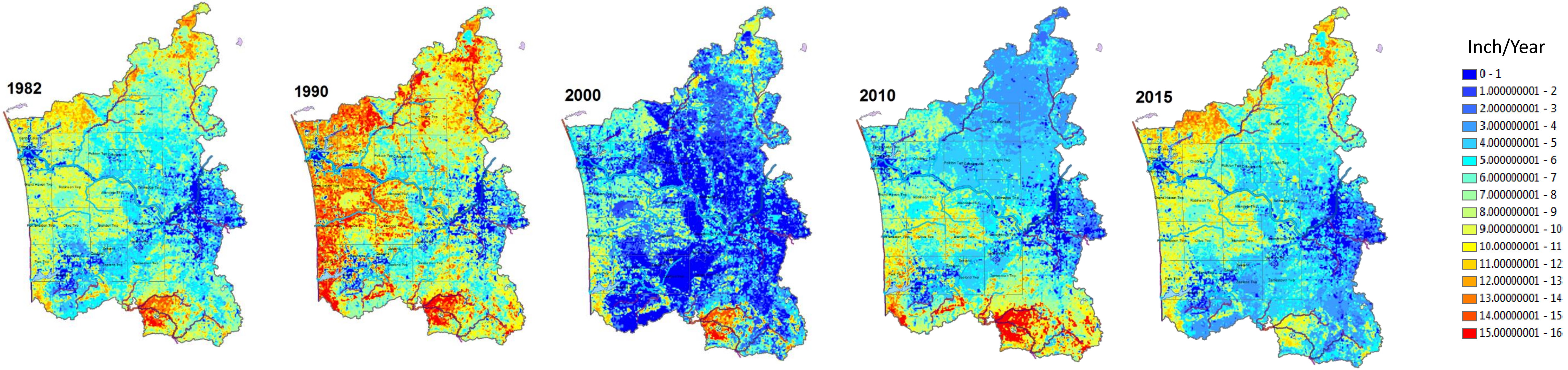
Nationwide PRISM Precipitation Data

Recharge Model Output: Daily Recharge Estimates at all Locations

Daily recharge to the aquifer system was computed from 1 Jan. 1981 to Dec. 31 2015. Annual averages were calculated at each grid cell location and used as input into the groundwater flow model at each time-step (see next slide). Recharge from 1981 was applied for the 1966-1980 time period of groundwater simulation, because the PRISM climate data did not extend back beyond 1981.

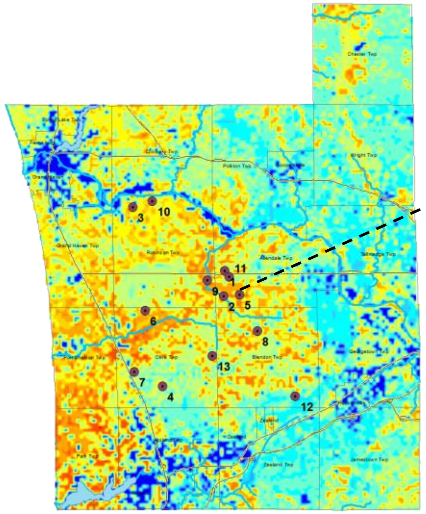


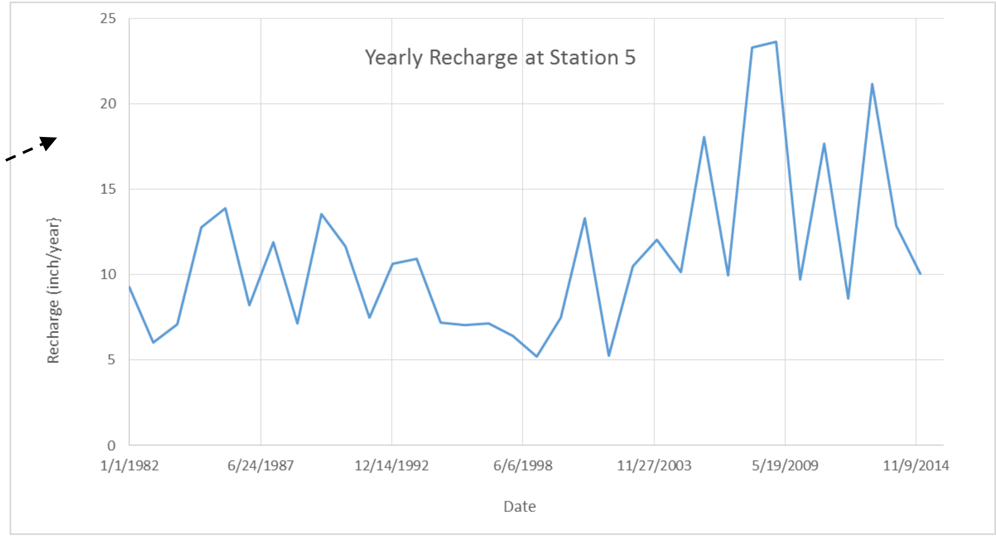
Annual Recharge Distributions



This slide shows simulated recharge distributions for selected time-step (above). Although there is significant year-to-year variability, the spatial distribution of recharge is generally consistent across years, i.e., the areas where recharge is relatively high and where recharge is relatively low are consistent across time. Note that daily PRISM climate data was not available prior to 1982, so the 1982 distribution was applied for the 1966-1981 time period.

Also shown here is illustrative an annual recharge time-series plot for a location in central Ottawa County (right). The plot suggests that both the average recharge and the sub-decadal variability has increased since roughly the year 2000.





FLOW MODEL DEVELOPMENT

The groundwater flow model consisted of three ‘conceptual layers’ – the fractured and unfractured bedrock and drift aquifers – which translated to seven computational layers used for solving the unsteady groundwater flow equation:

$$S_s \frac{\partial H}{\partial t} = \nabla(K \cdot \nabla H) + q$$

where S_s is the specific storage coefficient, H is the hydraulic head [L], t is time [T], K is the saturated hydraulic conductivity tensor [LT^{-1}], ∇ is the gradient mathematical operator, and q is the net source (positive) or sink (negative) term including pumping, recharge, and drains [LT^{-1}] . Interactive groundwater uses finite difference approximations of the governing differential equation to solving confined and unconfined flow conditions (see Li and Liu 2006; Li et al 2006; Liao et al. 2015 for details on algorithms/schemes). The glacial layer, which needs to resolve the strong vertical structure of the aquifer material distribution derived from the TP geologic model, was subdivided into five computational layers of equal thickness. The fractured and unfractured bedrock conceptual layers were not subdivided, and thus flow was assumed to be predominantly horizontal within these units. Note that across the model domain, the vertical grid spacing is not uniform and depends on the saturated aquifer thickness at each location.

The northern, eastern, and southern lateral boundaries were assigned as no-flow boundaries conditions for all layers in the assumption that significant groundwater does not pass under local topographic divides. Of course, this does not reflect actually groundwater conditions, and for this reason calibration was completed by using only observations from within Ottawa County, whose borders are far enough from the no flow boundaries to limit its influence. The western lateral boundary for the glacial layers was a constant head that represented the long-term average lake level of 579.3 ft (176.6 m) above mean sea level obtained from the Great Lakes Water Level Dashboard (Gronewald, et al. 2013). Some consideration was given to treating Lake Michigan as a time-dependent head boundary condition, but this was deemed an unnecessary level of complexity considering that the variability of the lake levels was much less than the observed drawdown in the groundwater level dataset used for calibration. The western lateral boundary for the bedrock layers was considered a no-flow boundary due to the proximity of the Coldwater Shale confining unit along Lake Michigan within the study domain. The land surface, modeled using the 10m DEM from USGS NED (2006) is treated as a one-way drain boundary that allows groundwater to discharge to the surface where the groundwater level intercepts the land surface:

$$q_{drain} = \begin{cases} L(h-z) & if\ h > z \\ 0 & otherwise \end{cases}$$

where q_{drain} [LT^{-1}] is the flux per unit area leaving the aquifer through the land surface, L [T^{-1}] is the leakance, and h [L] is the head the aquifer cell. Care was taken to ensure that this approach effectively captured the groundwater discharge to lakes, streams and wetlands in the model domain by comparing the surface seepage maps at different time-steps to the surface water network features obtained from USGS NHD (2010).

Model Initialization & Time-Marching Scheme

The initial groundwater head distribution was generated by simulating steady-state groundwater flow for 1966 conditions, which incorporated all *Wellogic* wells completed prior to 1967 as pumping withdrawals. An iterative vertical discretization scheme was proposed to avoid the issue of “dry” cells when sub-dividing one layer into multiple sub-layers. The approach was to first discretize the glacial aquifer using one vertical layer to solve the head distribution, and then use that in the next iteration to subdivide the saturated thickness of the aquifer into multiple computational layers, say 2 or 3, which are solved. The process was repeated until a steady-state head distribution was solved for 5 glacial layers and 2 bedrock layers.

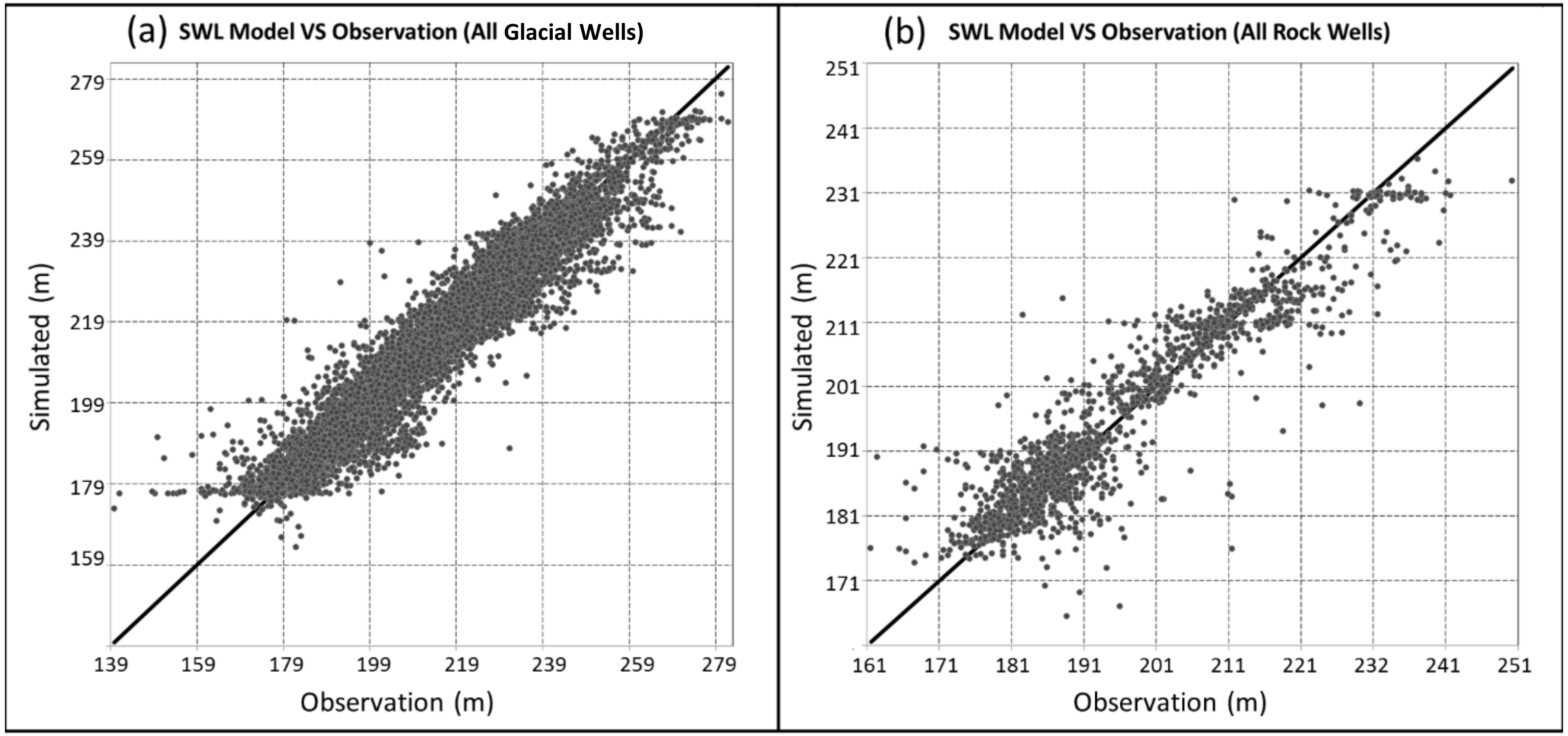
With the initial head distribution obtained from the 1966 steady-state solution, the simulation was advanced in time by solving the governing flow equation with 2-year time-steps. Annual recharge distributions were included in the source/sink term at each time step (e.g., if the model was proceeding from 1968 to 1970, the recharge distribution from 1970 was used to solve the groundwater flow equation). Withdrawals from wells constructed during the time period over which the time-step extends contribute to the source/sink term of the groundwater model cells for that time-step and continue operating at the calibrated pumping rate ad infinitum.

MODEL CALIBRATION

The groundwater model was calibrated manually using thousands of Static Water Level (SWLs) measurements from borehole records in the Wellogic database and the Ottawa County Environmental Health Department (see slide 45). Each SWL observation from a given time and location was compared to the interpolated value of simulation results from nearby groundwater model cells. Additionally, a comparison of SWL trends across time with model trends was made on a township-by-township basis to evaluate the model's ability to simulate long-term groundwater dynamics in different areas of the model domain. To summarize the discussion of water use and spatial parameterization, the following parameters were calibrated to improve model performance: hydraulic conductivities of each material set ('AQ_n', 'MAQ_n', 'PCM_n', 'CM_n') for three zones, including the horizontal conductivity (K_x) and the ratio of horizontal to vertical conductivity (K_x/K_z); hydraulic conductivities of different bedrock zones; and sector-specific pumping rates for domestic, public supply, irrigation, industrial/commercial wells.

Simulated and Observed SWLs Comparisons

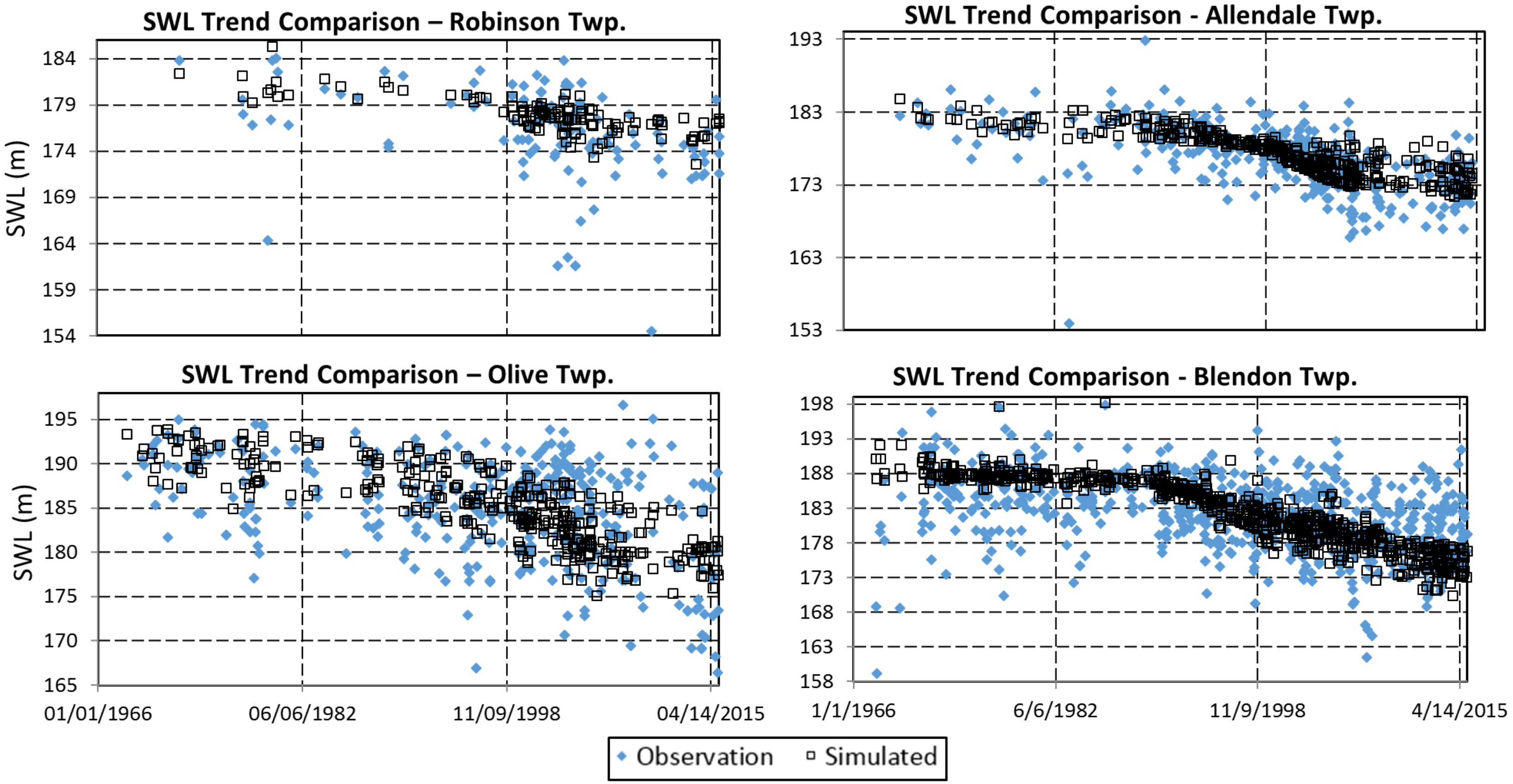
The comparisons of all observed SWLs with simulated hydraulic head from the calibrated model are shown on the right. The results show that the model performed reasonably well across both space and time, although the significant noise in the dataset results in a relatively large spread about the 45° line of perfect agreement. The large amount of noise is partially due to inaccuracies in SWL calculations, which may be caused by 1) approximate wells location derived from geocoding or indirect information reported by the driller; 2) measurement uncertainty introduced by inconsistencies from driller to driller, and 4) the fact that 2-year averaged simulated groundwater head was being compared to measurements taken from different times over that 2-year period. The subgrid spatial heterogeneity not resolved by the model may also contribute to the relatively large spread.



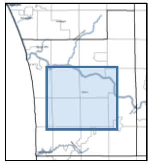
Note: 1 m = 3.28 ft.

SWL Trend Comparisons

To evaluate temporal trends in different areas of the model, subsets of the SWL dataset were created by aggregating SWLs within each township of Ottawa County (for both the glacial and bedrock aquifer), which were then plotted against time. Of course, SWL spatial variations within a township will create variability in SWL observations for a given time (in addition to other sources of inaccuracy in SWL measurements – see the previous slide). However, in some cases (i.e., the bedrock aquifer in central Ottawa County) the temporal trend may be stronger than the noise created, which is shown on the right. Also shown is the simulated head for each measurement time and location. Note that the model is able to reproduce the general downward trend observed in the SWL subsets, although the spread in the simulated dataset is less because the values are exact, i.e., there are no sources of error, although the effects of spatial aggregation is apparent. As noted on slide 47, for many of these charts created for the glacial aquifer (and for some of the bedrock aquifers), a temporal trend could not be detected, either because the noise was larger than the trend, or because a significant trend did not exist. Nonetheless, this township-by-township temporal analysis provided an additional constraint on the calibration that could not be discerned through the figures shown on the previous slide.



Note: 1 m = 3.28 ft.

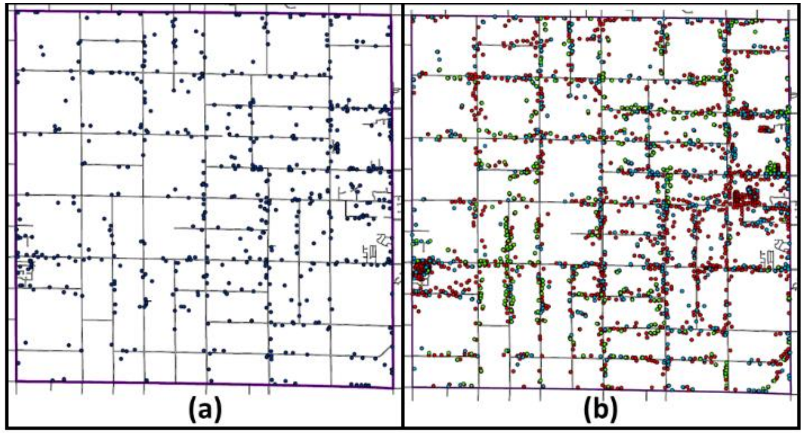


Calibrated Water Use Parameters

This slide presents the calibrated pumping rates of the different well types as well as average observed pumping rates as a comparison. The observed pumping rate for irrigation wells was derived from 2012-2013 self-reported agricultural withdrawals compiled by MDARD; the observed rate for public and industrial/commercial wells was calculated using 2012-2013 data made available by MDEQ; and the observed rate for domestic wells an analysis of water meter data provided by Ottawa County Public Utilities Department. The comparison between calibrated and observed pumping rates is reasonable, with a ratio of calibrated pumping rate to observed pumping rate of just over one for public supply, irrigation and industrial/commercial water use sector (1.03, 1.61, and 1.68, respectively).

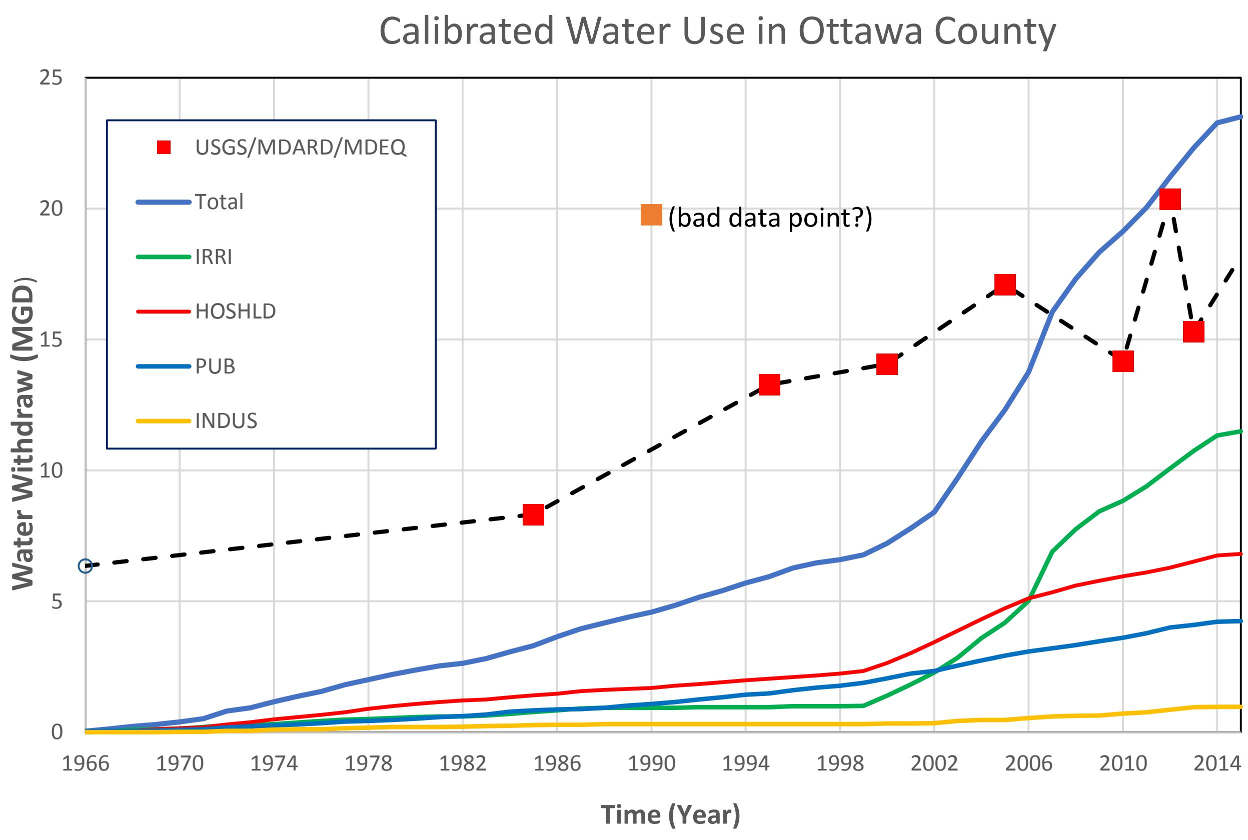
The slight overestimation may be because users are underreporting their water use, which may be incentivized by strict laws regulating large-capacity groundwater withdrawals in Michigan, or it may be because some wells are missing in well dataset used to create the water use model and thus, a higher simulated pumping rate was needed to reach an equivalent total water use that could reproduce the observed drawdown exemplified in the SWL trend comparisons. The latter is the likely reason why the calibrated pumping rate for domestic wells was 3.39 times larger than the observed pumping rate. There are roughly 1.3 million water wells in Michigan (MDEQ 2015), but thus far only about 550,000 wells have be incorporated into the Wellogic database. Although some areas of the state are more ’complete’ than others, undoubtedly some domestic wells are missing from the model, and thus it is reasonable to have a simulated domestic pumping rate a few times higher than the observed pumping rate, assuming the relative spatial density distribution of the well dataset used for modeling represents the actual relative spatial density distribution. This assumption was checked for a portion of the model domain by completely exhausting information from local water well records compiled by the Ottawa County Environmental Health Department and ‘visually’ adding wells, i.e., if properties did not have a well record but were not in proximity to water distribution line or any other source of potable water, a well was assumed to exist on the property (see graphic on right). Indeed, the relative spatial density distribution of the dataset used for modeling and that of the ‘actual’ well network is similar. Moreover, there are roughly 3 times as many wells in the latter dataset (most of which are domestic wells) as compared to the former dataset, suggesting that the ratio of 3.39 for simulated domestic pumping rate to observed pumping rate is relatively accurate in terms of producing the overall impact of domestic well withdrawals.

Well Type	Calibrated Pumping Rate (GPM)	Observed Pumping Rate (GPM)
Domestic	0.65	0.19
Public Supply	8.00	7.76
Irrigation	13.50	8.36
Industrial/ Commercial	13.50	8.03



Calibrated Water Use Curve

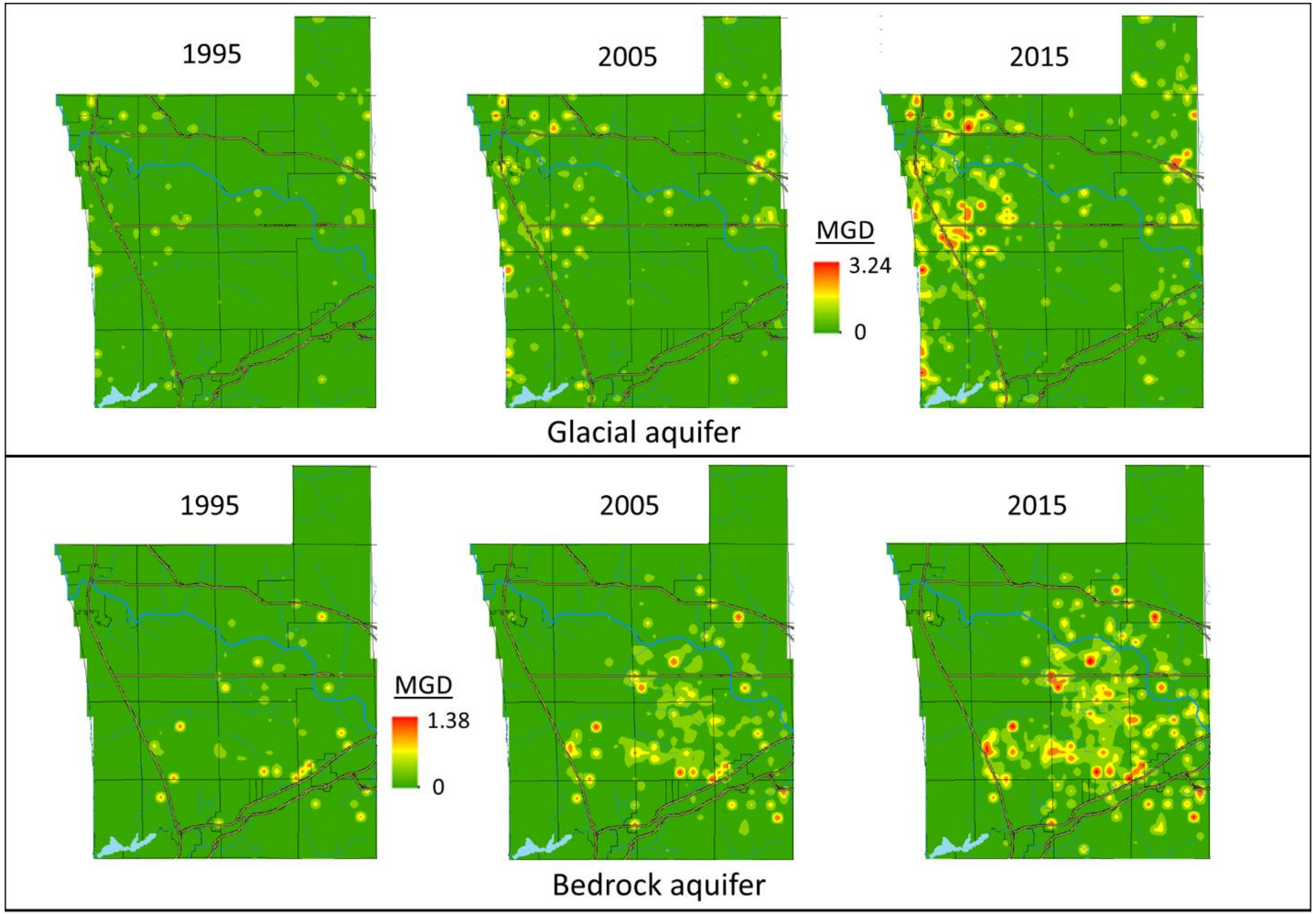
As a final check on the water use parameters, a comparison was made of total simulated water use with reported water use in Ottawa County, which is shown to the right. The solid lines represent the different water use curves as well as the total water use (blue). The water use attributed to irrigation has significantly increased since 2000, indicating expanded agricultural activity. Also note the importance of domestic well withdrawal increases. Overall, the total simulated water use is similar to the reported water use in recent years (2000-2013), however, in the more distant past (1985-1995) the simulated water use is less than that estimated by USGS water use surveys. Because our simulated water use is constrained both by observed pumping rates and long-term spatiotemporal calibration across the study area, we suspect there is a significant degree of overestimation in early estimates of countywide water use from the USGS surveys. Nonetheless, it is encouraging that there is some level of agreement between the observations and simulated water use, i.e., the estimates are consistently the same order of magnitude.



Calibrated Annual Water Use Distributions

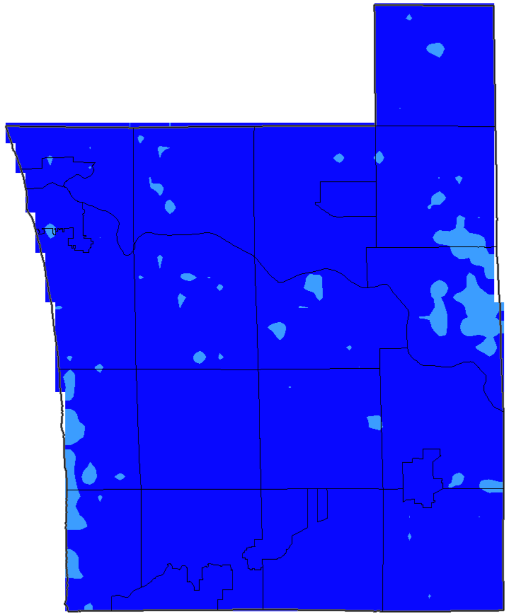
This slide presents examples of the final water use distribution in the glacial and bedrock aquifers for selected time-steps.

During early periods of simulation (1970-1990), water use is relatively low and isolated to a few different areas, but since post-1990, water use has increased in spatial extent and intensity, especially in 1) the central and eastern portions of the bedrock; and 2) in the western portions of the glacial aquifer.

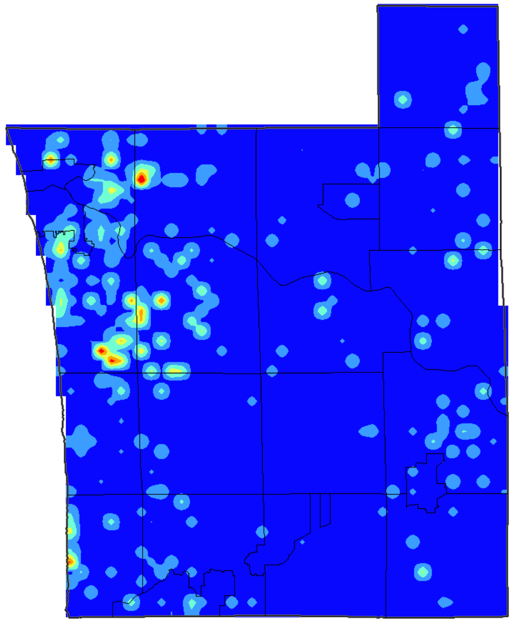


Glacial Layer Cumulative Water Use – By Sector

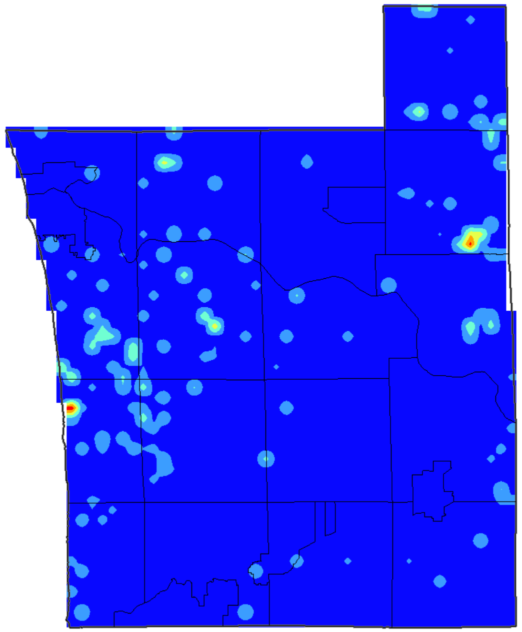
This slide shows the cumulative water use in the glacial aquifer by sector. Note that the dominant use of groundwater from the glacial aquifer is for irrigation and pubic supply.



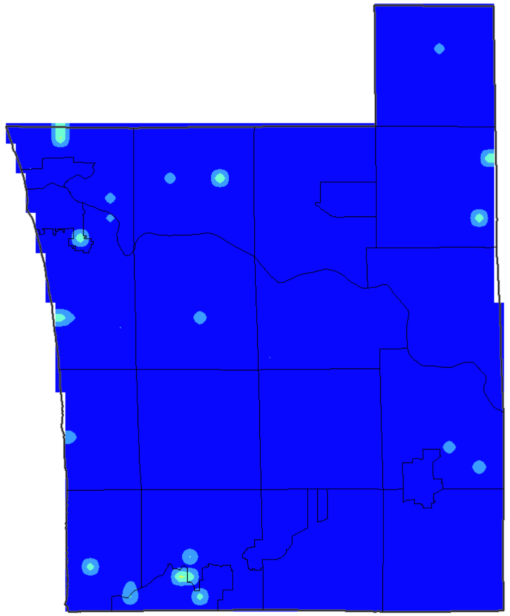
Domestic Wells



Irrigation Wells



Public Supply Wells



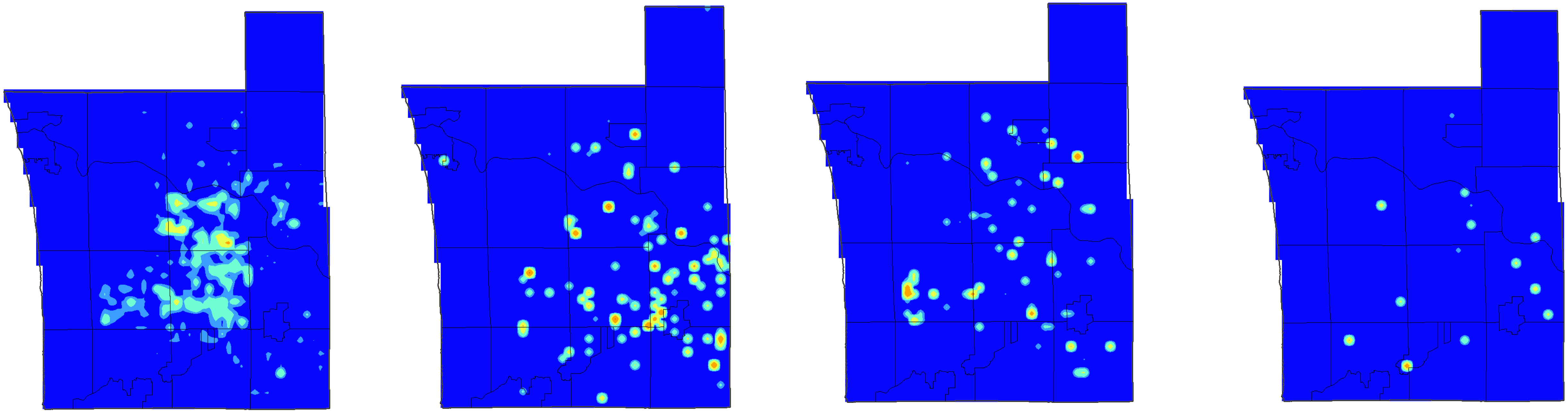
Industrial/Commercial Wells

Water Use (MGD)

- -3.241559982 - -2
- -1.999999999 - -1.5
- -1.499999999 - -1
- -0.999999999 - -0.5
- -0.5 - -0.1
- -0.099999999 - 0

Bedrock Layer Cumulative Water Use – By Sector

This slide shows the cumulative water use in the bedrock aquifer by sector. Not that the dominant use of groundwater from the bedrock aquifer is for irrigation and domestic use.



Domestic Wells | **Irrigation Wells** | **Public Supply Wells** | **Industrial/Commercial Wells**

Water Use (MGD)

- -1.381299973 - -1
- -0.999999999 - -0.5
- -0.5 - -0.25
- -0.25 - -0.1
- -0.099999999 - -0.05
- -0.05 - 0

Calibrated Hydraulic Conductivity Values

The final calibrated hydraulic conductivities for the glacial aquifer are shown on the right. The ‘River Zone’ (AQ1, MAQ1, etc.) has the largest relative horizontal conductivities and relatively small K_x/K_z, i.e., higher vertical hydraulic conductivities. The ‘Highland Zones’ (AQ2, MAQ2, etc.) and ‘Base Zone’ (AQ3, MAQ3, etc.) have the same K_x and K_x/K_z values for aquifer materials (AQ and MAQ), but the confining materials for the ‘Base Zone’ are less transmissive than those of the ‘Highlands Zones’. These patterns are consistent with the conceptual understanding of the three TP zones used to delineate areas of distinct geomorphologies (see slide 56).

The final calibrated horizontal hydraulic conductivities of the bedrock zones are also shown on this slide. Comparison with previous studies indicates the values are reasonable. For example, the transmissivity for the Marshall Formation in western Lower Michigan was estimated at approximately 2500 ft^2/d by Feinstein et al. (2010), and given that the Marshall Formation is relatively thin (<100 ft.) throughout a large portion of the study domain, the estimates of 7 ft/d and 2.5 ft/d for $K_{marsh,1}$ and $K_{marsh,2}$, respectively, appear to be realistic. The values for the confining units ($K_{cold,1}$, $K_{cold,2}$, K_{MI}) are at least two orders of magnitude less than those of the aquifer units, consistent with the conceptual understanding of the local hydrogeology (see slide 54).

Calibrated hydraulic conductivities (K_x) and the ratio of horizontal conductivity to vertical conductivity (K_x/K_z) for the glacial aquifer materials

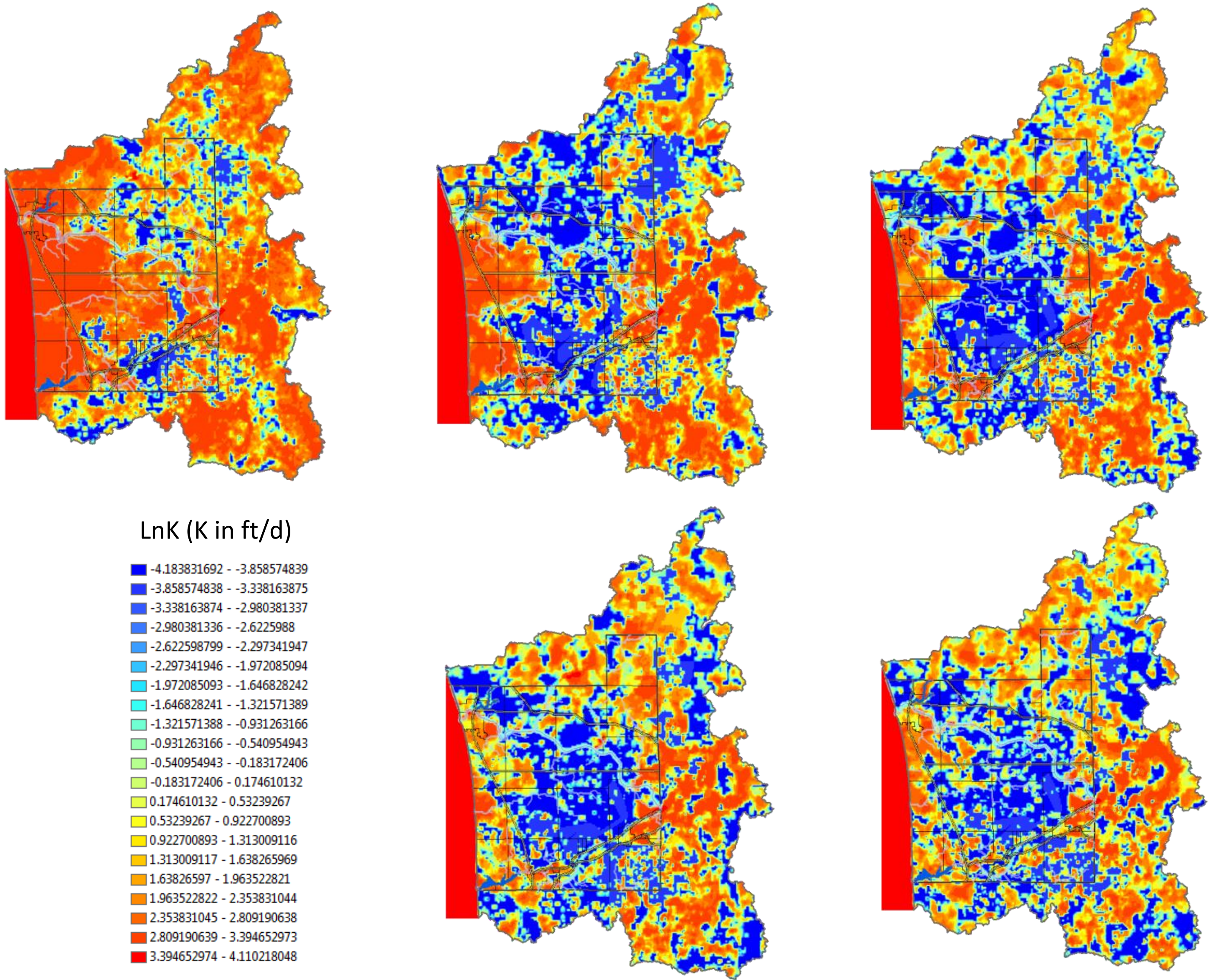
TP Zone	Material type	Kx (ft/d)	Kx/Kz
River Zone	AQ1	160	4
	MAQ1	10	4
	PCM1	1	500
	CM1	1	500
Highlands Zone	AQ2	80	20
	MAQ2	10	20
	PCM2	0.1	300
	CM2	0.1	300
Base Zone	AQ3	80	20
	MAQ2	10	20
	PCM3	0.05	1500
	CM3	0.05	1500

Calibrated hydraulic conductivities (Kx) of the bedrock zones

Zone	Kx (ft/d)
Kmarsh,1	7
Kcold,1	0.005
K_{MI}	0.01
Kave,1	2.5
Kave,3	5
Kmarsh,2	2.5
Kcold,2	0.001
Kave,2	1.25

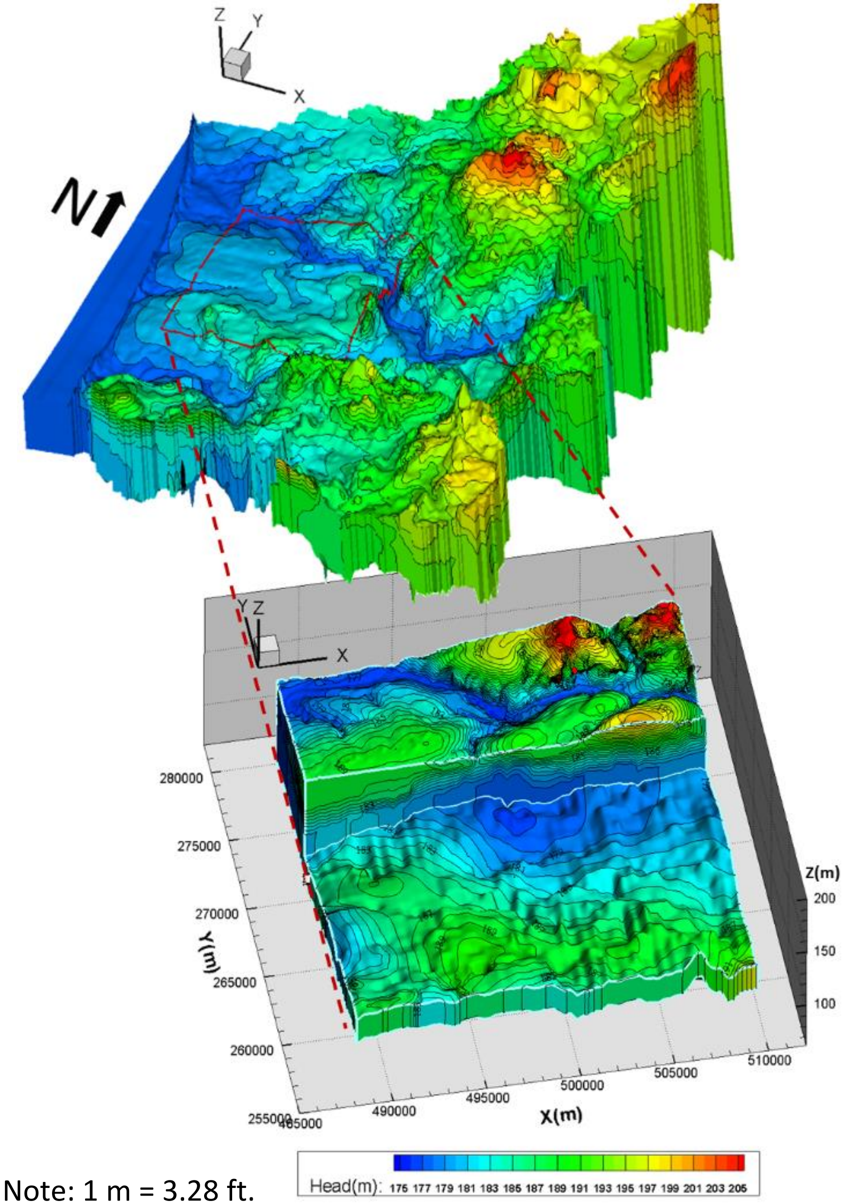
Hydraulic Conductivity Distributions of the Glacial Layers

The final horizontal hydraulic conductivity distributions for the five glacial layers are presented here. There is a relatively continuous unit of low K_x extending across multiple layers in the central portion of the model domain, which has implications for groundwater recharge (or lack thereof) to the underlying bedrock. The eastern portion of the modeling domain is highly heterogeneous, while the western portion consists primarily of high K_x material. Note that these large-scale patterns are consistent with the understanding of the large-scale geology (see slide 50). Also note that the spatial complexity of the K_x distribution was achieved using a fairly small number of parameters. Moreover, this was done using an unbiased geostatistical representation of the aquifer material distribution rather than being done randomly or arbitrarily, which can be time-consuming, difficult and impractical (if not impossible) to calibrate.



CALIBRATED MODEL RESULTS

The outputs from the transient groundwater model are the hydraulic head distributions and resulting velocity vectors for each computational layer from 1966-2015. There is strong 3D variability in the head distribution, especially near the local recharge nears of the glacial aquifer and where groundwater is converging to major streams and discharge areas. The central subregion with a portion of the head distribution made transparent is also shown to illustrate the area of relatively low hydraulic head in the deep (bedrock) aquifer south of Grand River.



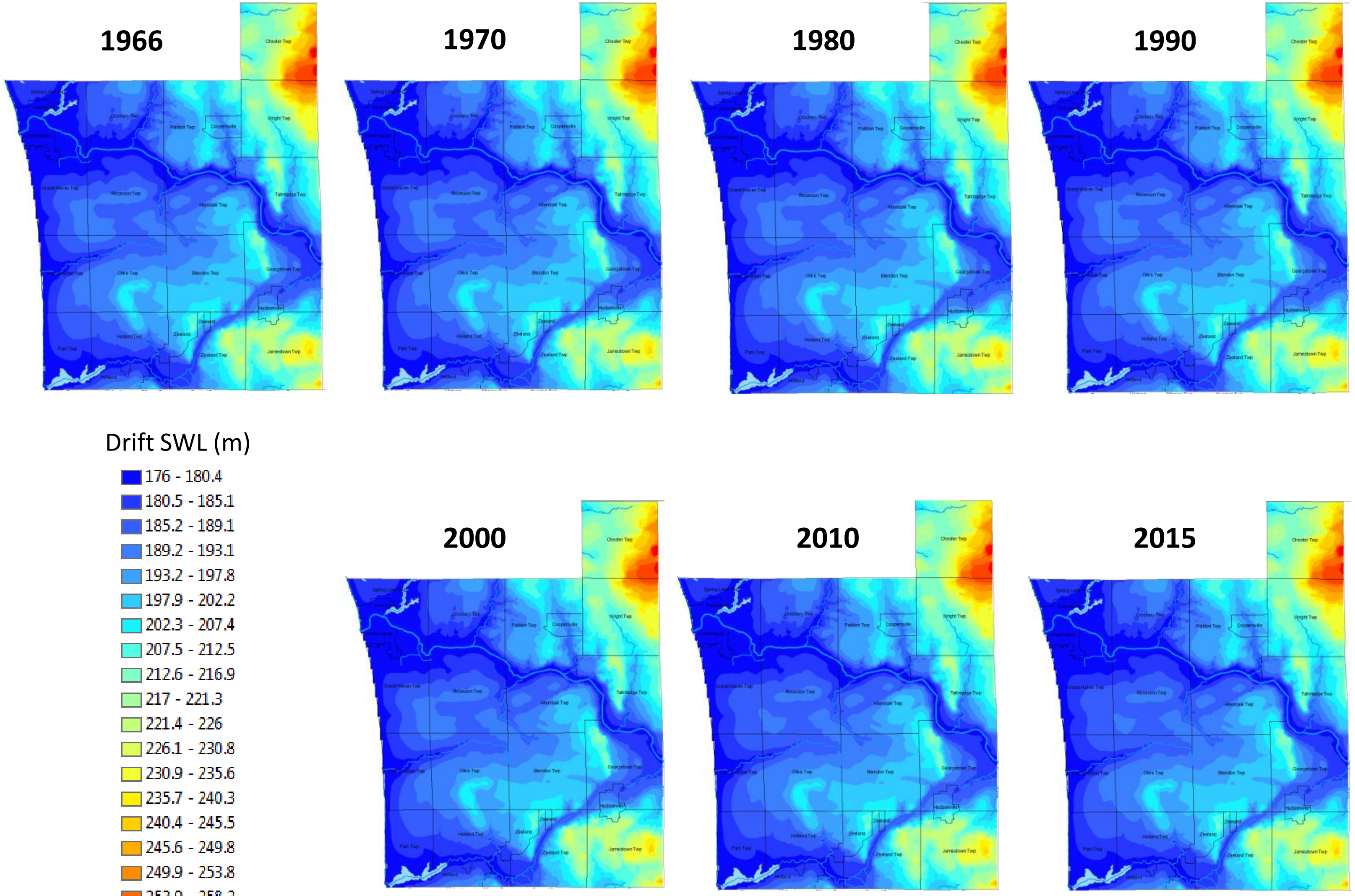
Note: 1 m = 3.28 ft.

Glacial Layer Simulated SWL Dynamics

This slide presents the simulated SWL distributions in the glacial aquifer for selected time-steps. Note that calibrated model suggests very little large-scale changes in glacial SWLs has occurred over the past 50 years.

It's worth noting that there is significant water use in parts of the glacial aquifer (see slide 75), although, in general, the transmissivity is much higher than the bedrock aquifer so that the resulting decline in SWLs is considerably less than that of the bedrock aquifer.

Some of this water use appears to be related to the SWL decline "hot-spots" in the glacial aquifer (i.e., more than 5 ft. of decline was observed, which is not insignificant, albeit difficult to notice in the graphics shown here). This was observed in south Grand Haven Twp. and west central Crockery Twp. Continued monitoring in these areas is recommended for managing long-term changes in SWLs that may result from continued increases in pumping (see slide 158).



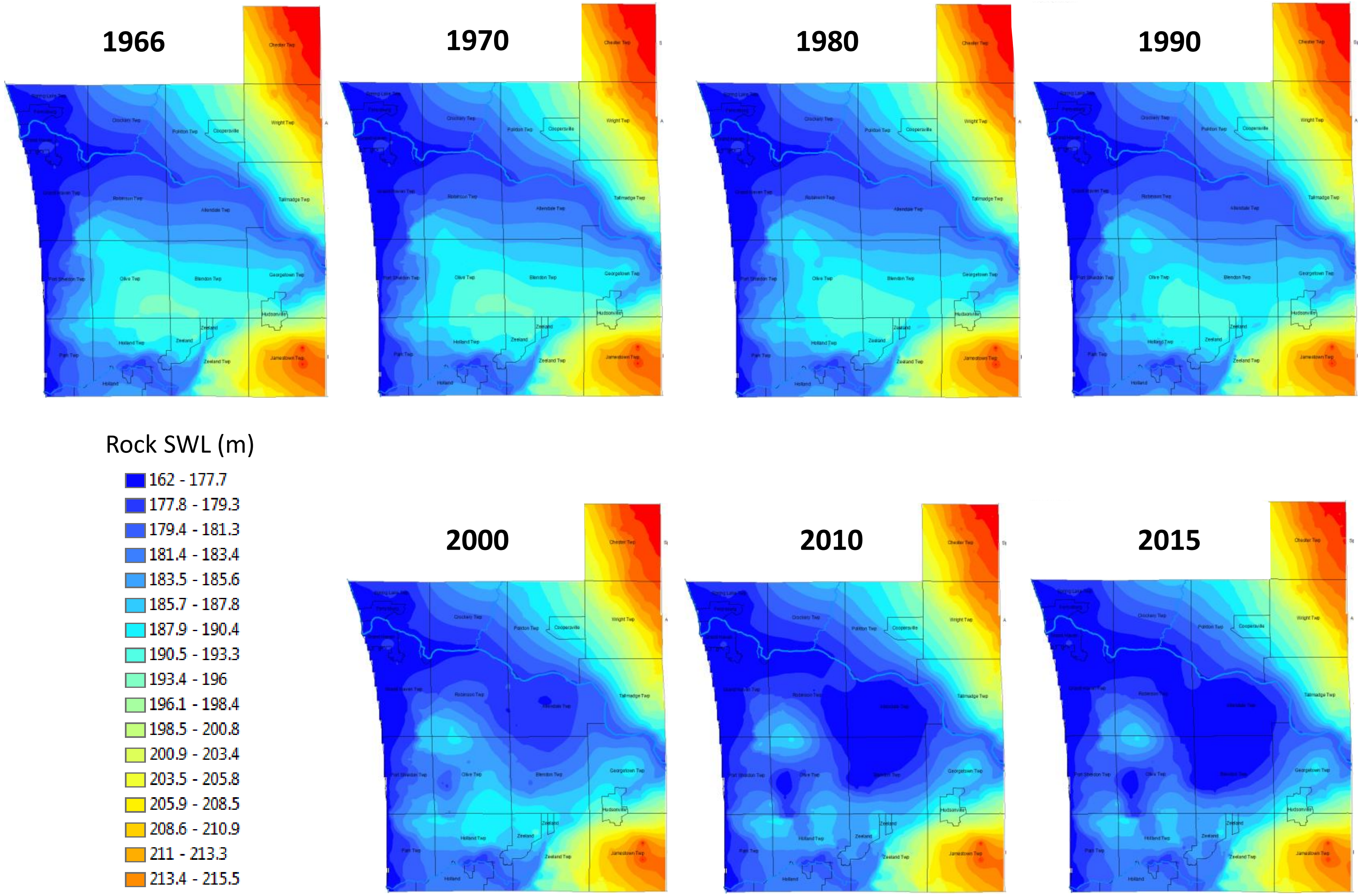
Drift SWL (m)

- 176 - 180.4
- 180.5 - 185.1
- 185.2 - 189.1
- 189.2 - 193.1
- 193.2 - 197.8
- 197.9 - 202.2
- 202.3 - 207.4
- 207.5 - 212.5
- 212.6 - 216.9
- 217 - 221.3
- 221.4 - 226
- 226.1 - 230.8
- 230.9 - 235.6
- 235.7 - 240.3
- 240.4 - 245.5
- 245.6 - 249.8
- 249.9 - 253.8
- 253.9 - 258.2
- 258.3 - 264.9
- 265 - 277.2

Note: 1 m = 3.28 ft.

Bedrock Layer Simulated SWL Dynamics

Analysis of the simulated bedrock head distribution across time indicates that this groundwater levels have decreased over time, especially in the last 15 years. The decreases are focused primarily to the central townships: Allendale, Blendon, Olive, and Robinson.



Rock SWL (m)

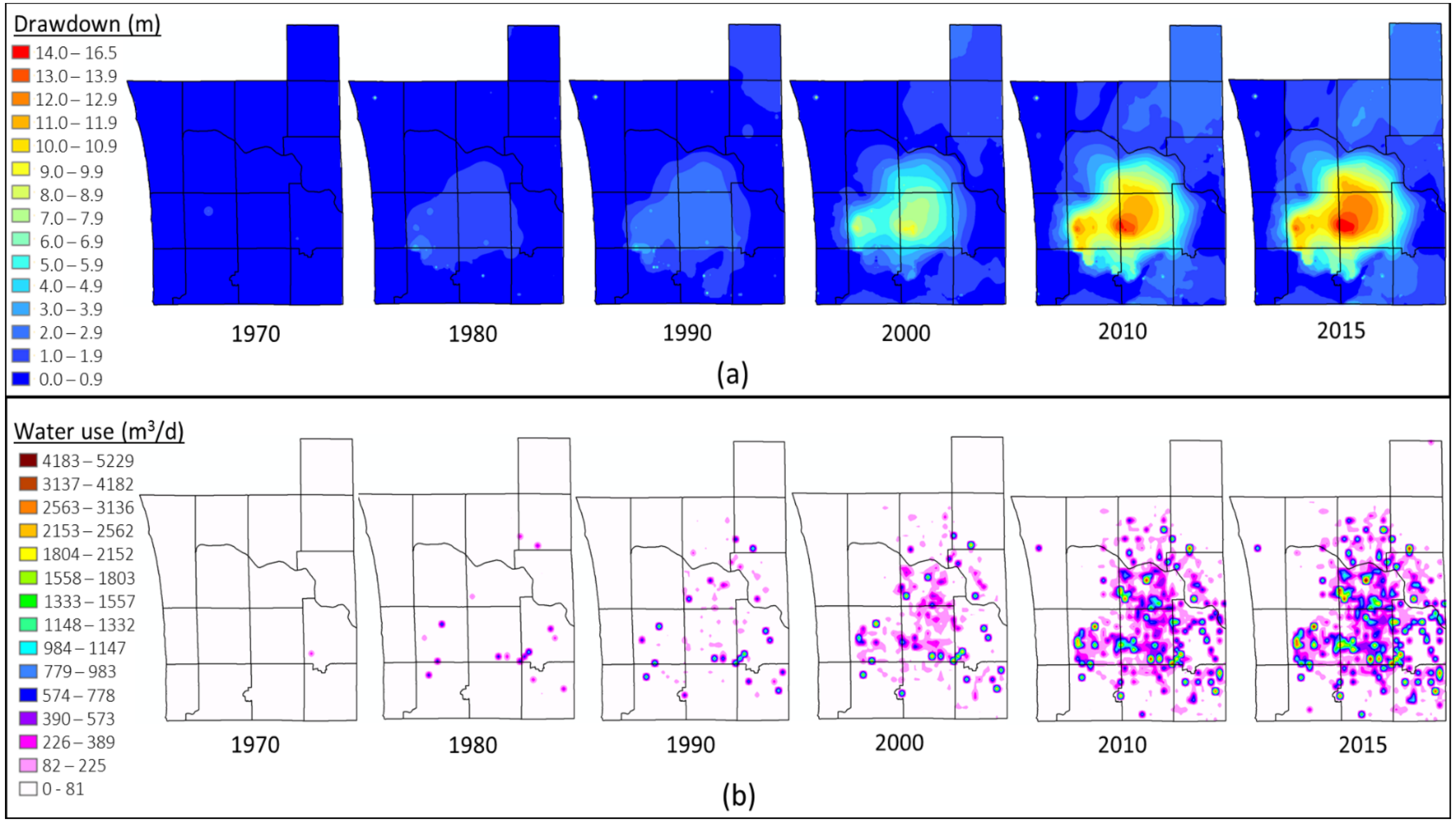
- 162 - 177.7
- 177.8 - 179.3
- 179.4 - 181.3
- 181.4 - 183.4
- 183.5 - 185.6
- 185.7 - 187.8
- 187.9 - 190.4
- 190.5 - 193.3
- 193.4 - 196
- 196.1 - 198.4
- 198.5 - 200.8
- 200.9 - 203.4
- 203.5 - 205.8
- 205.9 - 208.5
- 208.6 - 210.9
- 211 - 213.3
- 213.4 - 215.5
- 215.6 - 217.6
- 217.7 - 220
- 220.1 - 224.5

Note: 1 m = 3.28 ft.

BEDROCK DRAWDOWN DUE TO PUMPING

The simulated bedrock aquifer drawdown (difference between the 1966 head distribution and the distribution of the year indicated) and water use is shown on this slide. Clearly, the significant drawdown in the central portion of the bedrock aquifer has become systematically deeper and more extensive with time, especially since 1990. The evolution of water use for this area is fairly consistent with the drawdown evolution: during early periods of simulation (1970-1990), water use is relatively low and isolated to a few different areas, but since post-1990, water use has increased in spatial extent and intensity, especially in the central and eastern portions of the study area.

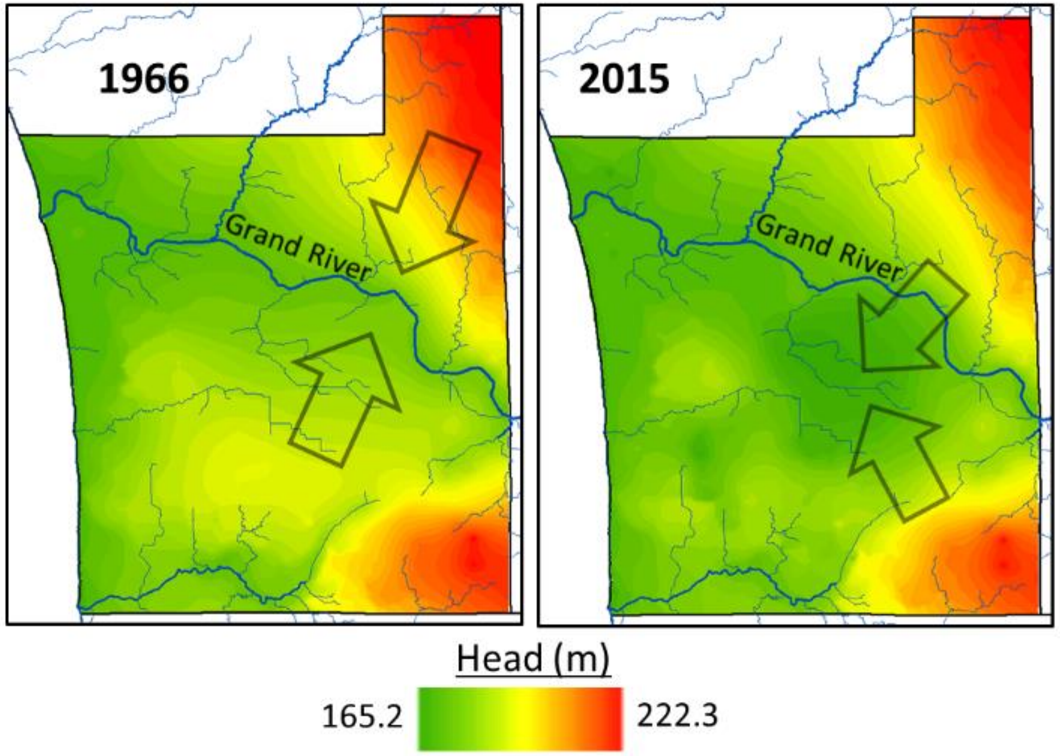
The relatively continuous clay layer of central Ottawa County precludes freshwater from the glacial aquifer to the bedrock aquifer. Thus, the impact of deep bedrock pumping is localized within the deeper bedrock aquifer, at least in most of the central portion of the study area. In the east, northeast and southeast portions of the bedrock the overlying glacial sediments are dominated by alluvial and deltaic sands mixed with boulders, gravel, and fine-grained sediments in a strongly mixed matrix of geologic material (Farrand and Bell 1982; Apple and Reeves, 2007). Consequently, the vertical connection between surface recharge and the bedrock is stronger and drawdown is less severe that that seen central Ottawa County.



Impacts on the Grand River

While many of the surface water bodies are isolated from the bedrock in the central portion of Ottawa County, the Grand River (GR) is well connected to the bedrock aquifer. With a drainage area of over 14,245 km^2 (USACE 2007), this large 6^{th}-oder stream is a major control of groundwater flow in west-central Michigan. And although bedrock exposures and shallow depths to bedrock are relatively rare along most of GR, relatively thin alluvium deposits (<40m) over the bedrock surface have been reported along most reach passing through the study domain (Churches and Wampler 2013) resulting in a natural connection between the bedrock groundwater and GR in Ottawa County. Indeed, the calibrated bedrock head distribution from 1966 shows flow converging to the Grand River from local recharge areas. Given the insignificant bedrock water use up to 1970, this distribution can be considered 'natural' or pre-development conditions. By 2015, the drawdown in the central portion of Ottawa County has had significant impact on bedrock flow patterns: a new major discharge zone has developed south of GR in the area of intense groundwater use. Bedrock groundwater that would have ultimately discharged to the Grand River appears to now discharge to drinking water wells, especially in the central portion of the study domain. In fact, some present-day bedrock flow originating north of GR may actually bypass it to discharge in the area south of the GR. In other words, part of the Grand River that naturally/historically *gained* water from the bedrock is no longer doing so (or perhaps is even *losing a small quantity of* water to the bedrock), since the head in the aquifer is now lower than the stage of the Grand River for that particular stream reach (see next slide for more details).

Additionally, the local recharge mound in south-central Ottawa County shown in the 1966 head distribution has been significantly lowered, in some places to the point where it now represents a local discharge area (e.g., the smaller discharge zone that has developed in the south-west portion of the county).

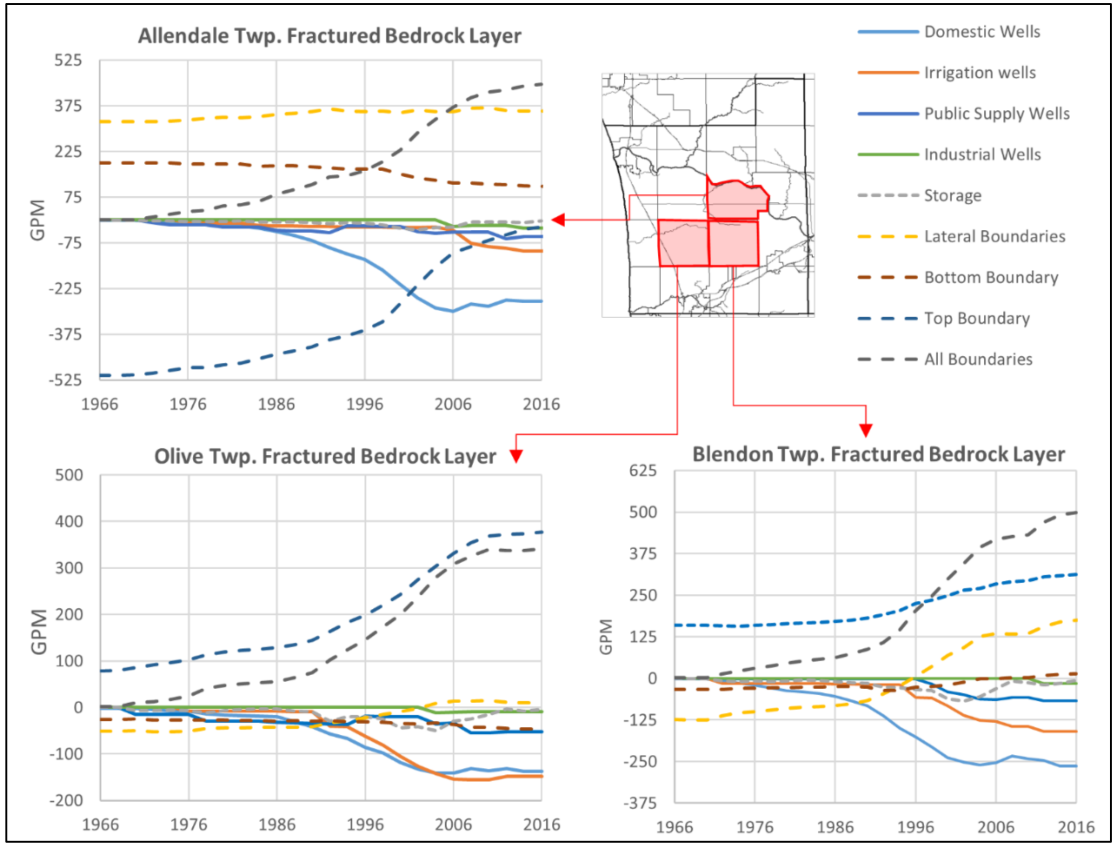


Note: 1 m = 3.28 ft.

Impacts on Township Water Balances

An estimate of the quantitative impact of the changes in the bedrock head distribution was obtained by performing bedrock aquifer water balance analyses for each township in Ottawa County over the past 50 years. Examples of transient bedrock aquifer flux balances for three townships over which most of the significant drawdown has occurred is shown on the right. The values plotted represent net flux values (where positive fluxes represents water added to the township from the specified source and negative fluxes represent water removed) and the bedrock aquifer was modeling using two computational layers, with the top-most layer representing the top 60 ft. of the fractured bedrock where a majority of the wells are screened hence the presence of bottom boundary fluxes (i.e., water moving vertically to/from the deeper bedrock aquifer).

For all three townships, the net flux out all of the boundaries of analysis was equal to zero during pre-development (i.e., inputs and outputs along boundaries were balanced). However, as the amount of groundwater being withdrawn from the bedrock has increased, particularly from domestic wells and irrigation wells, inputs from surrounding aquifer units have increased to balance the water budget (as evidenced by the growing, significant positive fluxes for 'All Boundaries'). For Olive Twp. and Blendon Twp., net increases in flux through lateral boundaries was observed, particularly for Blendon Twp., whose lateral fluxes changes from -125 GPM in 1966 to over +125 GPM in 2015. Through significant increases in pumping, the bedrock aquifer in Blendon Twp. has been converted from a local recharge area to a local discharge area. In Olive Twp. most of the increase in net boundary flux appears to have been satisfied with contributions from the glacial layer above. For Allendale Twp., whose northern boundary includes the Grand River (GR), net top boundary flux has increased from -520 GPM (water leaving the bedrock to the glacial layer above) to roughly zero as pumping withdrawals have significantly increased. Due to the large degree of connectivity between GR and the bedrock, and the relative isolation of other smaller streams from the bedrock due to the continuous clay layer, a majority of this change in top boundary flux can be considered a net loss in baseflow to the GR along the segment cutting through Allendale Twp. Overall, this loss in baseflow represents a small amount of the overall flow in the lower GR, although is surprising that a portion of such a large, 6th-order stream located in a major regional discharge area could essentially lose its natural connection to the deeper aquifer system because of water well withdrawals.



SUMMARY OF WATER QUANTITY FINDINGS

The modeling and analysis of water quantity in Ottawa County can be summarized as follows:

- A continuous clay layer covers a large portion of Ottawa County, and restricts freshwater recharge to the underlying bedrock aquifer.
- The transmissivity of the bedrock aquifer is low, making the impacts of pumping more localized
- Long-term, distributed increases in groundwater withdrawals has reduced SWLs in parts of the aquifer system, particularly in the central portion of the bedrock aquifer.
- Small-capacity domestic wells have had a significant cumulative impact on SWLs, especially in the bedrock aquifer system
- Water use for irrigation purposes has also had an important role in controlling SWL changes in parts of the aquifer system.
- Large-scale changes in SWLs in the glacial aquifer were not observed

OTTAWA COUNTY GROUNDWATER QUALITY

SUMMARY OF CL^- DATA COLLECTION

In this study, rather than use TDS concentrations as a measure of groundwater salinity, which is the approach used in most geochemical studies, we used Cl^- concentrations as a proxy for salinity. This was because Cl^- concentrations were available in historical water quality records used for this study (while TDS concentrations were not), and it was possible to collect far more Cl^- field samples than TDS samples given the resources available for this study. Nonetheless, because the brines down-dip from the Marshall subcrop are composed primarily of calcium chloride ($CaCl_2$) and sodium chloride (NaCl) (Ging et al. 1996), Cl^- was considered an effective indicator of groundwater salinity for the purposes of this study.

A large dataset of Cl^- concentrations across space and time was compiled from field-collected water well samples and historical data mined from water well records. We collected over 545 groundwater samples from 467 locations during the fall of 2015 and the summer of 2015. A total of 2,639 historical Cl measurements were mined from water well records obtained from the Ottawa County Environmental Health Department (Ottawa County 2014). This included 378 historical entries from 249 sites visited during field sampling, allowing for direct comparison of Cl^- concentrations at different times for the *same* location (lateral position and well depth). 1644 entries were mined from 933 of the 4571 parcels in Allendale township to model the 3D plume extent for different decades in an area of increased groundwater withdrawals. An additional 617 entries were mined from “targeted” locations, i.e., where Cl^- data were needed for 2D and 3D countywide spatial interpolation of Cl concentrations.

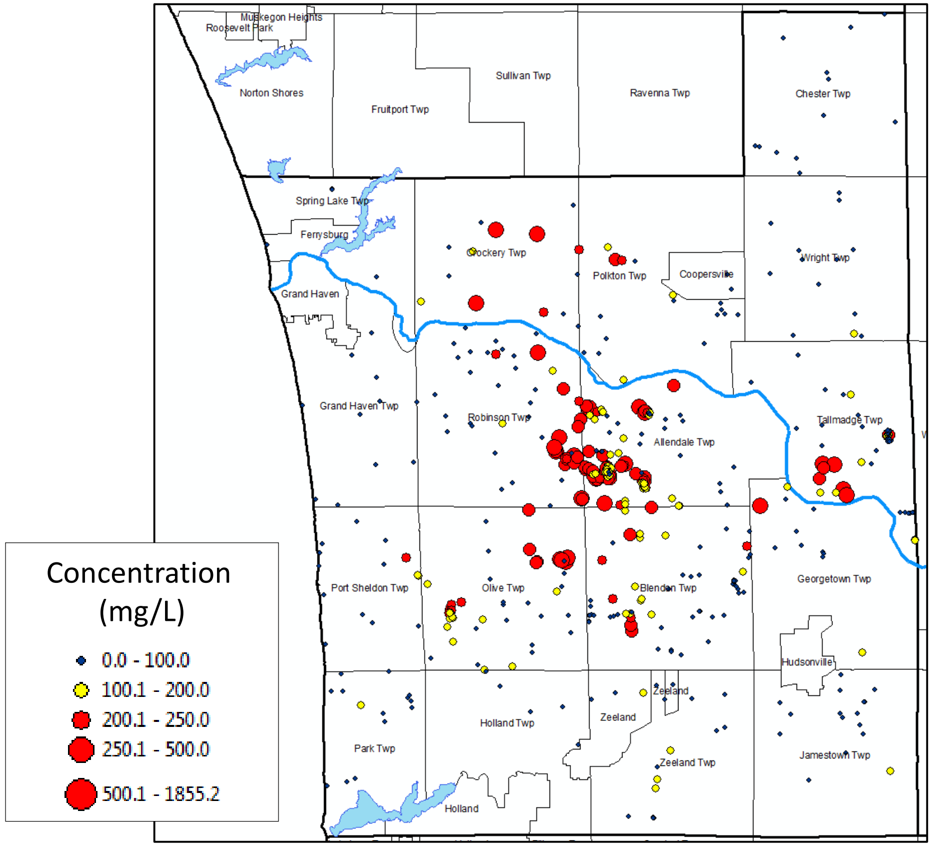
COUNTYWIDE SAMPLING CAMPAIGN

A synoptic, countywide sampling campaign was conducted characterize the present-day 3D structure of the Cl^- concentrations. Groundwater samples (545 total) were collected from water wells at 468 locations. Wells completed in either the glacial deposits or the Marshall bedrock aquifer were used in the analysis, and well depths were obtained by cross-referencing information from the *Wellogic* driller logs and local water well records compiled by the Ottawa County Environmental Health Department (Ottawa County 2014). Well location (latitude, longitude) was measured at the wellhead when possible – otherwise it was measured at the sampling point – and was acquired using GPS-enabled smart-phones which delivered sub-10m accuracy. Samples were collected primarily during the fall months of 2014, although roughly one fourth of the samples were collected during the summer months of 2015. After the fall 2014 data were analyzed, they were used to guide the 2015 into critical areas: the fall 2014 data collection was relatively evenly dispersed across the aquifer system (both in lateral and vertical directions), and once analyzed, was used to identify locations where more data were needed (i.e., in areas where Cl^- concentrations were high and Cl^- gradients were large).

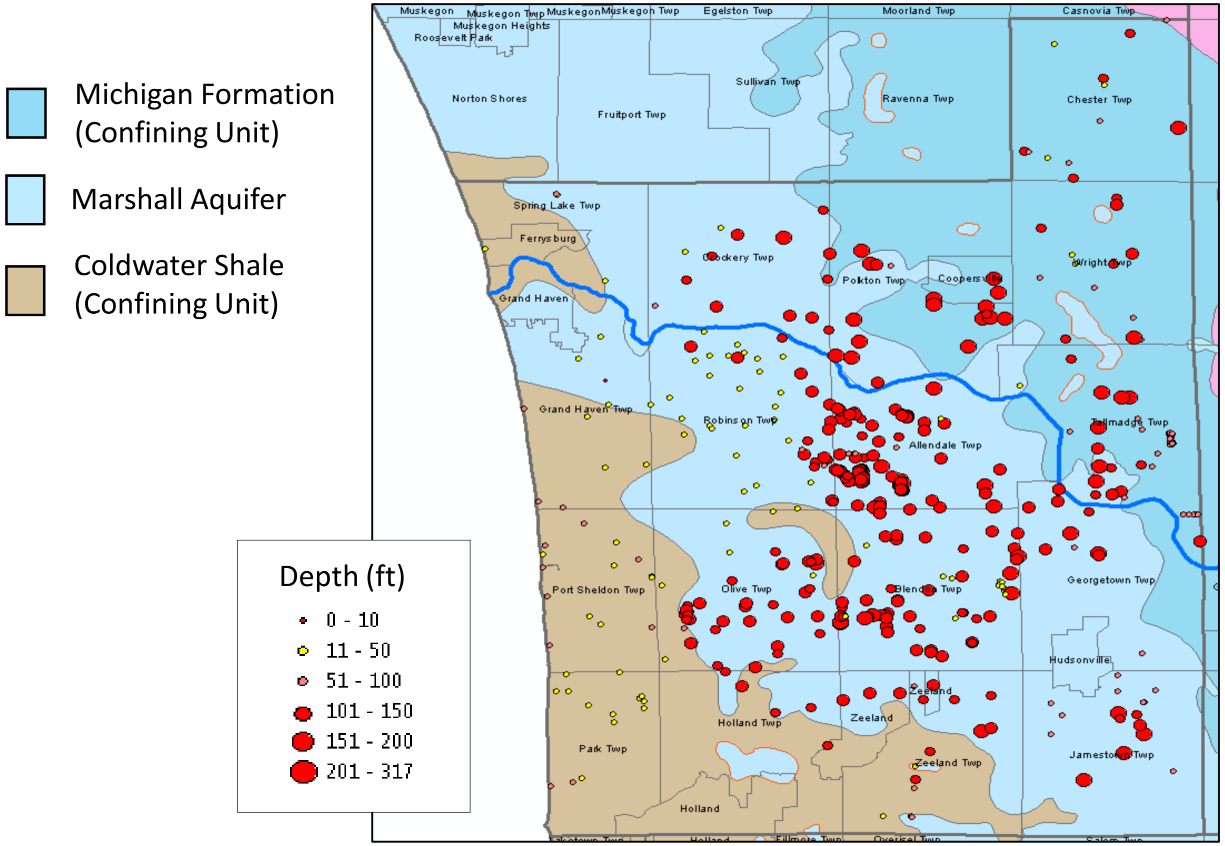
Samples were collected from outdoor spigots or indoor faucets into polypropylene, wide-mouth bottles that had been pre-rinsed with de-ionized water. Special care was made to sample from discharge points delivering untreated well water, i.e., groundwater that has not passed through a water softener, as periodic regeneration of such devices using brine solutions may artificially elevate chloride concentrations until the freshwater flushes through the system. Additional details regarding sample collection and the analytical measurement of dissolved-chloride concentrations can be found in Curtis et al. (2017).

Field Sampling Results: 2D Spatial Maps

This slide presents results from the field sampling campaign. The graphic on the left symbolizes the Cl^- concentration at each sampling location. The graphic on the right symbolizes the well depth at each sampling location, with the data overlaid to the bedrock subcrop map. Note that the spatial patterns of Cl concentrations is consistent with the analysis of the WaterChem dataset. However, the field sampling provides details on the 3D structure of Cl concentrations that is not included WaterChem dataset (see next slides).



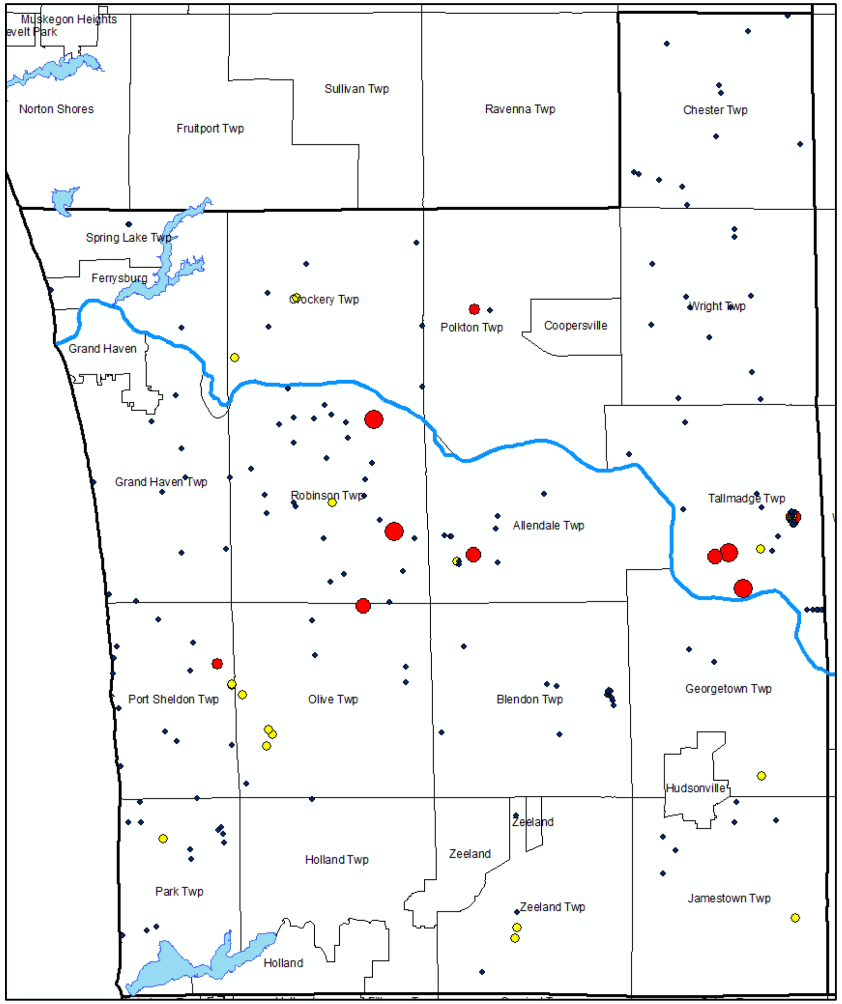
Cl point-measurements



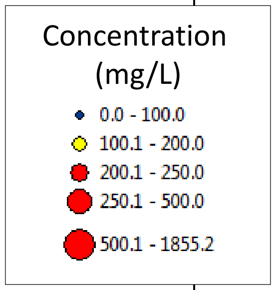
Sampling depth

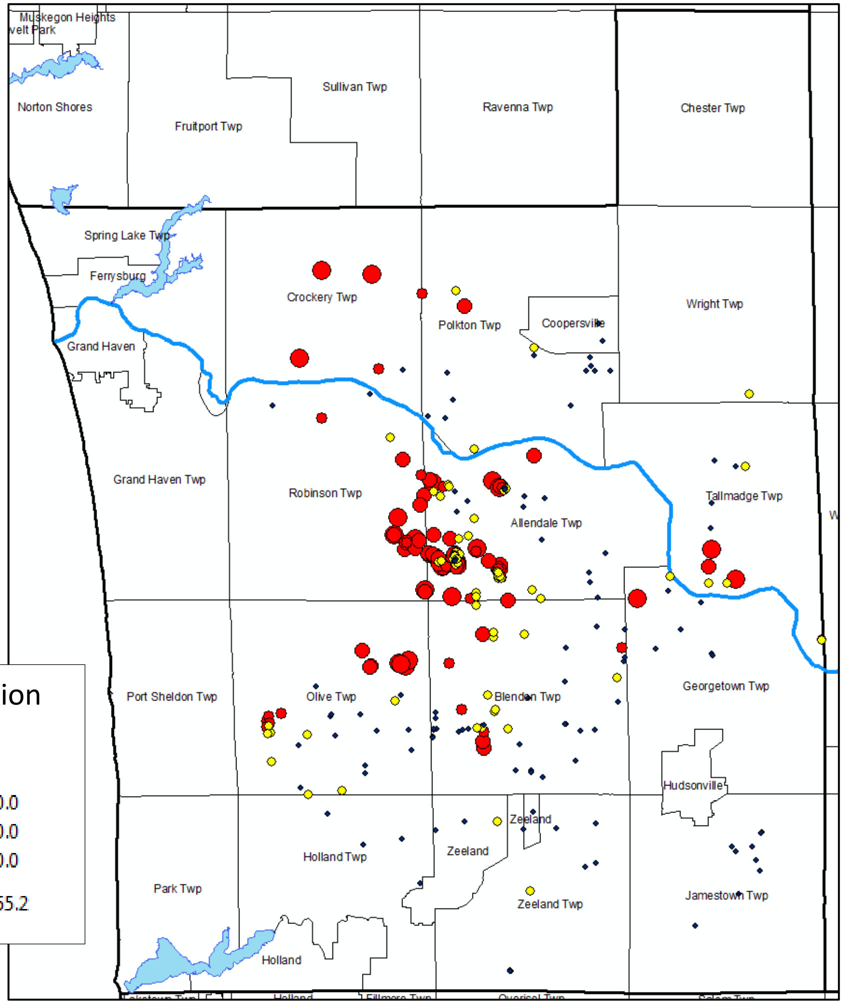
Field Sampling Results: 2D Spatial Maps

Well depth and aquifer type were determined using the borehole information included in Wellogic or Ottawa County Environmental Health water well records. This slide shows two subsets of the field data: 222 samples collected from wells screened in the glacial aquifer; and 323 samples collected from wells terminating in the bedrock aquifer. These results show that a majority of the elevated samples (Cl^- >200 mg/L) were collected from bedrock wells. A cluster of high concentrations was found in west Allendale/east Robinson Twp. Other notable clusters of high concentrations are found in Tallmadge Twp. (both glacial and bedrock aquifers) and in Crockery and west Polkton Townships. (bedrock aquifer).



Glacial aquifer samples

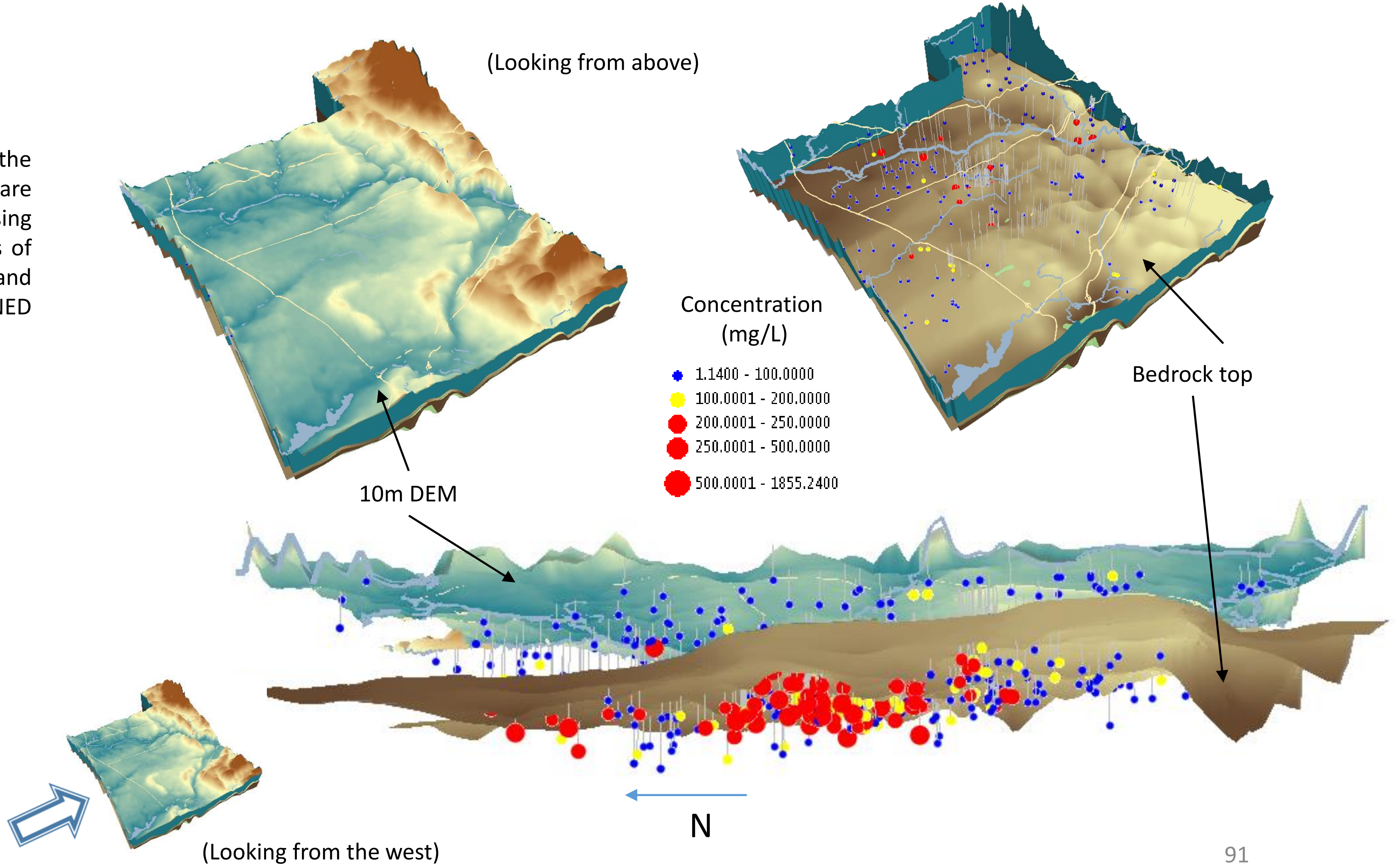




Bedrock aquifer samples

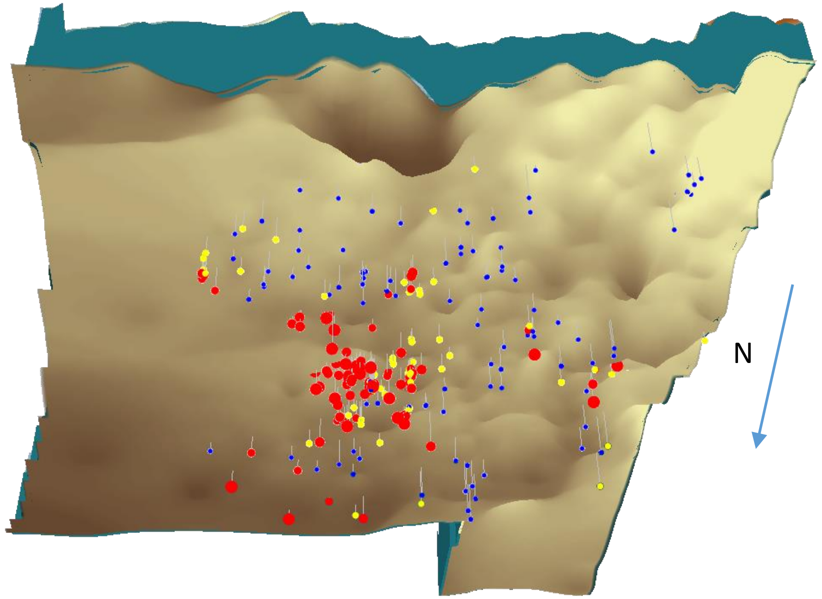
Field Sampling Results: 3D Visualizations

To get a sense of the complex 3D structure of the plume, 3D visualizations of the Cl^- point-data are provided. The bedrock top was delineated using lithologic information from the Wellogic records of wells located in Ottawa County (MDEQ 2014), and the 10m DEM (32.8 ft.) was generated from the NED dataset (NED USGS 2010).

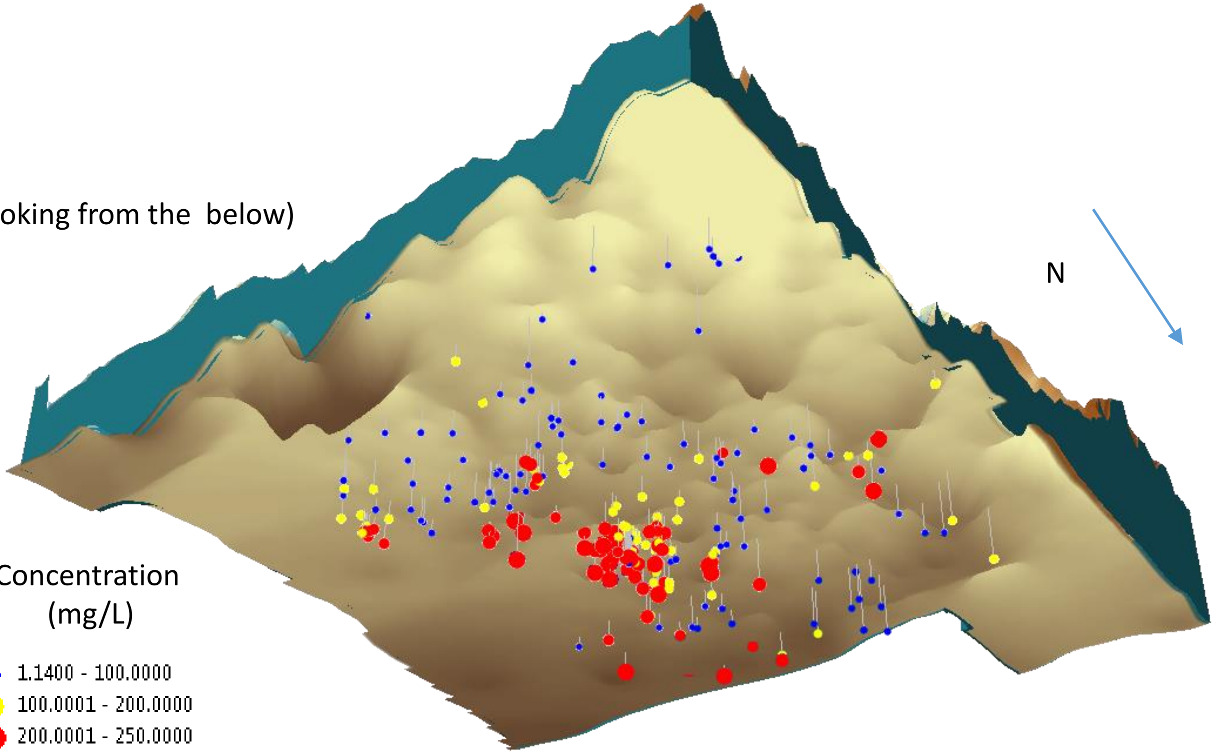


Field Sampling Results: 3D Visualizations

This slide presents two additional 3D perspectives of the Cl^- field data (looking from below, deep in the aquifer system). Clearly, elevated Cl^- concentrations are focused in the Marshall bedrock aquifer, and all but a few of the glacial wells with elevated Cl^- concentrations are screened at or near the bedrock surface. However, there are a significant number of bedrock samples yielding low concentrations (<100 mg/L), demonstrating that the Cl "plume" – although extensive and widespread - is highly variable (concentrations can change very quickly across space).



(Looking from the below)



Concentration (mg/L)

- 1.1400 - 100.0000
- 100.0001 - 200.0000
- 200.0001 - 250.0000
- 250.0001 - 500.0000
- 500.0001 - 1855.2400

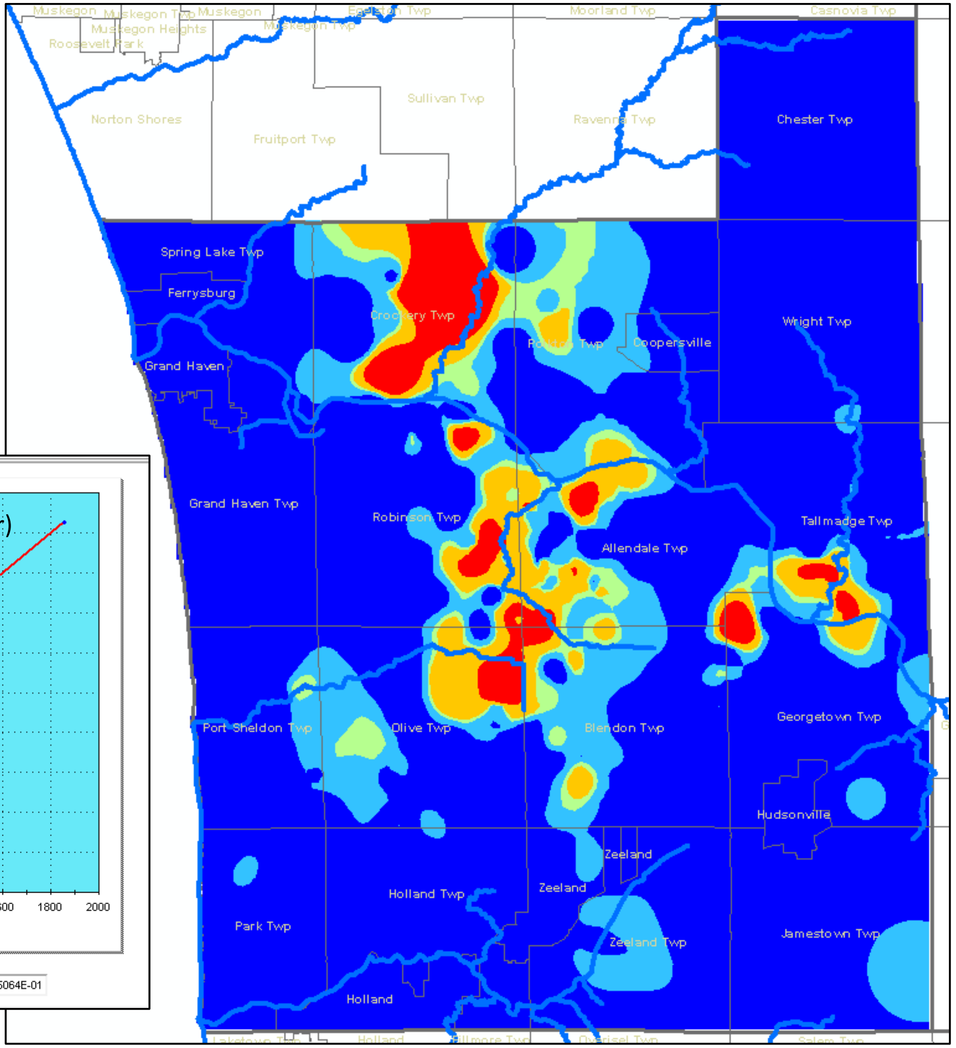
Field Sampling Results: 2D Interpolation

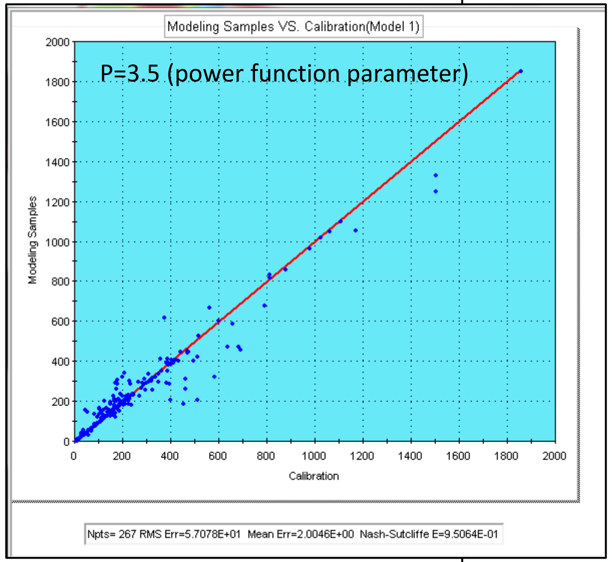
Two-dimensional maps generated from the Cl^- point data provide information on ‘hot-spot’ spatial boundaries where concentrations are higher than background conditions.

The spatial interpolation shown here was done using all of the field-collected Cl^- data (both glacial and bedrock aquifer samples). Interpolation was done using a 300m x 300m grid and weights were assigned using Inverse Distance Weighting (IDW). This approach assigns values to unknown points with a weighted average of the values available at the known points, under the assumption that measured values closest to the prediction location have more influence on the predicted value than those further away. For each estimation point, the nearest 10 data points were used to calculated a weighted average. The calibration chart (interpolated Cl vs. measured Cl) is provided to show that the spatial interpolation was able to reasonably reproduce measured values.

Concentration (mg/L)

- 2.190090895 - 100
- 100.0000001 - 200
- 200.0000001 - 250
- 250.0000001 - 500
- 500.0000001 - 1,855

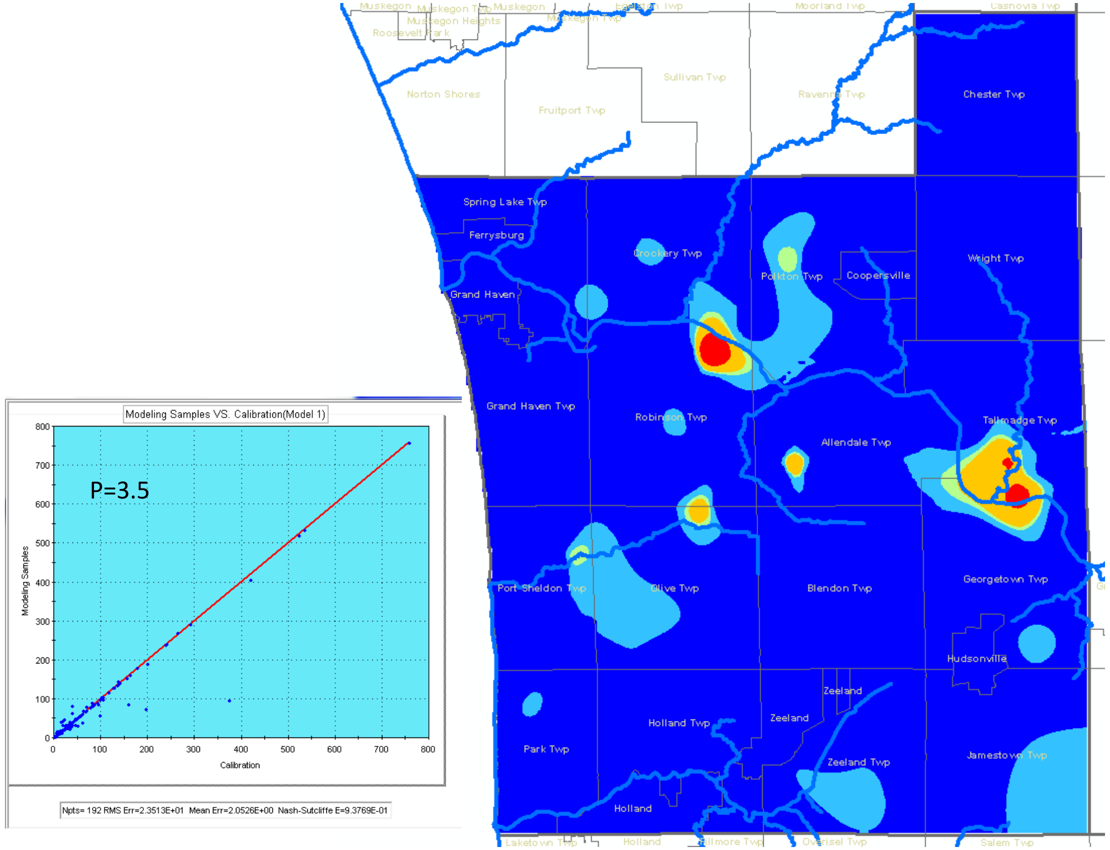




Calibration chart (model vs. data)

2D Interpolation For Each Aquifer

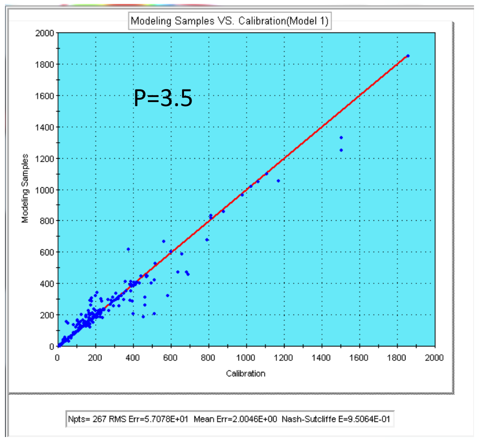
Spatial interpolation of Cl^- concentrations was also completed for the two subsets of field data (glacial aquifer samples and bedrock aquifer samples). The extent of the interpolation for the bedrock layer is limited by the fact that samples from confining units were not available (since water wells do not terminate in confining units). In both cases, a 300m x 300m grid was utilized and the nearest 10 points were used to calculated a weighted average at each estimation point. The glacial layer has two localized hot spots along the Grand River in Robinson and Tallmadge Townships. Concentrations are generally higher in the bedrock aquifer, with large regions exhibiting concentrations of 200 mg/L or more.

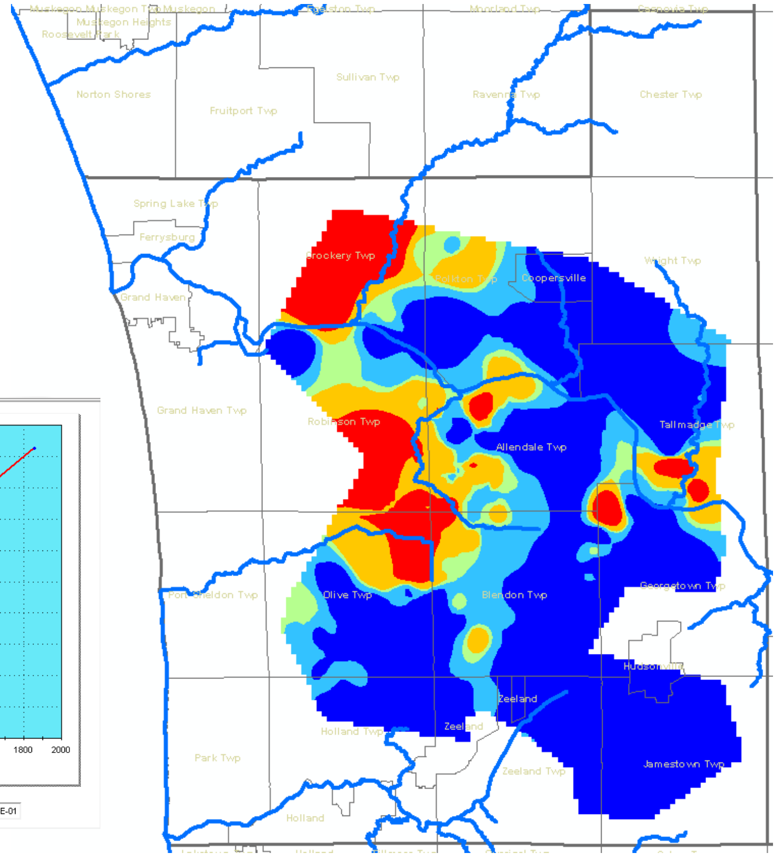


Glacial Layer

Concentration (mg/L)

- 2.190090895 - 100
- 100.0000001 - 200
- 200.0000001 - 250
- 250.0000001 - 500
- 500.0000001 - 1,855

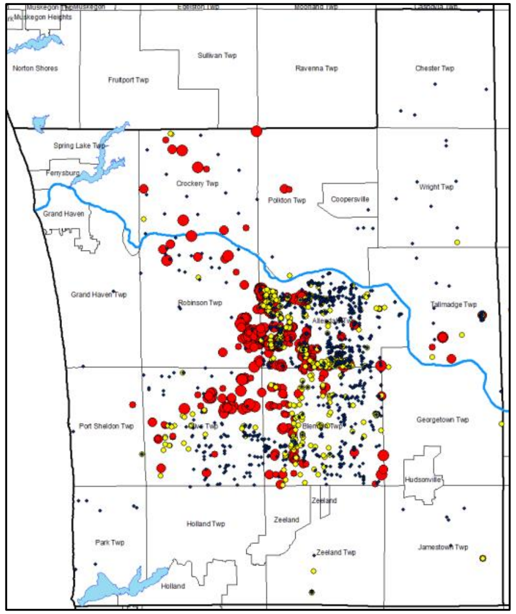




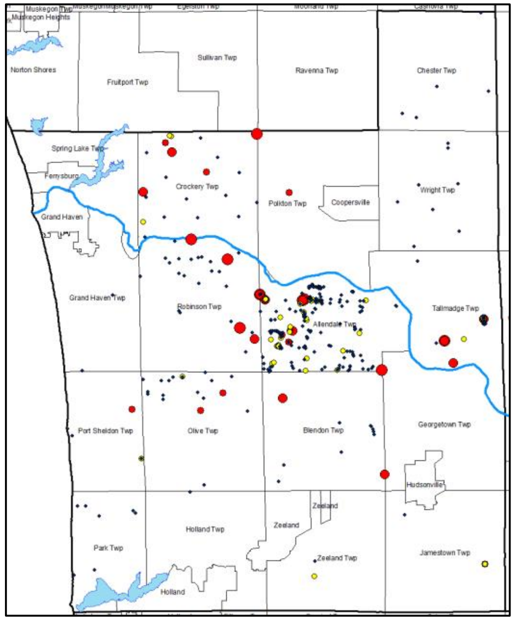
Bedrock Layer

HISTORICAL CL DATA MINING

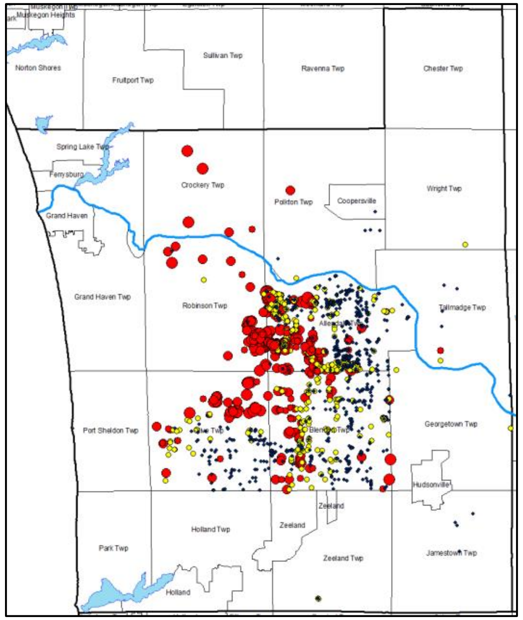
Historical Cl^- data and the associated 3D locations (latitude, longitude, and well depth) and collection times were extracted from a file management system maintained by Ottawa County Department Health Department. This system organizes, on a property-by-property basis, borehole records and well logs from *Wellogic* or local government agencies (or even directly from the drillers themselves, especially in the case of older wells) with documentation from water quality testing (i.e., sodium, fluoride, hardness, iron, nitrate, nitrite, and sulfate). These tests, referred to as Partial Chemical tests, are completed in Michigan typically at the time of well installation, when an older well or well pump is maintained, during a real estate exchange, or when property owners are experiencing water problems. Samples are analyzed at local health departments following the guidelines established at the State of Michigan's Drinking Water Analysis Laboratory (MDEQ 2010). Well depth was extracted from the well log or borehole profile available for each property. Well location was often given in the borehole records, but in some cases was estimated using the Ottawa County Interactive Mapping tool to obtain the latitude and longitude of the centroid of the property (Ottawa County, 2016). This introduced some uncertainty in some of the well locations associated with the Cl^- data, but it is much less than the distance between most sampling locations used in the countywide analysis. In total, 2639 Cl^- data points were extracted from roughly 1800 locations (some locations contained more than one water quality test result). Samples were extracted for the years 1966-2015, but most of the data are form 1990 or later. On-going geospatial analysis of concentrations revealed that the highest concentrations and concentration gradients occurred in the bedrock aquifer and that concentrations were generally low in the glacial aquifer. Therefore, the data mining effort was steered towards wells screened in the bedrock aquifer.



All historical data (2639 points)



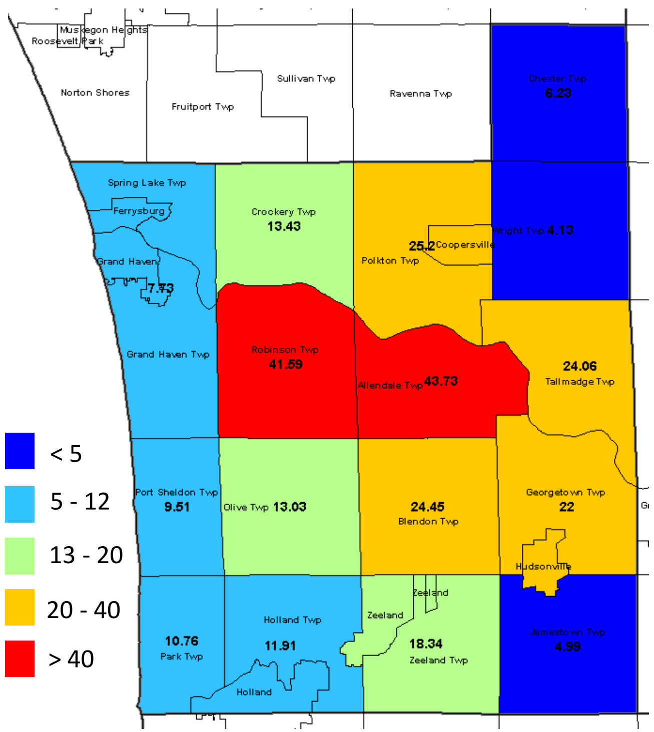
Glacial aquifer historical data (557 points)



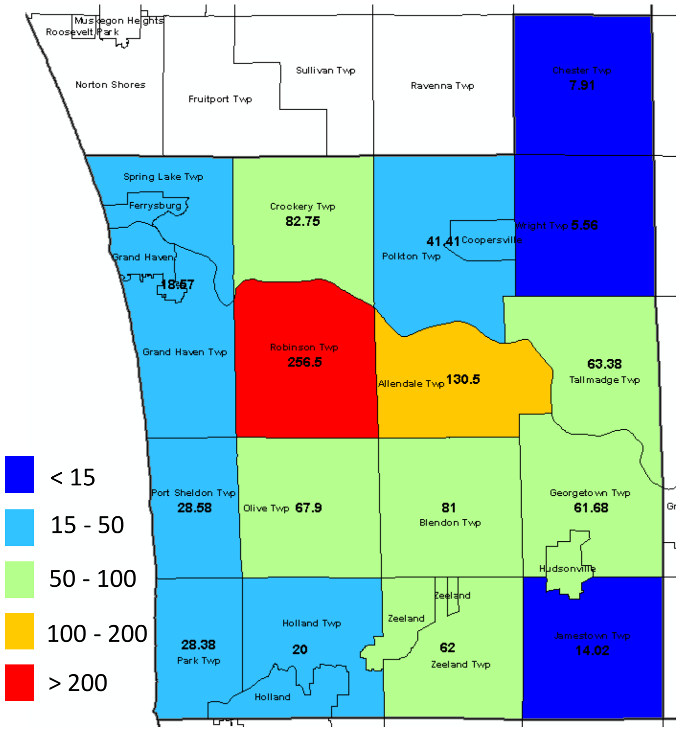
Bedrock aquifer historical data (2058 points)

WATER QUALITY SEVERITY RANKINGS

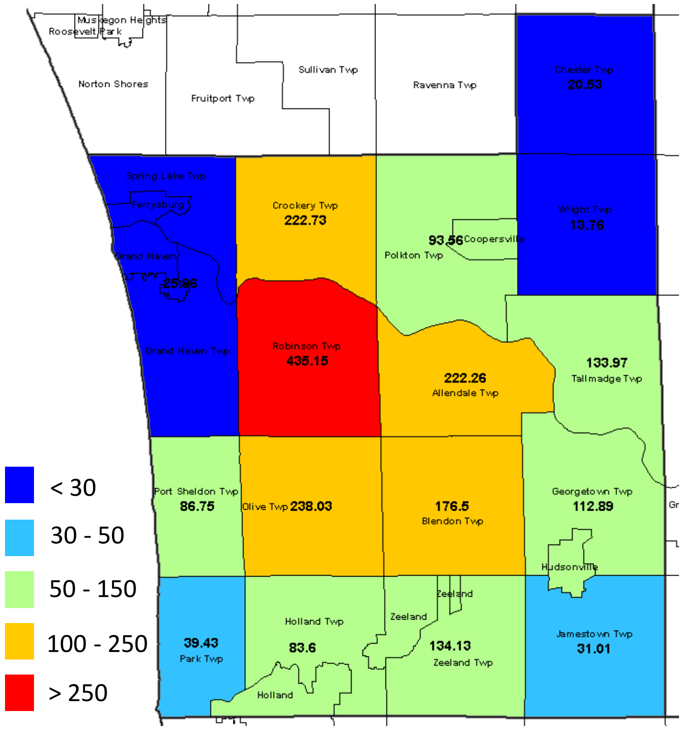
Using all of the field-collected and historical data, township-wide statistical analyses were completed to characterize the severity of Cl^- pollution across the county. In particular, for each township, the 25th, 50th, and 75th percentiles Cl concentration were computed, e.g., a 25th percentile concentration for a given township is the concentration at which 25% of the data (in the township) is less than, and 75% of the data is greater than. The results are for each percentile and each township are shown below. Robinson township has the highest concentration at each percentile (in other words, it has the most severe quality ranking in the county). The central townships and Crockery Township have the highest 75th percentile concentrations, indicating that a significant amount of the data (25%) in those townships are elevated (above 100 mg/L).



25th Percentile Cl Concentration



50th Percentile Cl Concentration

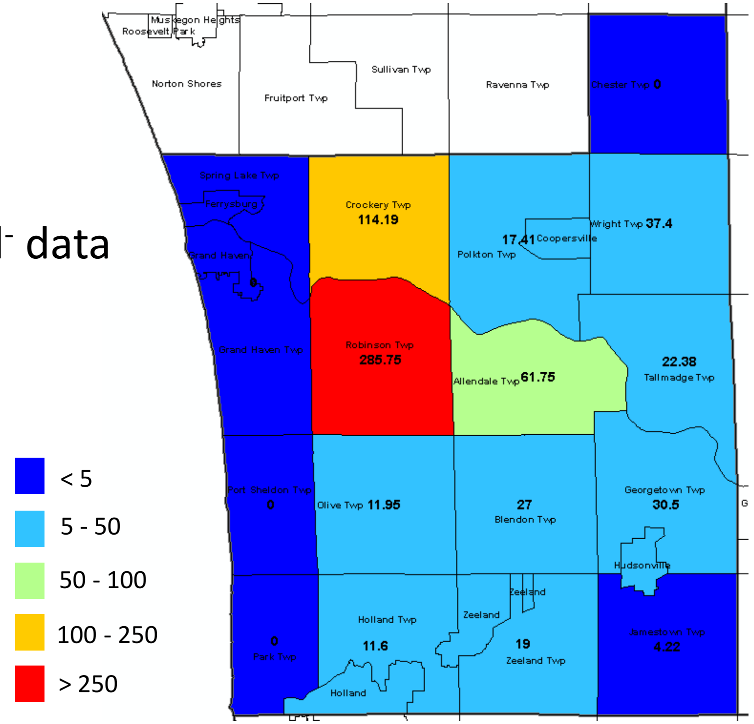


75th Percentile Cl Concentration

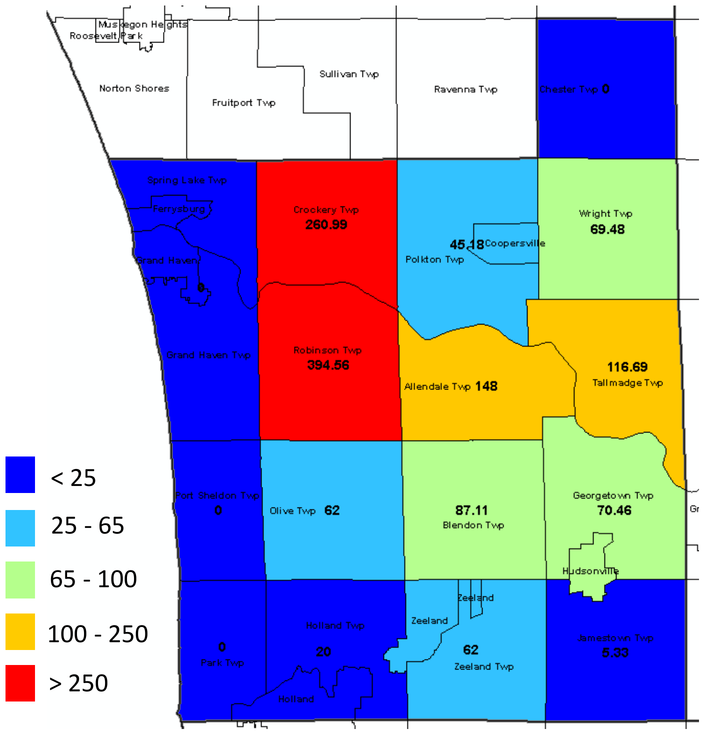
Water Quality Severity Rankings – Bedrock Only

The proceeding slides clearly show that the majority of elevated Cl concentrations are from the bedrock aquifer. Therefore, water quality severity rankings were generated using only the bedrock data. The results are shown below. The distribution of high percentile concentrations is similar to the distribution resulting from analysis of the entire dataset (glacial and bedrock samples). When considering just bedrock data, the water quality ranking for Crockery Township ranks as one of the most severe, along with Robinson Township. The central townships again rank as most severe.

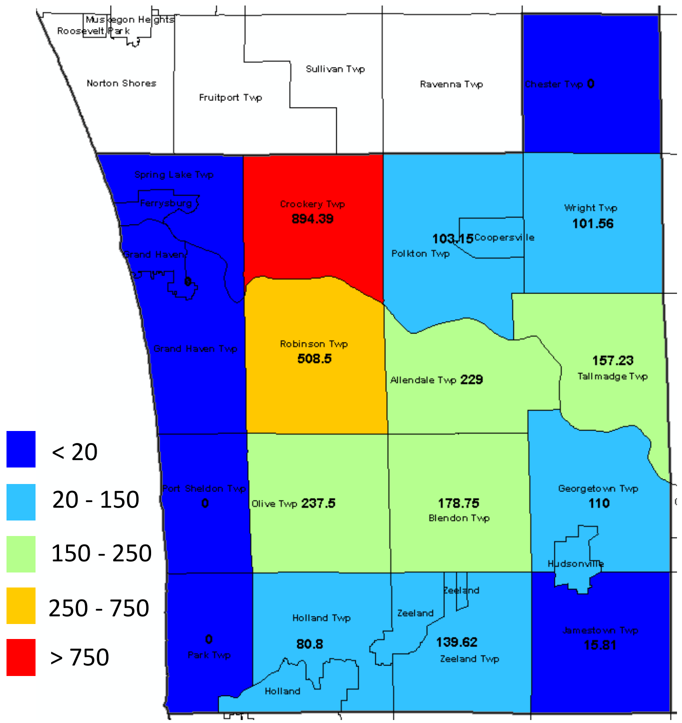
Bedrock Cl^- data



25th Percentile Cl Concentration



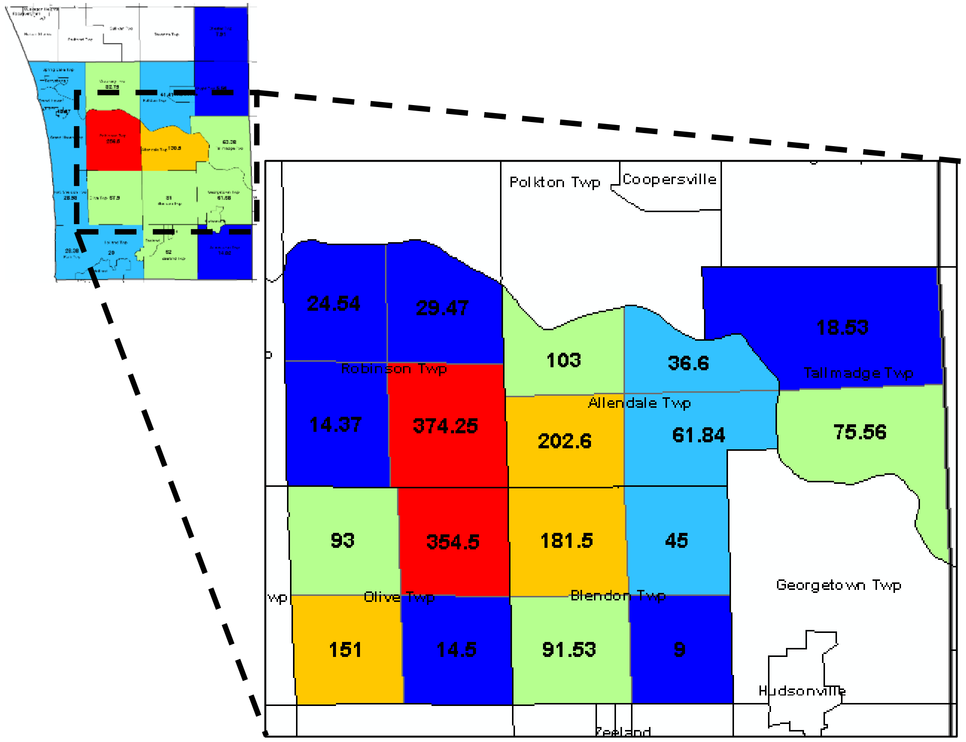
50th Percentile Cl Concentration



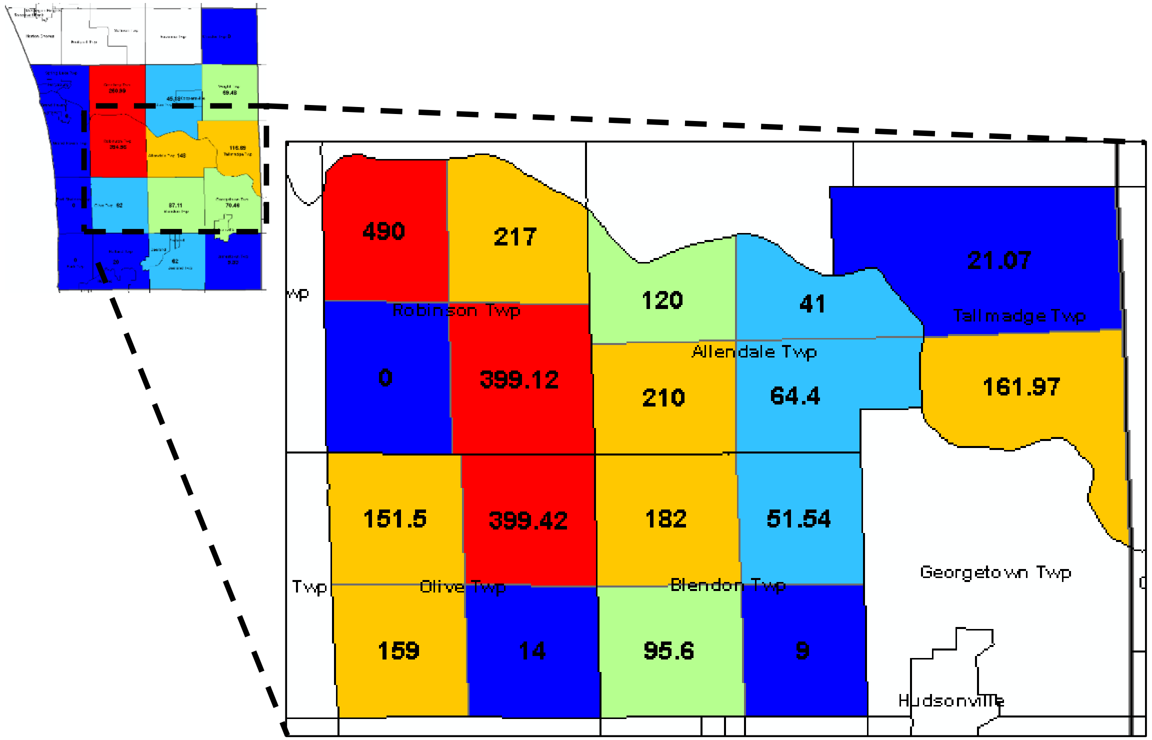
75th Percentile Cl Concentration

Water Quality Severity Rankings – "Hotspot" Subregion

Enough data were Compiled in the "hot-spot" area (the central townships of Ottawa County) that the statistical analysis could be completed at the sub-township level. This provides more detail on the spatial variability of water quality severity. Shown below are the results for the 50th percentile concentrations using i) both glacial and bedrock data and ii) only bedrock data. The water quality is most severe in the bedrock in the eastern portion of Robinson Township, the southwestern portion of Allendale Twp., and the western and northeastern portion of Olive Twp.



50th Percentile Cl Concentration
(drift and bedrock samples)

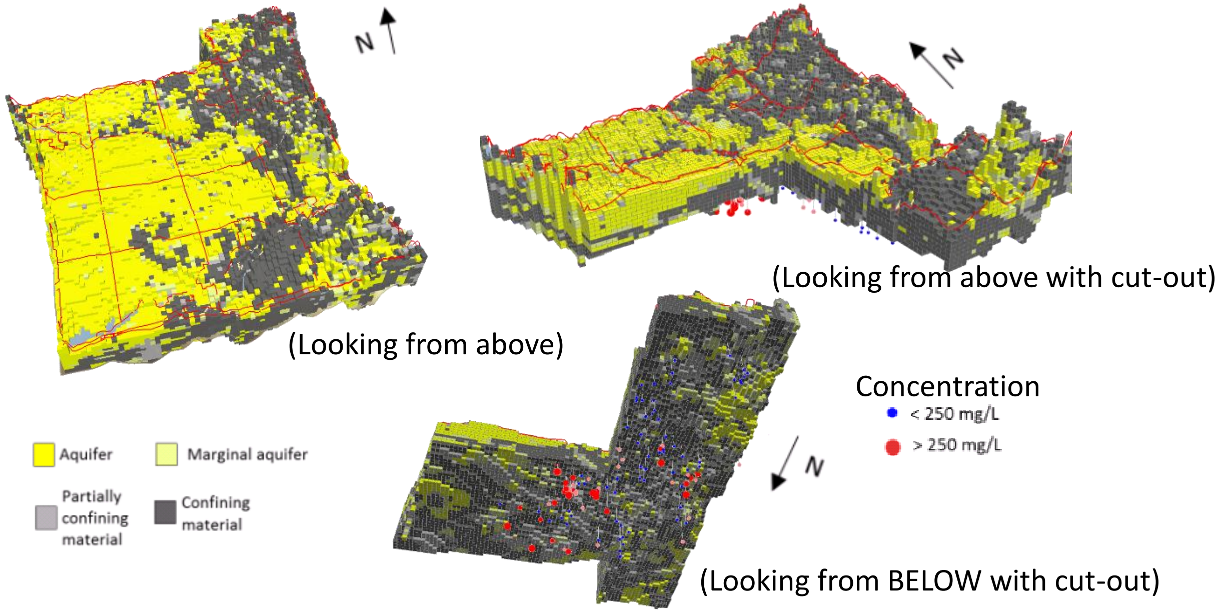


50th Percentile Cl Concentration
(bedrock samples only)

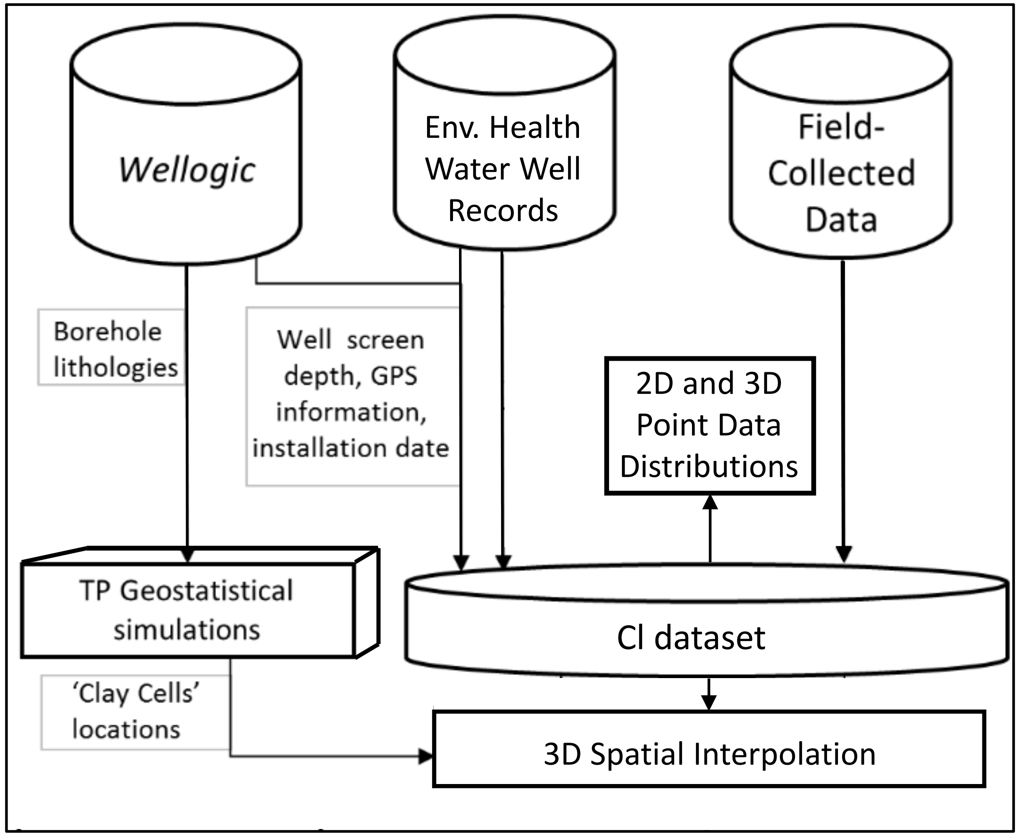
3D INTERPOLATION OF COMBINED CL DATASET

A sub-set of the Cl- data was used to create a 3D spatial interpolation of the current Cl- 'plume', including all field-collected data and the most recent historical Cl- data available. In most areas, data from 2010 or later were used for 3D interpolation. In other areas, earlier data were used in the case that a field sample was not obtained or a historical record from 2010 or later was not available, although this represented a small proportion of the 1048 historical samples used in the interpolation. The total number of samples used was 1593, 338 of which were from wells completed in the glacial aquifer and 1255 from wells completed in the bedrock aquifer.

One key aspect of the 3D interpolation was the need to account for the thick, confining clay layer occurring throughout the central portion of the study area. The results from the aforementioned geostatistical simulations were used to do this. Details are discussed on slide 51.

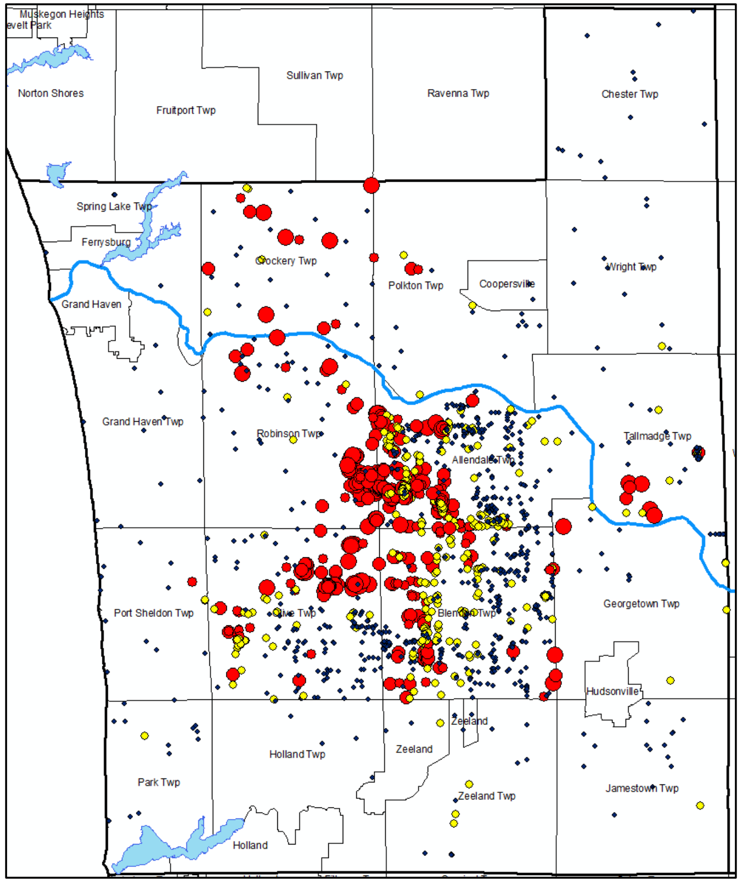


(Looking from above)
(Looking from above with cut-out)
(Looking from BELOW with cut-out)

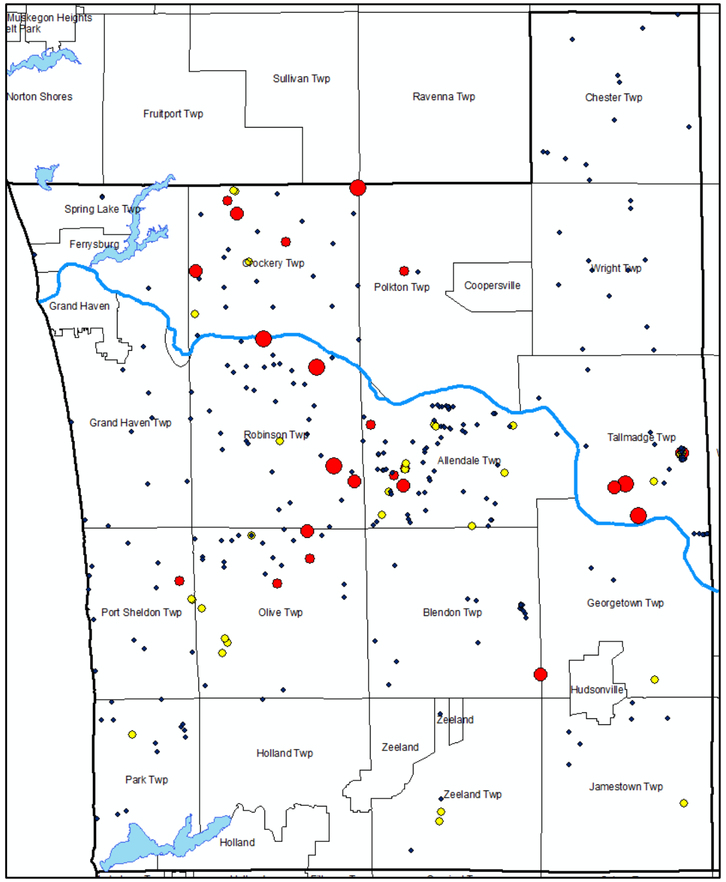


Combined Cl Dataset: 2D Distribution of Point Data

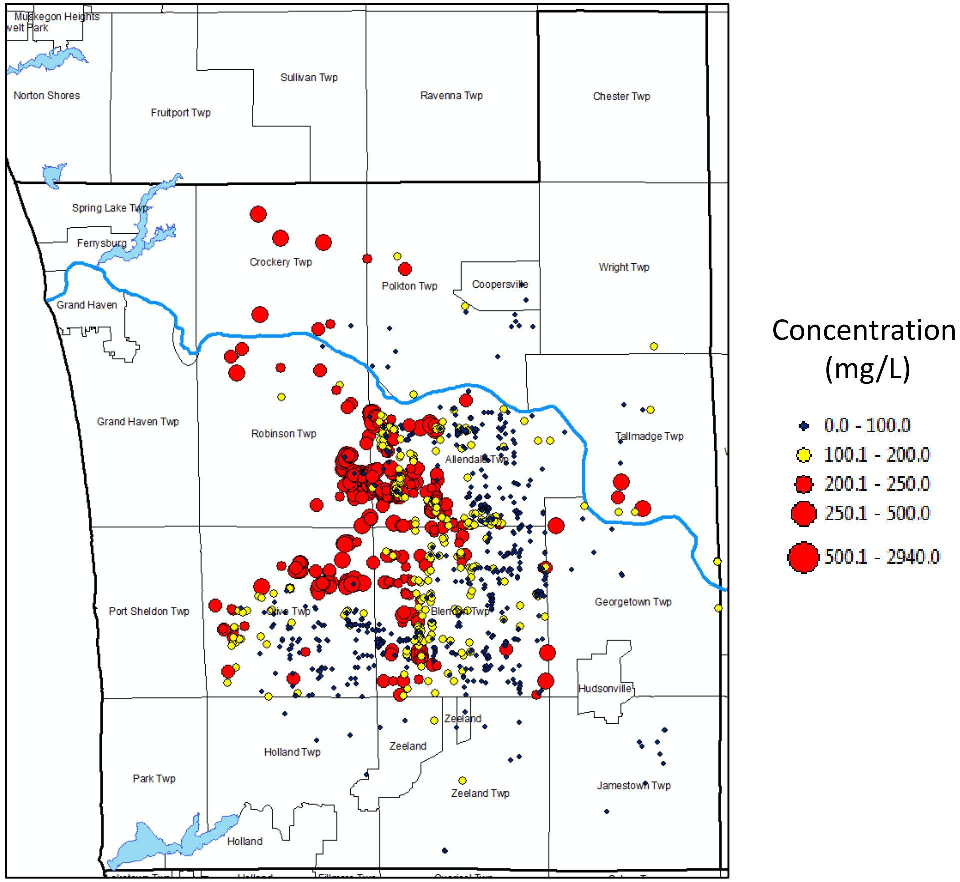
The 2D distribution (plan-view) of the combined Cl dataset used for 3D spatial interpolation of Cl concentrations is shown below. The left-most graphic shows the data points (and their Cl^- concentrations) for the complete dataset of 1593 point measurements. The center graphic and the right-most graphic shows the 338 glacial aquifer samples and the 1255 bedrock aquifer samples, respectively, used in the analysis.



All ‘recent’ Cl data



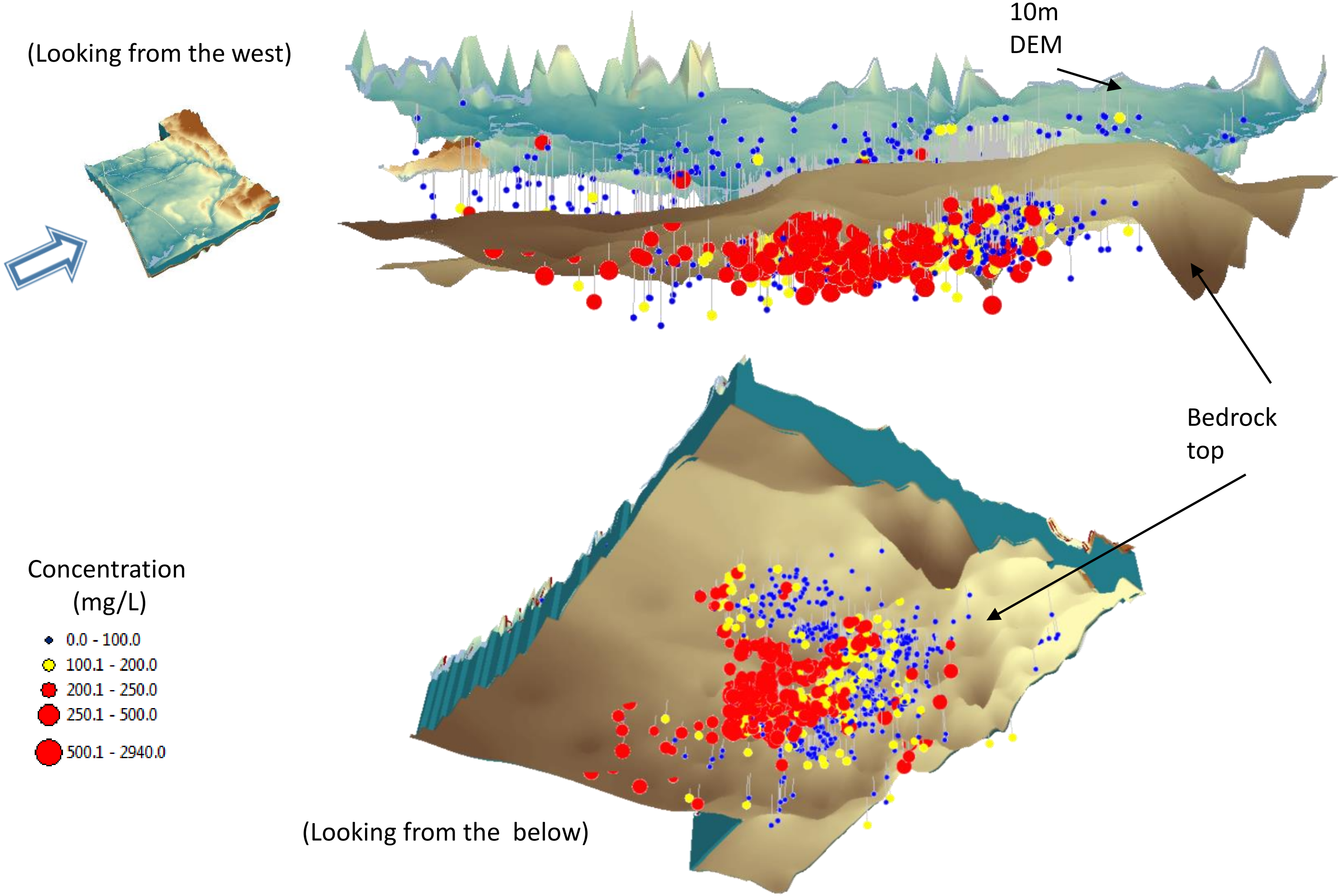
‘Recent’ glacial aquifer data



‘Recent’ bedrock aquifer data

Combined Cl Dataset: 3D Visualization of Point Data

This slide presents a 3D visualization of the combined dataset used for 3D interpolation of Cl Concentrations. Note that the 3D distribution of elevated Cl concentrations is generally consistent with 3D distribution of field-collected Cl concentrations (see slide 91). Also note that the spatial coverage of Cl data is greatly improved by combing recent historical measurements with present-day field measurements.

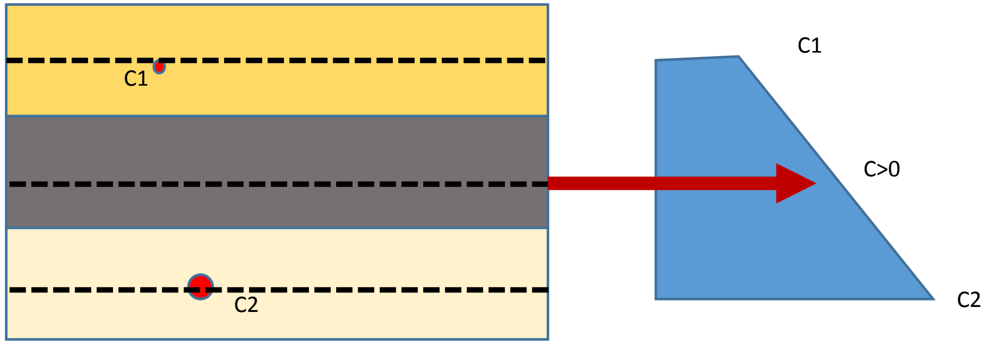


Incorporating the Effect of the Clay Layer

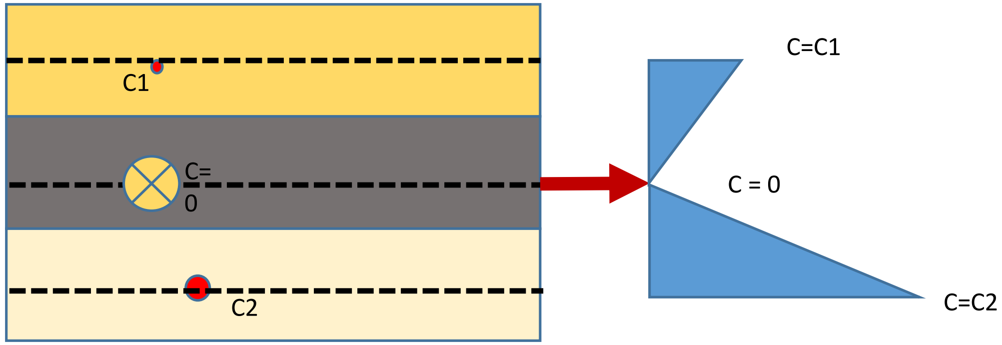
The clay layer in central Ottawa County impedes the movement of groundwater and is expected to have relatively low Cl^- concentrations (i.e., close to zero) other than in locations directly adjacent to aquifer material with high Cl^- concentrations, in which case diffusion may allow Cl^- to transport a relatively short distance into the clay layer. However, there are very few (if any) wells completed in this layer because of the impractical yield it provides, and thus, Cl^- observations in this key part of the aquifer were not available. For this reason, we created 'clay control' points that were assigned a Cl^- concentration of about zero.

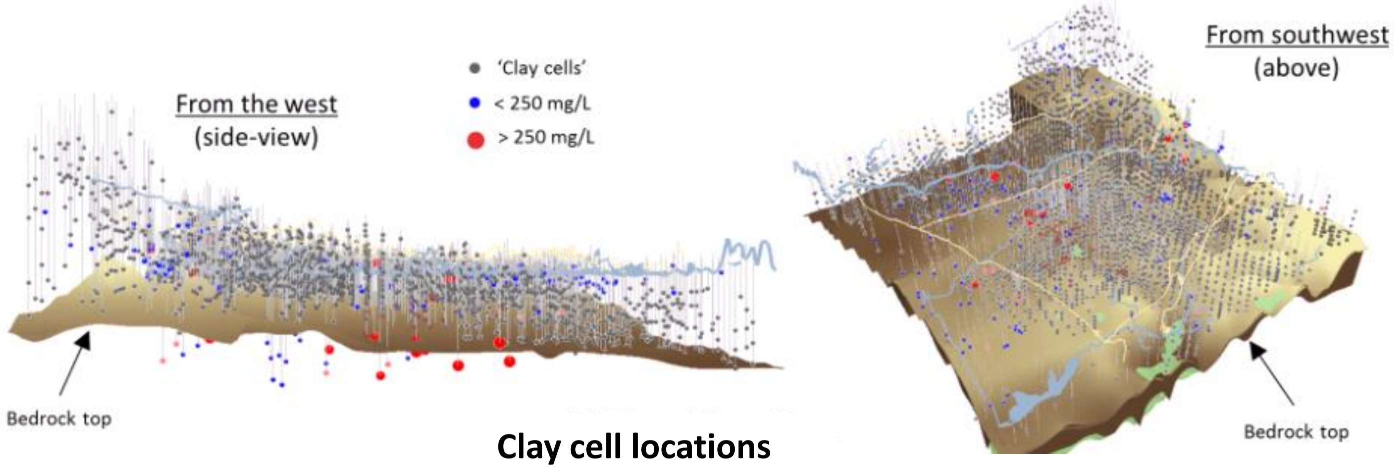
Clay control points were extracted from locations where the 3D geologic model predicted partially confining or confining material. The extraction utilized a 1000m by 1000m grid (horizontal direction), although we experimented with a 400m by 400m and 800m by 800m grids. Based on graphical comparison of interpolated Cl^- concentrations verses observed Cl^- concentrations, the 1000m by 1000m grid was deemed most appropriate.

Interpolation without clay cells



Interpolation *with* clay cells

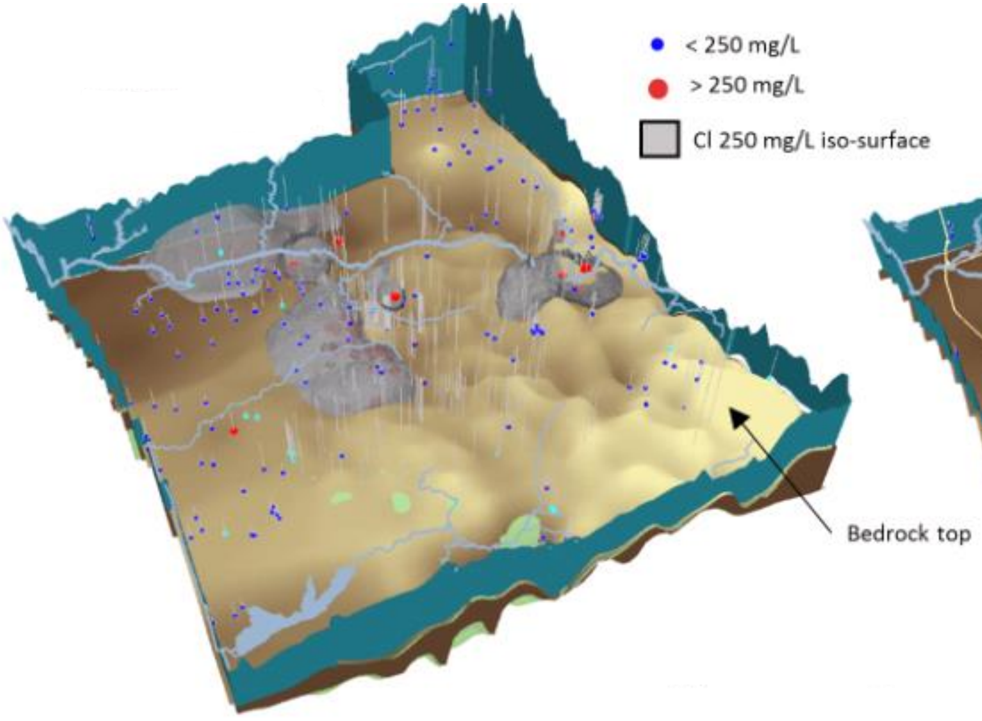




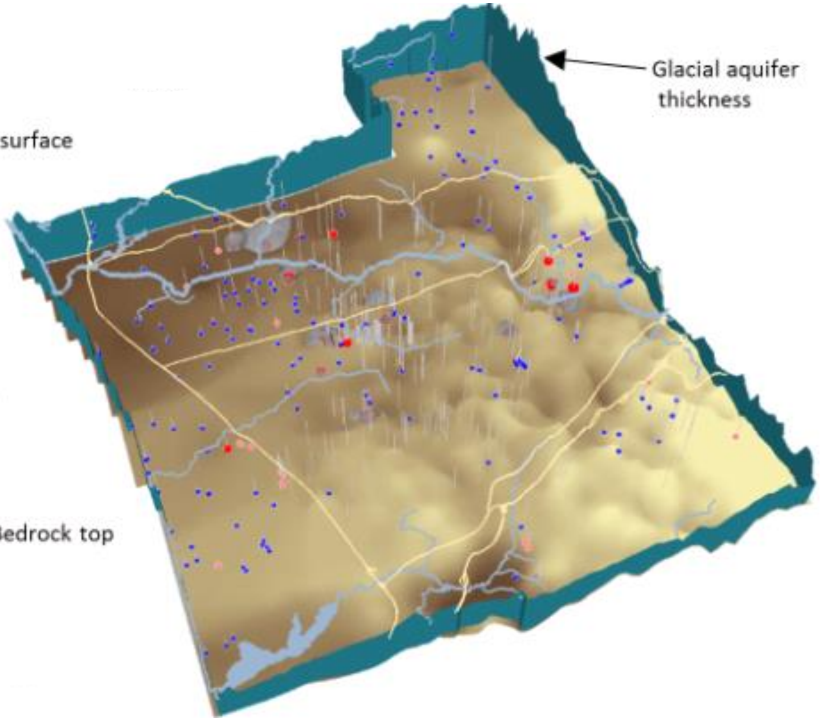
Clay cell locations

Plume Comparison (With & Without Clay Cells)

A comparison of the Cl 'plume' – defined as the spatial extent of Cl^- > 250 mg/L in the aquifer system – with and without control points is shown below. The bedrock surface is shown with zero transparency, i.e., only the samples and plume extent for the glacial aquifer are depicted. Note that the Cl^- plume is generally inconsistent with the Cl^- data in the case of that control cells were not used. Conversely, the case in which clay cells were used, the Cl^- plume largely does not spread into the glacial aquifer, which is what is suggested by the available point data.



'Plume' without clay cells

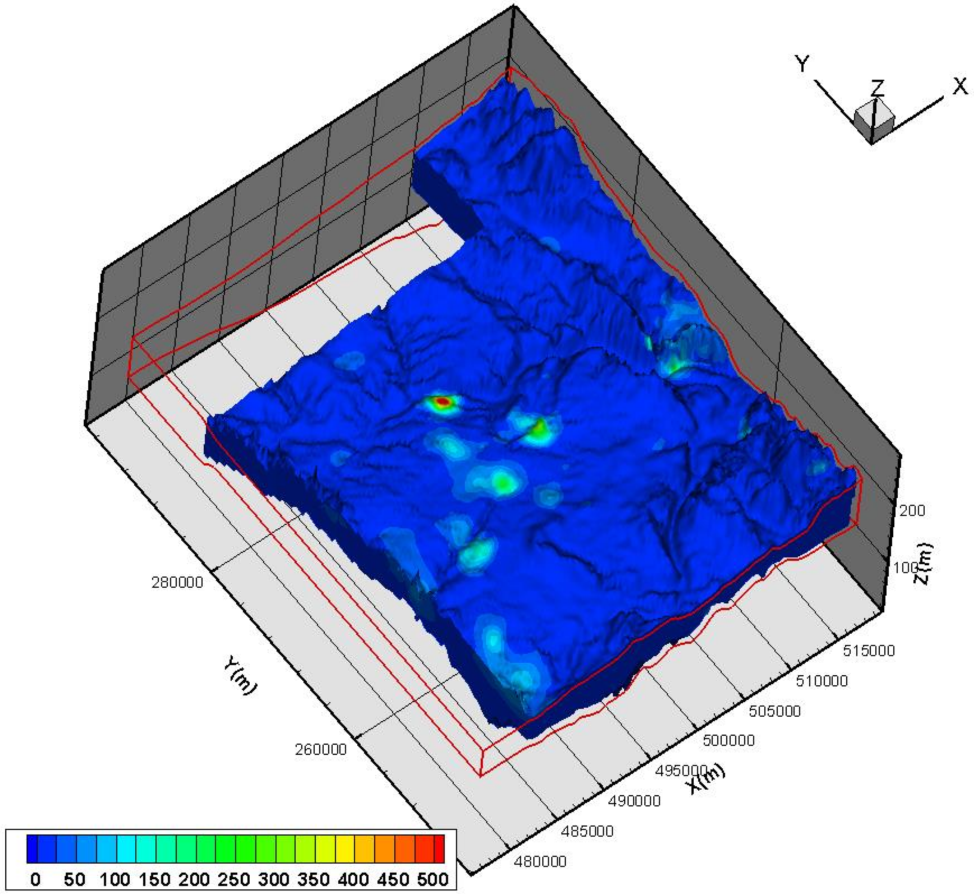


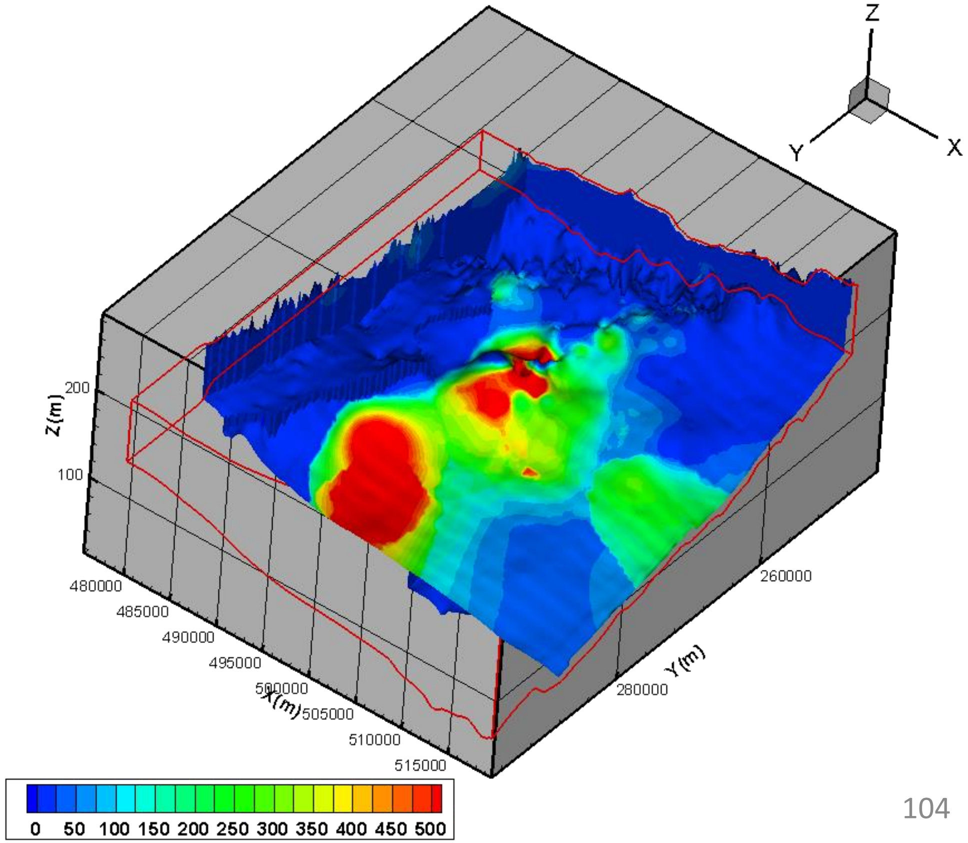
'Plume' *with* clay cells

COUNTYWIDE CL PLUME

Three-dimensional spatial interpolation was completed using kriging, a preferred method in geostatistics (Sun et al. 2009; Varouchakis and Hristopulos 2013). In this approach, estimates of Cl^- concentrations at any point were computed as a weighted sum of Cl^- concentrations at surrounding points, with weights apportioned based on spatial correlations (Isaaks and Srivastava 1989). The weights are calculated by fitting a mathematical model to a graphical representation of semivariance (dissimilarity) in values between pairs of Cl^- data versus lag (separation distance).

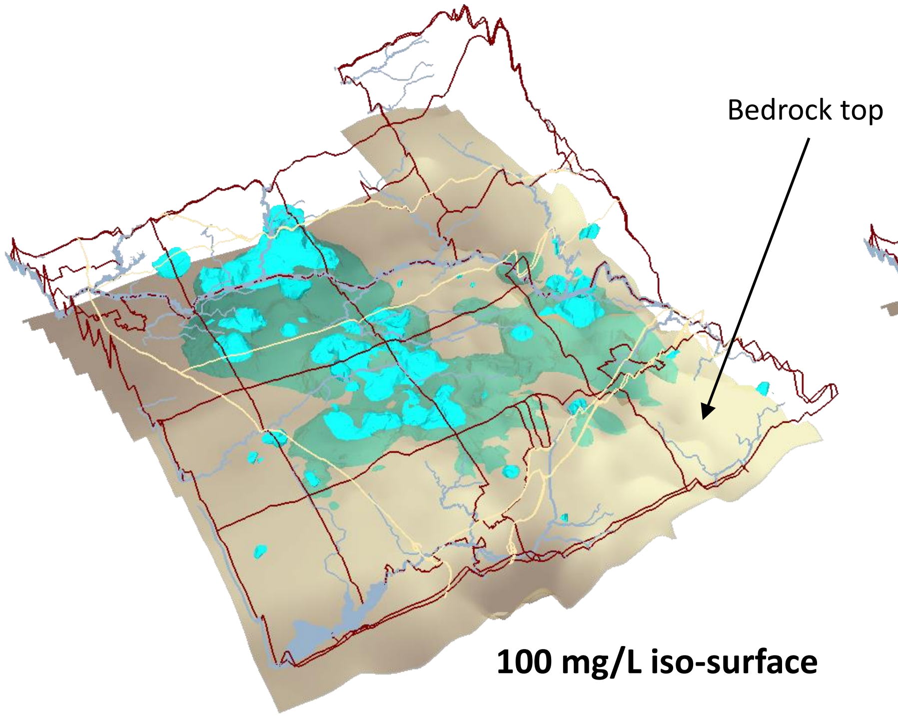
The results are shown below (left: view from above; right: view from below). The results are consistent with the point data, i.e., the highest Cl^- concentrations are found in the deep bedrock aquifer.



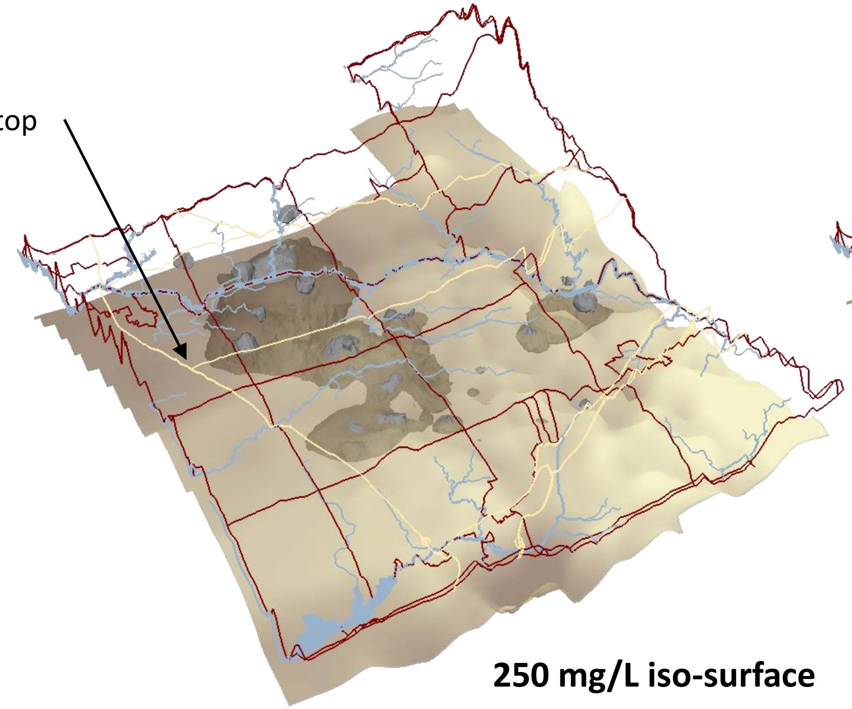


3D Cl Iso-Surfaces

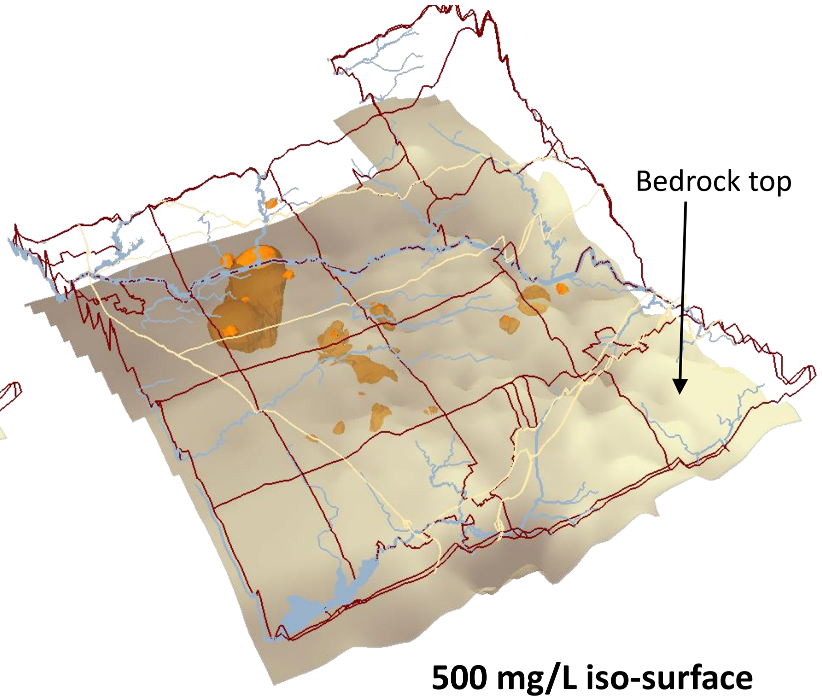
A useful way to visualize the results from 3D interpolation of Cl^- concentrations is to generate Cl^- Iso-surfaces (see below). These are surfaces that represent points of constant value (e.g., 100 mg/L, 250 mg/L or 500 mg/L) within the volume of the aquifer system. In the 3D visualizations shown below, the lighter shades indicate where the iso-surface is above the bedrock top surface (and the darker shades indicate where the iso-surface is below the bedrock top surface). In general, as the concentration increases, the extent of the Cl^- iso-surface decreases.



100 mg/L iso-surface



250 mg/L iso-surface

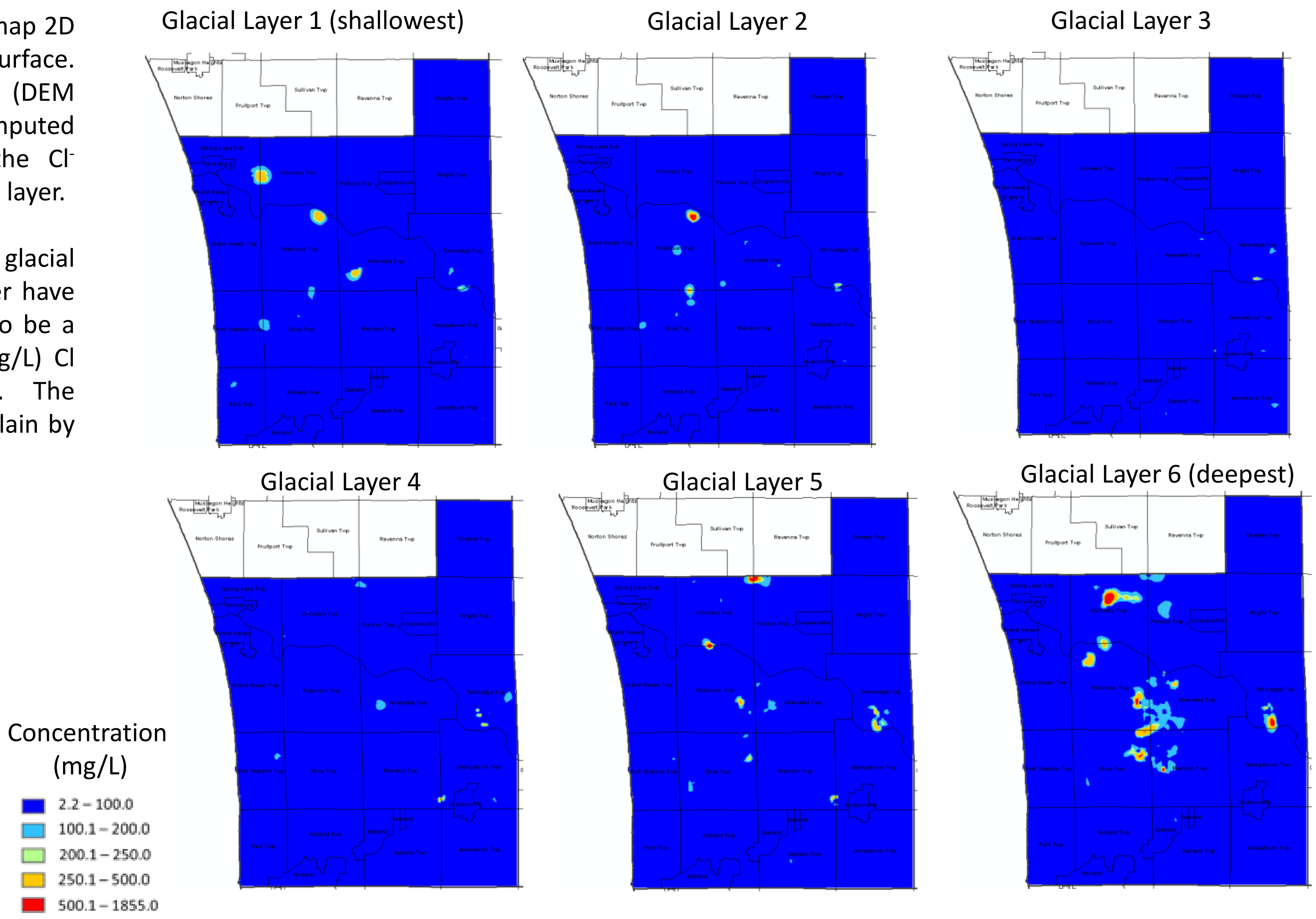


500 mg/L iso-surface

2D Maps of Cl at Various Depths from the Land Surface

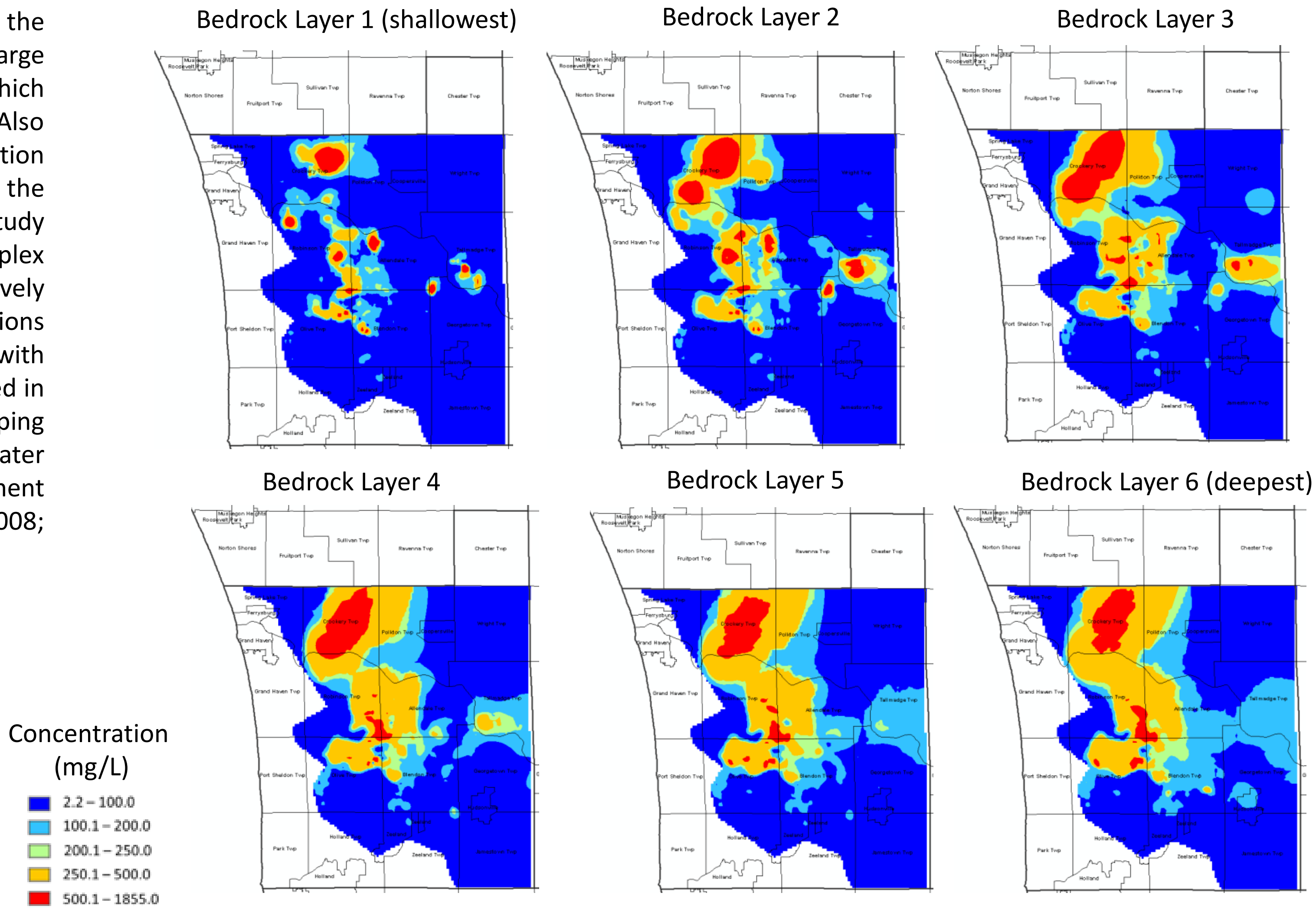
Another way to visualize the results of the 3D Cl^- plume is to map 2D distributions of Cl concentrations at various depths from the surface. At each grid cell location, the aquifer system thickness (DEM elevation minus the Coldwater Shale top elevation) was computed and sub-divided into 9 layers of equal thickness, and the Cl^- concentration was extracted from the midpoint of each vertical layer.

This slide presents 2D maps of Cl concentrations for the glacial aquifer. Note that many locations throughout the drift aquifer have concentrations of 100 mg/L or less, although there appear to be a few scattered (and isolated) occurrences of high (> 250 mg/L) Cl concentrations near the land surface (Glacial Layers 1 and 2). The deepest drift layer contains high concentrations in areas overlain by clay and underlain by the bedrock aquifer.



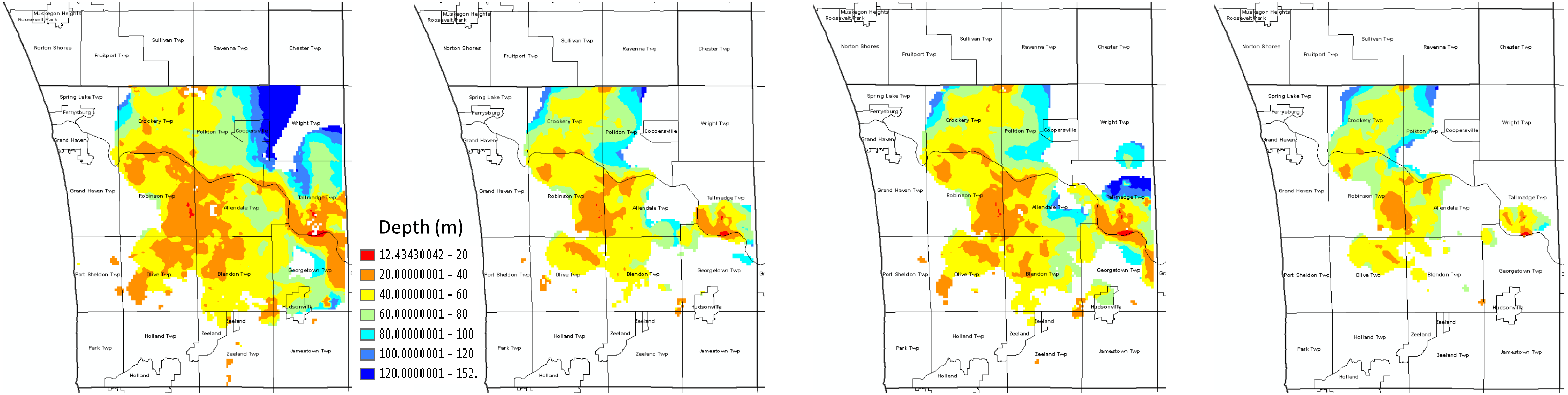
2D Maps of Cl for the Bedrock Aquifer

This slide presents 2D maps of Cl^- concentrations for the bedrock aquifer. Note that all of the maps contain large areas of high (> 250 mg/L) chloride concentrations, which is in stark contrast to the results for the drift aquifer. Also note that the extent and severity of the contamination increases with depth into the aquifer system, e.g., in the northwest, central and east-central portions of the study domain. This 3D Cl^- spatial structure resembles complex "upconing" of deeper saline water - plumes of relatively high Cl^- groundwater migrating from deeper saline regions of the large-scale groundwater system and mixing with the overlying freshwater. This phenomenon is discussed in a number of saltwater intrusion studies in which pumping induces a localized rise in the freshwater–saltwater interface underneath areas of groundwater development (Schmork and Mercado 1969; Paster and Dagan 2008; Jakovovic et al. 2011).



Depth-to-Cl Maps

Generated using the results from the 3D interpolation of Cl concentrations, the figures below displays the spatially-variable depths at which one might expect to encounter groundwater of a given concentration (e.g., 50 mg/L, 100 mg/L, 150 mg/L and 250 mg/L). These maps are useful for estimating the water quality that may be encountered when installing new wells at a given depth and location.



Depth to Cl=50 mg/L

Depth to Cl=100 mg/L

Depth to Cl=150 mg/L

Depth to Cl=250 mg/L

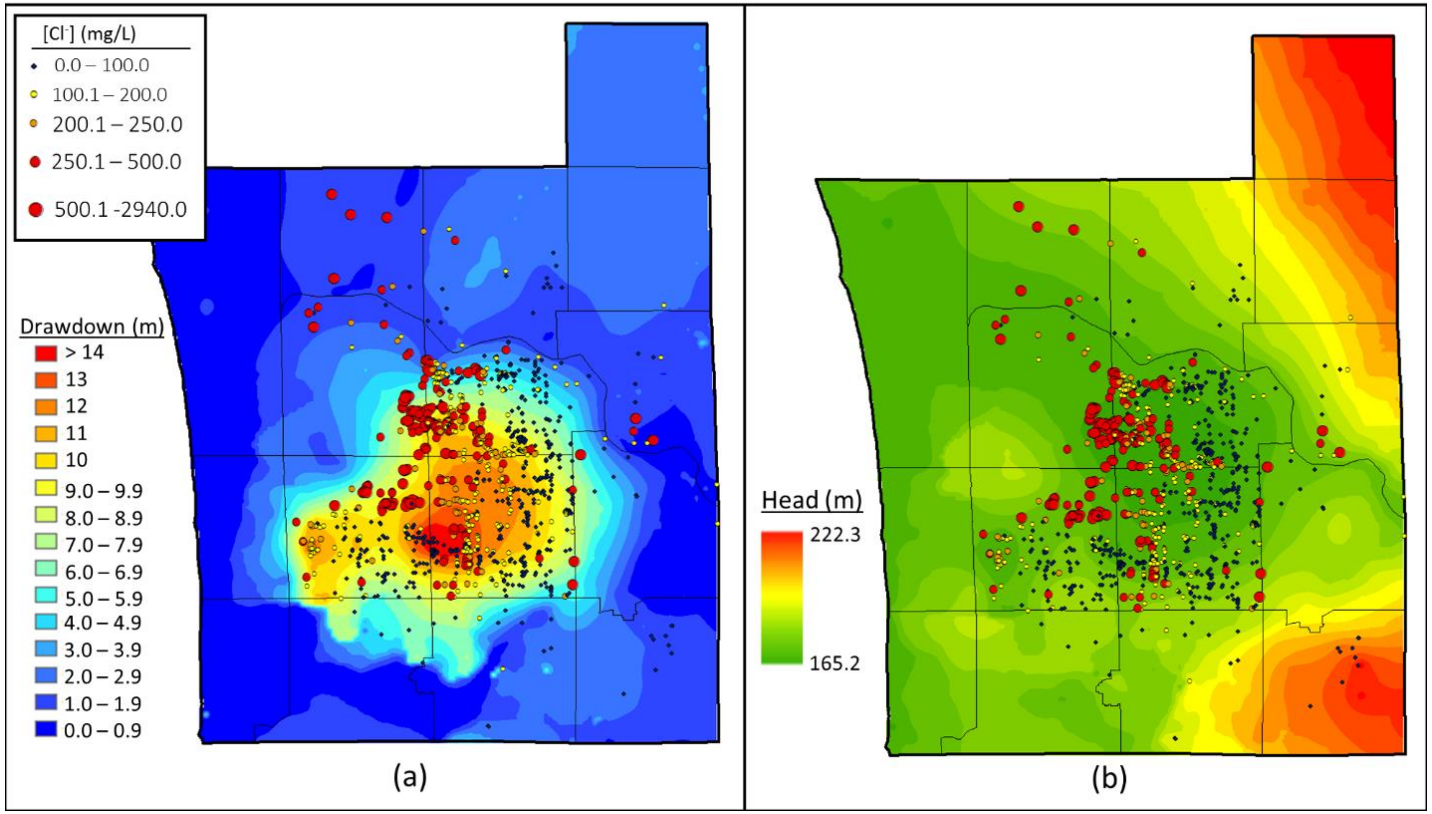
CL TEMPORAL DYNAMICS AND IMPACTS OF PUMPING

With a characterization of the flow system dynamics and a compiled dataset of Cl^- concentrations across space and time, an analysis of the possible causal relationship between pumping and water quality was possible. One approach might consist of constructing a 3D interpolation of Cl^- concentrations for different time periods and identifying locations of significant changes, and although a significant amount of Cl^- data was available for analysis, applying this approach with reasonable statistical confidence for different time periods was not possible given the large scales involved. Alternatively, modeling Cl^- mass transport using the velocity vectors from the numerical flow modeling requires an accurate treatment of the boundary (source) conditions, which was an impractical (if not impossible) task given the scale and complexity of the problem. However, through the use of 2D graphical overlays and aggregated statistical analyses, it becomes increasingly clear that pumping has exacerbated the brine upwelling in the region.

Spatial Relationships Between Cl Concentrations and Groundwater Flow Dynamics

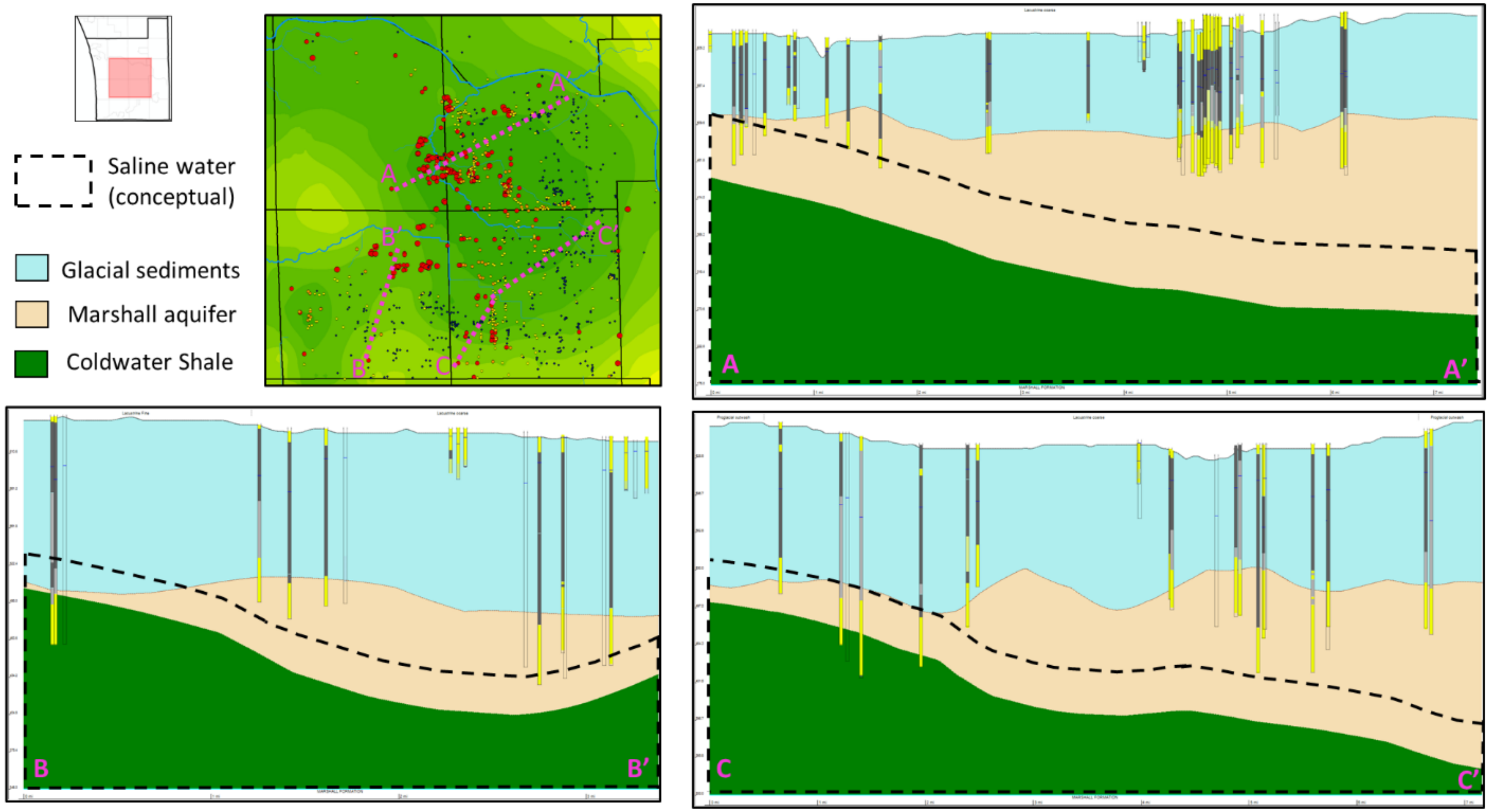
This slide presents overlays of all Cl^- concentration point data extracted from all bedrock wells (field collected and historical) with the simulated drawdown (1966-2015) and 2015 SWL distributions. In general, many of the elevated samples ([Cl^-] > 250 mg/L) occur in the ‘drawdown cone’ (drawdown of 5m or more) of central Ottawa County, although there are a number of samples with [Cl^-] <125 mg/L also occurring within this area, especially along the eastern flank (Box a). Moreover, there are a number of samples with very high concentrations occurring in areas with very little or no drawdown, e.g. northwest or east Ottawa County. There is a somewhat better correlation between the occurrence of elevated Cl^- concentrations and groundwater ‘valleys’, or areas of low SWLs (Box b) where groundwater is expected to have a relatively greater upward flow component. All of elevated samples occur in groundwater valleys, including those samples in the northwest east portion of the study domain. Some of the areas in the bedrock aquifer have historically contained naturally low SWLs, for example, along the Grand River and in northwest Ottawa County, whereas some areas are “artificially low” of because increased groundwater withdrawals, e.g. south of the Grand River in central Ottawa County.

It is worth noting that the occurrence of low Cl^- concentrations in areas of low SWLs demonstrates the spatial complexity of the Cl^- ‘plume’ in the deep portions of the aquifer system. The large concentration gradients within the groundwater valleys indicate preferential upwelling to discrete points or sub-regions rather than a widespread salinization of the near-surface environment. However, analysis of subsurface geology suggests that aquifer geometry plays an important role as well (see next slide).



Potential Impact of the 3D Geometry of the Bedrock Aquifer on Cl ‘Plume Detection’

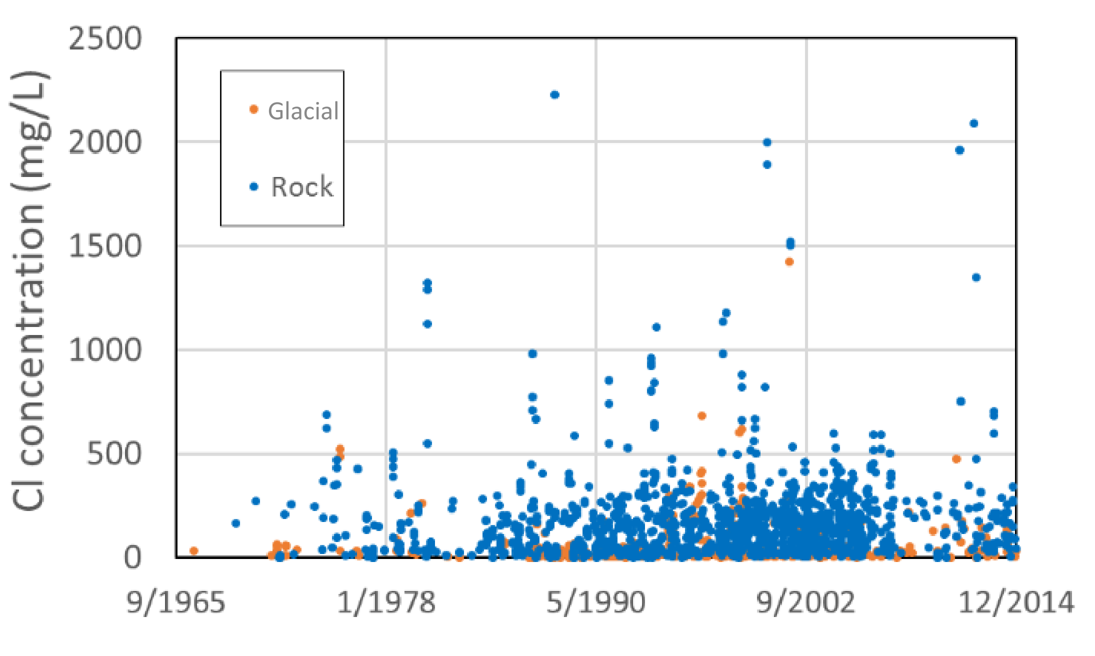
This slide presents cross-section visualizations across concentration gradients within three sub-regions of central Ottawa County. Water wells with colors indicative of the aquifer material type (see previous slides on geologic modeling) were extracted from *Wellogic* and the Marshall aquifer and Coldwater Shale top surface was delineated using lithologic information from the borehole records. Also depicted are hypothetical extents of the saline groundwater in the deep aquifer system (it was assumed that the denser, saline groundwater will occupy a portion of constant thickness at the bottom of the aquifer system, i.e., along the Coldwater Shale-Marshall aquifer interface). Due to the highly variable top surface of the Coldwater Shale unit, these hypothetical ‘saline pools’ of constant thickness will extend to different elevations across the aquifer system. Generally speaking, the wells completed in this part of the county will drill through the clay layer and terminate shortly after penetrating into the Marshall formation. Therefore, as illustrated in each cross-section, its possible that the wells yielding elevated Cl^- concentrations are completed in areas where the Marshall aquifer is relatively thin, whereas the ‘non-detection’ wells are completed in areas where the Marshall aquifer is thick. Clearly, this treatment of the saline plume is an oversimplification of reality; nonetheless, it provides a useful way to understand the subtle details of the controls of the Cl^- distribution in the aquifer system.



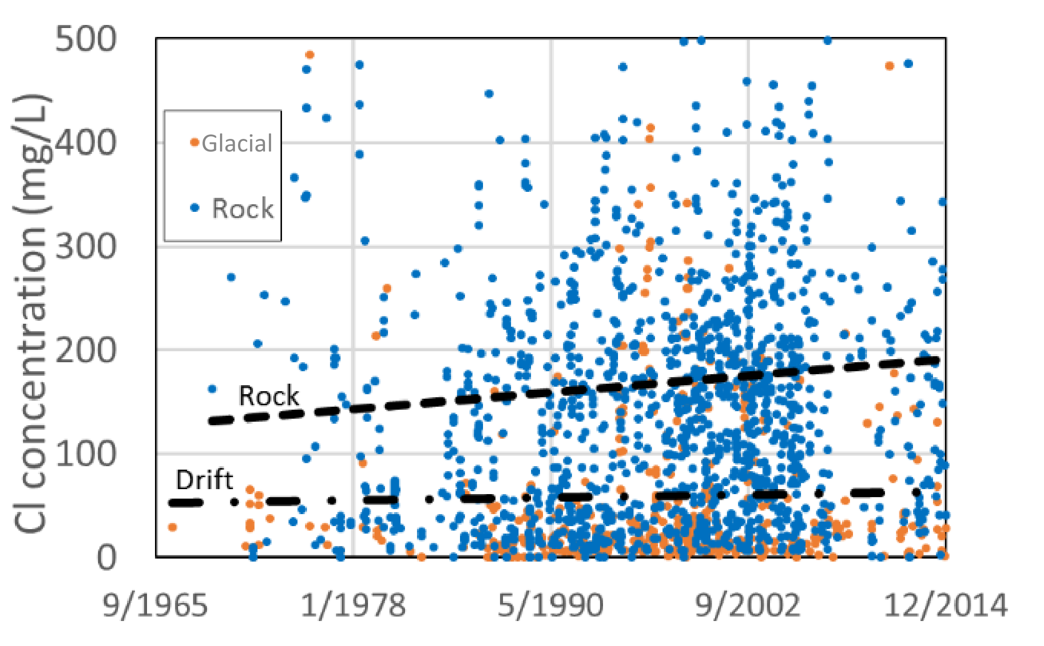
Cl Concentrations Over Time

From the proceeding slides, it is evident that that the spatial distribution of Cl^- concentrations are controlled primarily by two mechanisms: 1) natural discharge of high-Cl^- groundwater into the bedrock aquifer beneath the County; and 2) pumping-induced migration of high-Cl^- groundwater into areas of significant drawdown. For areas impacted by the latter mechanism, increases in Cl^- concentrations with time are expected.

Using the entire historical Cl^- dataset (drift and bedrock wells), concentrations were plotted as a function of time to determine if an overall increase in concentrations has occurred (see below). The bedrock and drift wells are differentiated with different colors, and a reduced y-axis scale ($0 < [Cl^-] < 500$ mg/L) is shown in (b), with linear trendlines for the two data series included. The analysis shows that the number of samples yielding very high concentrations is increasing with time and that, on average, the concentrations in bedrock wells are increasing with time. Conversely, the glacial wells do not exhibit an average increase in concentrations, although there are more wells with high concentrations in recent times.



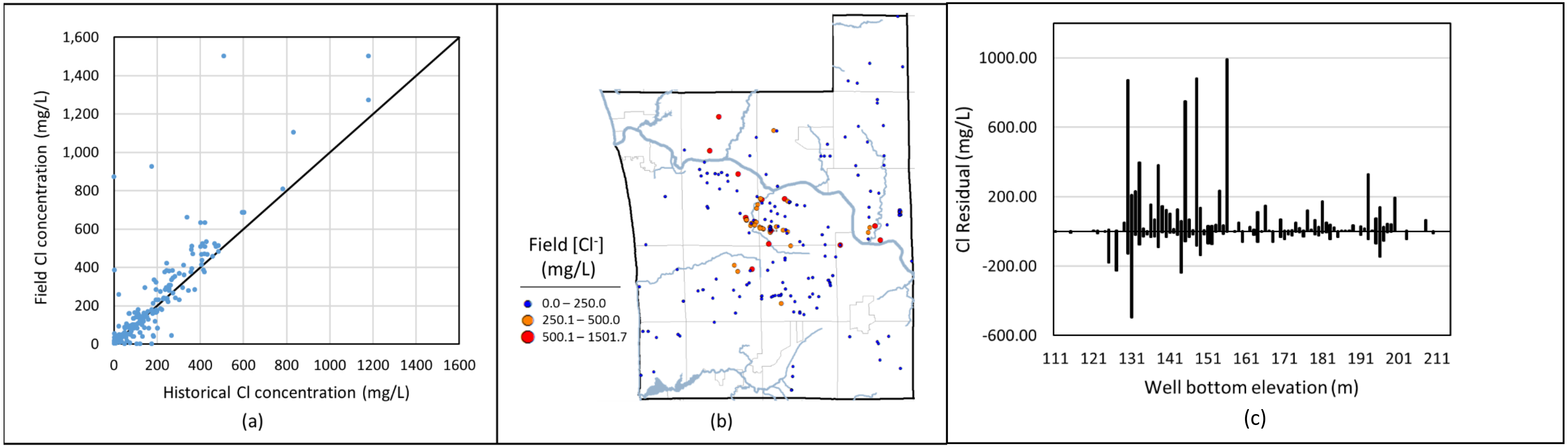
(a)



(b)

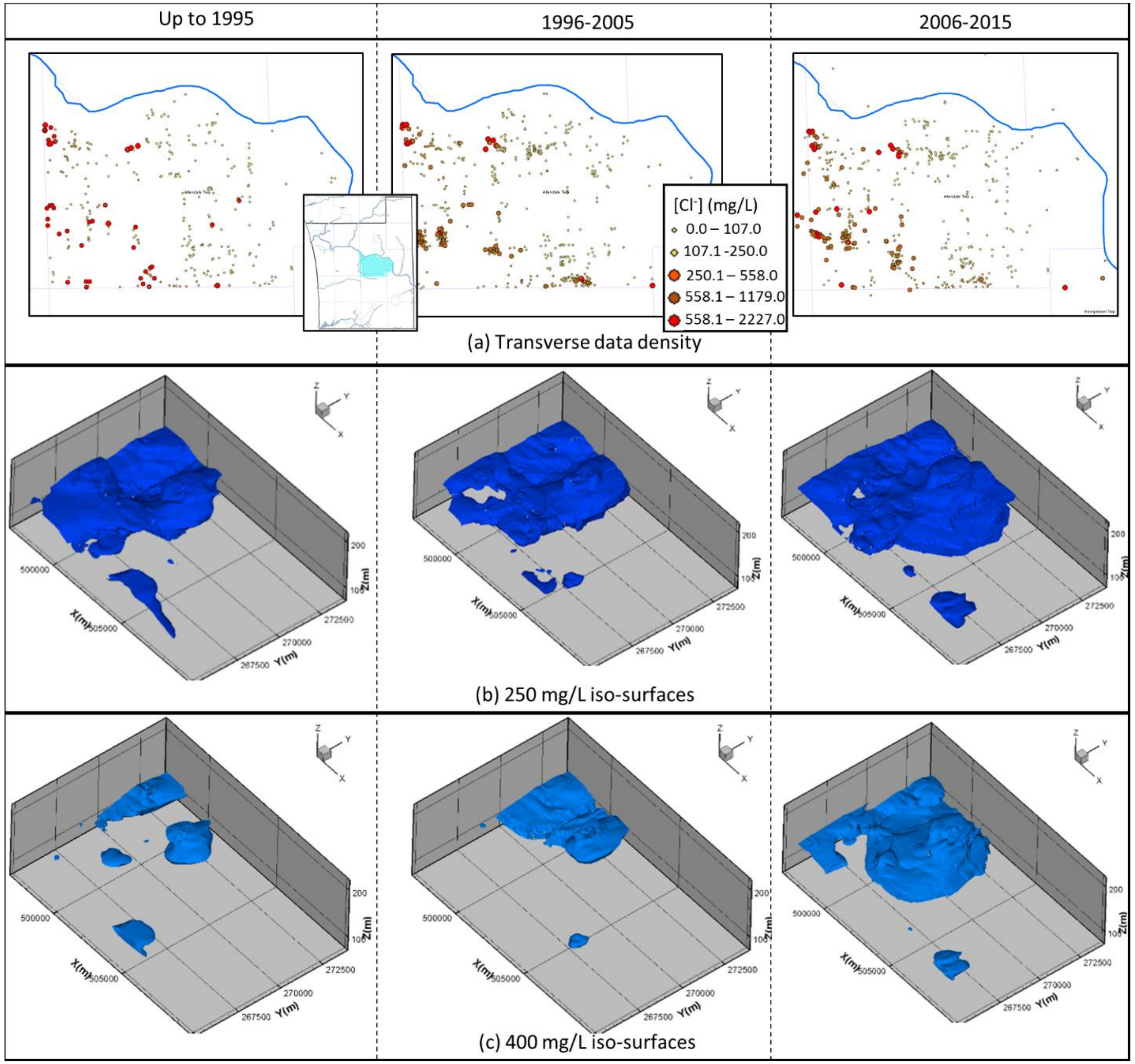
Cl Concentrations at Locations Yielding Historical Data and Field Samples

Although pumping-induced migration of brines toward the land surface may be responsible for the general upward trend in Cl^- concentrations yielded from bedrock wells, it is possible that some of newer wells are drilled deeper than older wells (and are therefore penetrating into the deeper saline water). Therefore, an analysis was completed using samples from locations yielding historical data and where field data were collected. This allowed for comparing samples taken at different times from the *same* wells. This slide presents the results. Comparing the field-collected Cl^- concentration versus the historical Cl^- concentration (Box a) for 248 of the locations visited during the field sampling (Box b) shows a general increase in Cl^- concentrations, i.e., most of the data points fall above the 45 degree line of perfect agreement. This is especially the case for locations with a field-collected concentration of 250 mg/L or more, with 62 of 75 (83%) such locations showing an increase in time. Most of these locations occur in the area where significant drawdown has occurred (central Ottawa County), although there are also locations with low concentrations (<250 mg/L) that not exhibit a significant temporal trend. Analysis of Cl^- residuals (field-collected concentrations minus the historical concentration) and well screen elevations shows that most of the significant increases in Cl^- concentrations are occurring in deeper portion of the aquifer system (Box c). Of the 59 locations with Cl residuals of 50 mg/L or more, 40 (68%) are associated with wells screed at elevations of 160 m or lower, which is a reasonable approximation of the average bedrock top surface in Ottawa County (Churches and Wampler 2013).



Plume Migration for an Area With Significant Drawdown

As previously mentioned, constructing and visualizing countywide 3D interpolations of Cl^- concentrations for different time periods was not possible. However, there was enough data in the key area in central Ottawa County with high Cl^- concentrations and large increases in Cl^- to perform separate 3D interpolations for the past three decades. Shown here (Box a) is the transverse data density for Allendale Twp. for the time periods: up to 1995; 1966-2005, and 2006-2015 (note the relatively even distribution of Cl^- data across space and time). Also shown are the 250 mg/L and 400 mg/L Cl^- iso-surfaces for the three specified time periods. Clearly, the extent and severity of Cl^- contamination is becoming worse, especially in the western portion of the aquifer subregion where the Marshall bedrock is relatively thin and drawdown is significant. This is additional evidence for the pumping-induced migration of brine-influenced groundwater over past years of development.



SUMMARY OF IMPORTANT WATER QUALITY FINDINGS

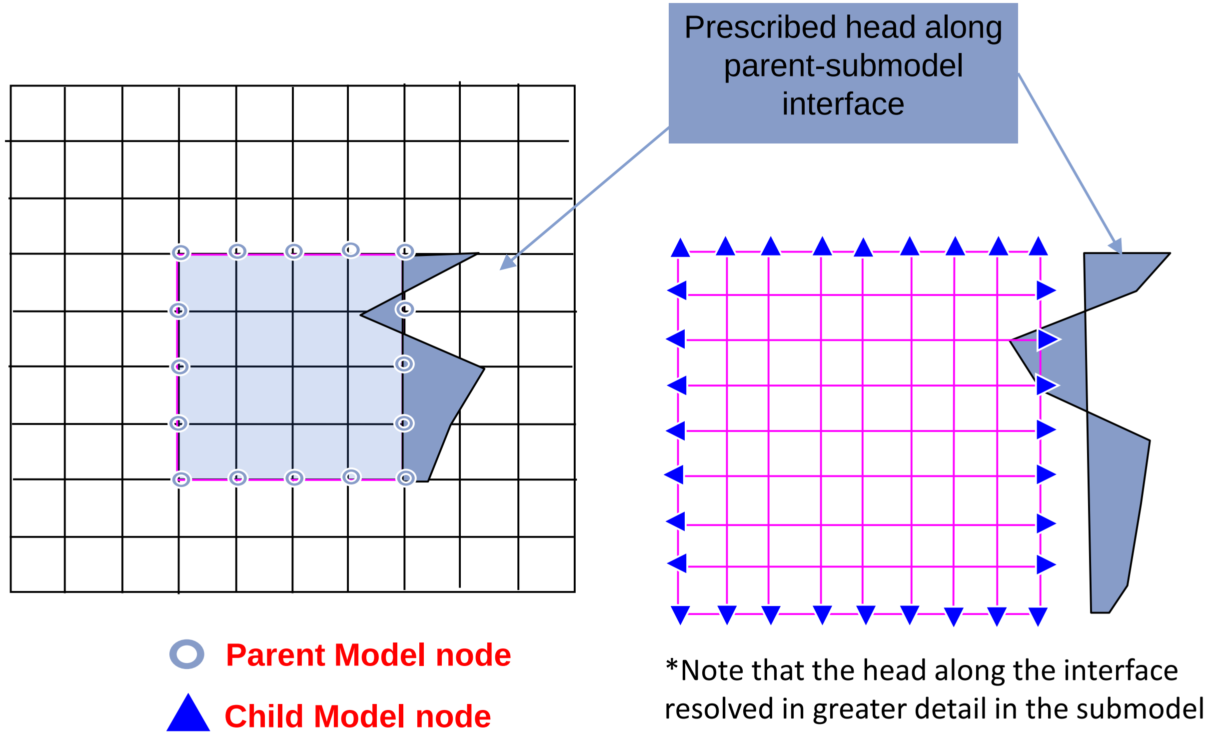
- High chloride concentrations are primarily occurring in bedrock, especially where the clay layer restricts freshwater flushing of recharge from the surface
- High chloride concentrations are focused to areas where groundwater elevations are low, either naturally (e.g. along streams and the Grand River) or artificially (due to pumping)
- there is a general increase in Cl^- concentrations with time, especially for wells currently yielding high Cl^- concentrations
- most of the significant increases (>50 mg/L) have occurred in deeper portions of the aquifer, especially in areas where significant increases of pumping have lowered groundwater elevations.
- This suggests that pumping has slowly induced more of the brine-influenced groundwater towards the near-surface environment, although there is significant spatial variability and natural variability, or 'noise' (i.e., changes less than 50 mg/L, especially for low Cl^- concentrations).
- This final point is why time series analysis of a few individual wells with multiple historical samples were deemed ineffective for evaluating temporal trends – it is only though an aggregated statistical analysis that an evaluation of the system-wide temporal dynamics can be made.

‘HOT SPOT’ DYNAMICS

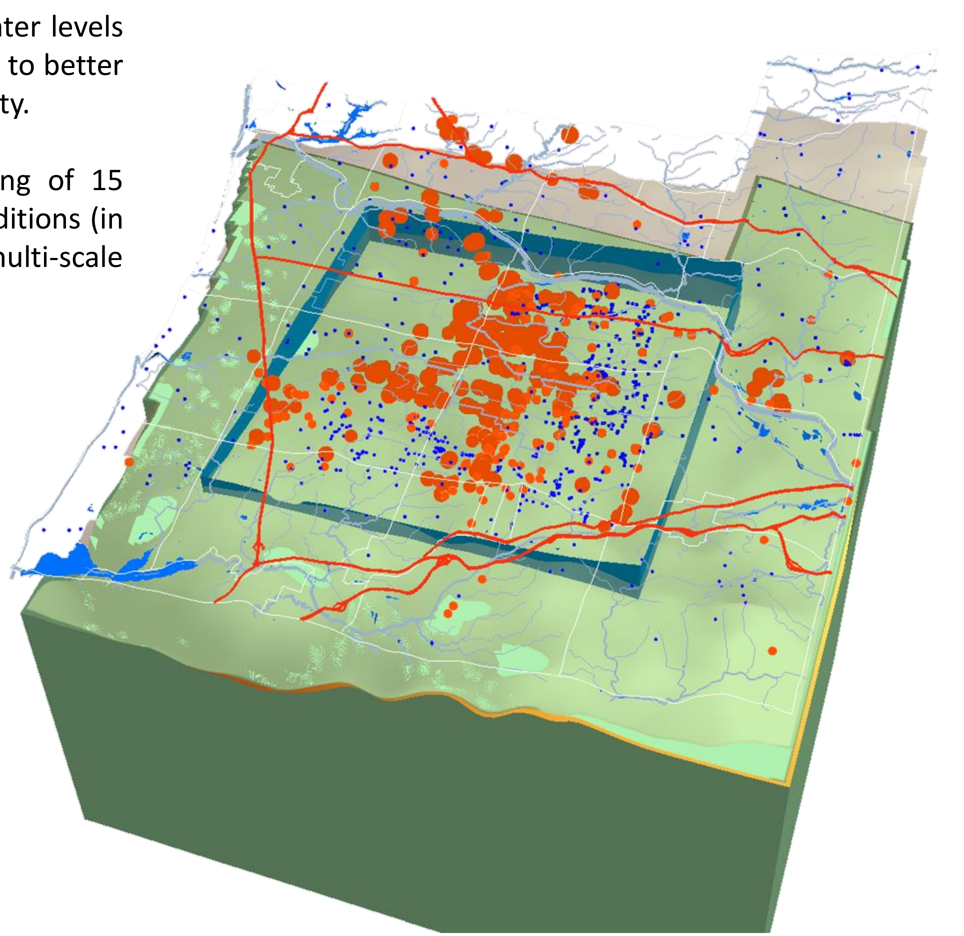
SUB-MODEL DEVELOPMENT

A submodel was developed for the central portion of the County where significant changes in groundwater levels and fluxes were observed and where the highest Cl concentrations generally occur. The primary goal was to better resolve SWL dynamics and visualize 3D flow directions to better understand impacts on groundwater quality.

The submodel utilized a smaller grid size (100m) and delivered greater vertical details by consisting of 15 computational layers (as compared to 7 layers used in the countywide model). Boundary and initial conditions (in the form of head values) were derived from the countywide model (see below). More details of this multi-scale modeling approach are provided in Liao et al. (2015)



*Note that the head along the interface resolved in greater detail in the submodel



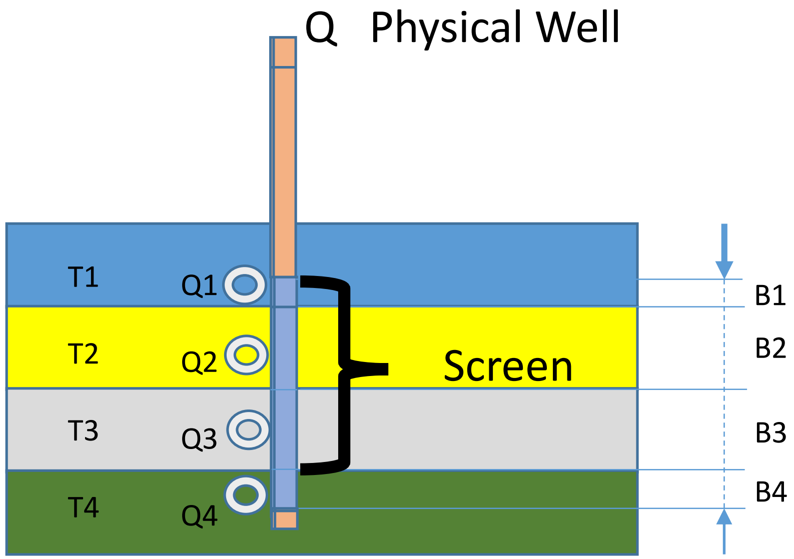
Well Approximation Scheme

With more vertical layers, it was possible that some of the well screen intervals spanned across multiple computational layers in the submodel. Thus, it was necessary to develop a scheme for properly allocating withdrawals from a single well to the different computational layers. The approach was to use 'screen transmissivity' as a weighting factor to split one physical well into multiple computational wells depending on number of computational layers included within the screen interval. The hydraulic conductivity and interval length of each computational layer is used to compute the transmissivity for each layer. The final pumping rate allocated to each layer is weighted by the layer's transmissivity (see graphic and annotations).

Additionally, well withdrawals often needed to be mapped to multiple model nodes because of the close proximity of multiple nodes to one well in the submodel. A similar scheme was also applied in the horizontal direction as was applied in the vertical direction, i.e., withdrawals from a single well were allocated to the nearest four nodes, where weightings were assigned based on the distance to the node and the hydraulic conductivity of the model cell.

Note that, in the countywide model, most wells were predominantly closer to one model node than the others (because of the large cell sizes) and screen intervals rarely spanned multiple computational layers (because of the thicker and fewer number of vertical layers). Therefore, we mapped each well to a single node and used the screen interval height as the weight for each computational layer for the regional modeling. This significantly reduced the required computational resources while providing similar results to the more sophisticated schemes used in the submodel.

Vertical Approximation Scheme

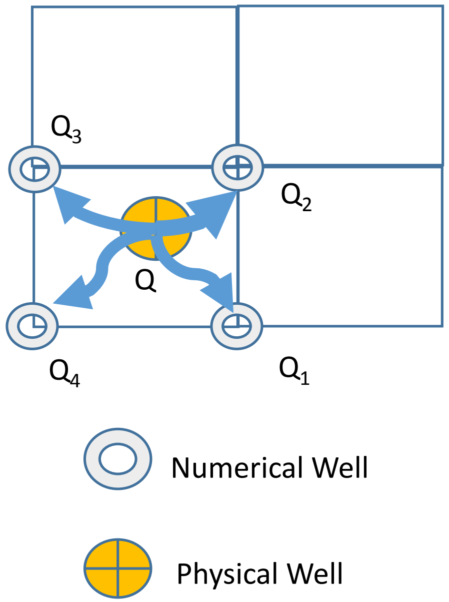


Transmissivity weighted: $Q_i = \frac{Ti}{\sum T} Q$ and $Q = \sum Q_i$

where $T_i = B_i K_i$ is the transmissivity of the i^{th} layer the well's screen goes through

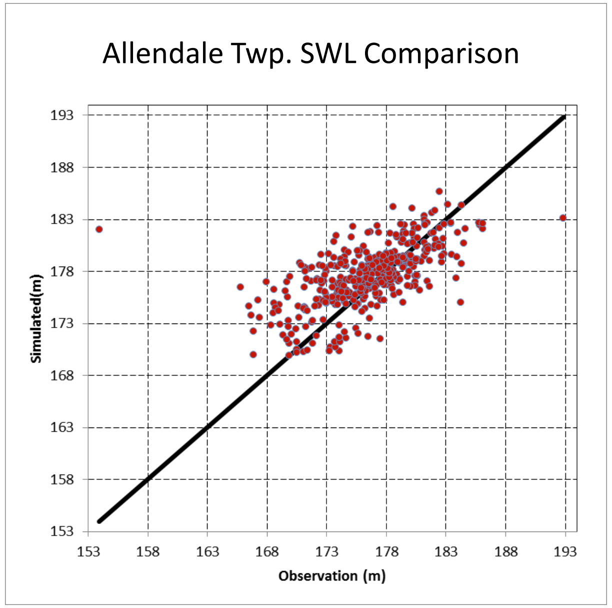
B = computational layer thickness at cell location
K = hydraulic conductivity of computational layer at cell location

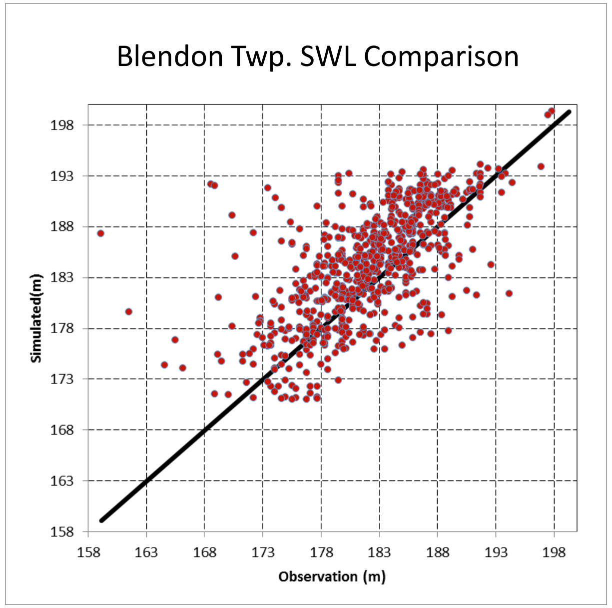
Horizontal Approximation Scheme

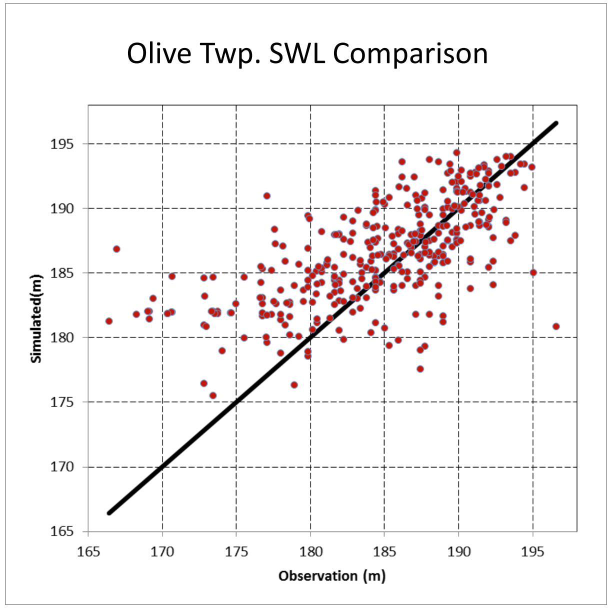


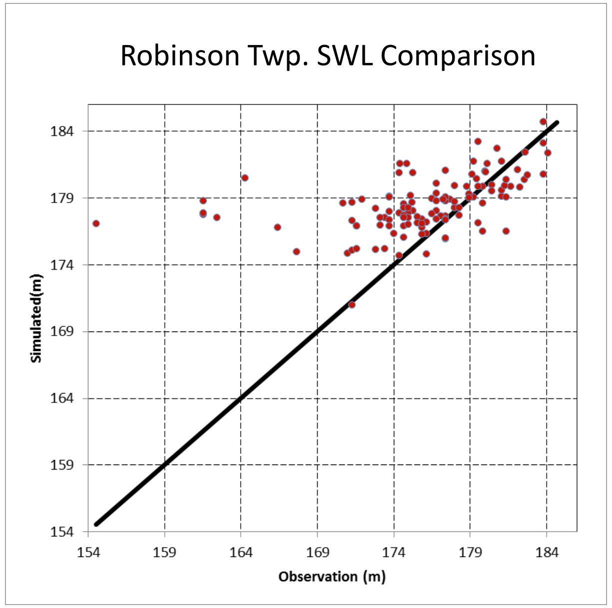
SUB-MODEL CALIBRATION

The performance of the submodel was evaluated in the same way that the countywide model was evaluated. Comparisons of all observed SWLs with simulated hydraulic head from the calibrated model was done for each township included in the submodel, which are shown below. The results show that the submodel does a reasonable job of reproducing SWLs for different times and locations in the submodel.





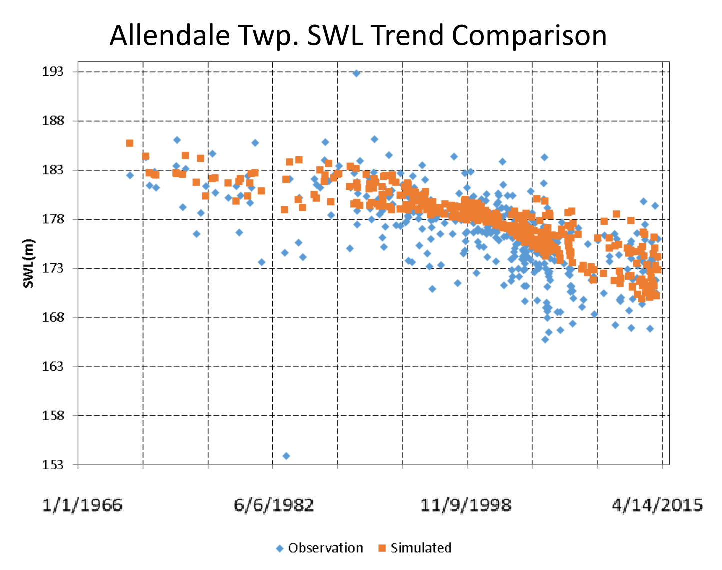


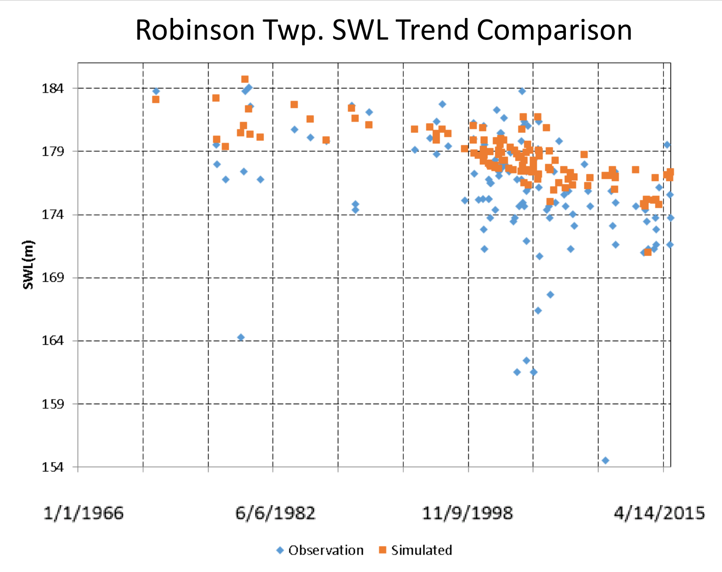


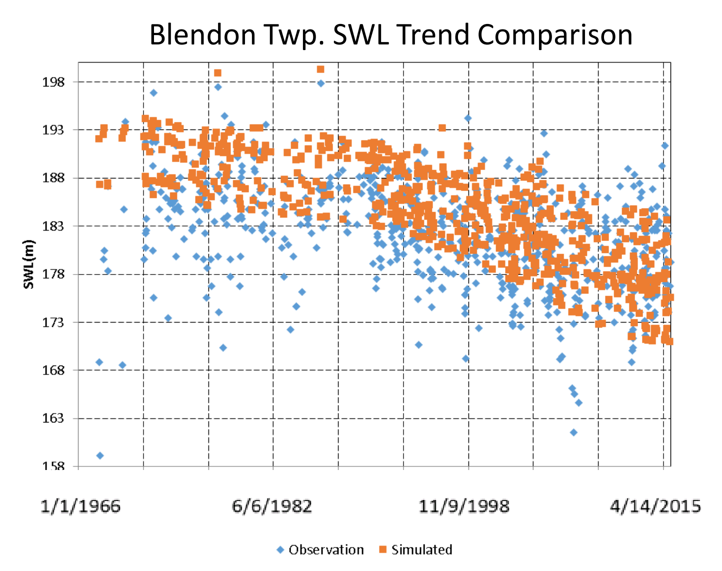
Note: 1 m = 3.28 ft.

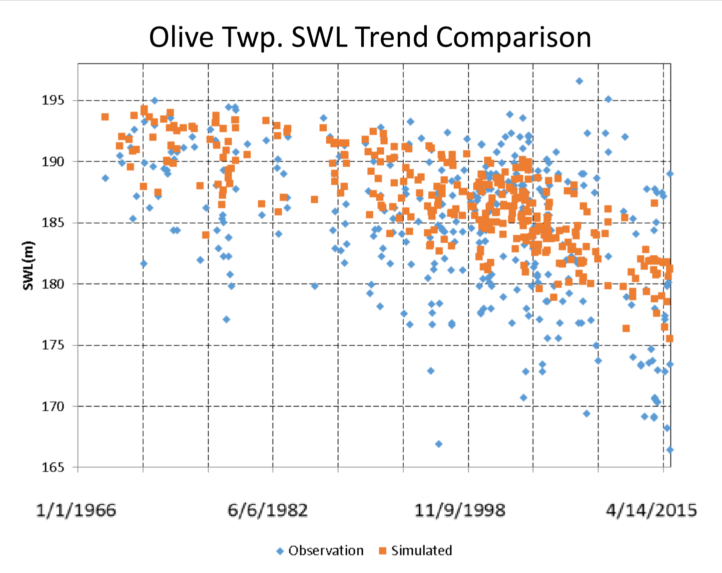
Submodel SWL Trends

This slide presents the simulated SWL temporal trends and the observed SWL trends. Note that the submodel is able to reproduce the general downward trend observed in the SWL subsets.



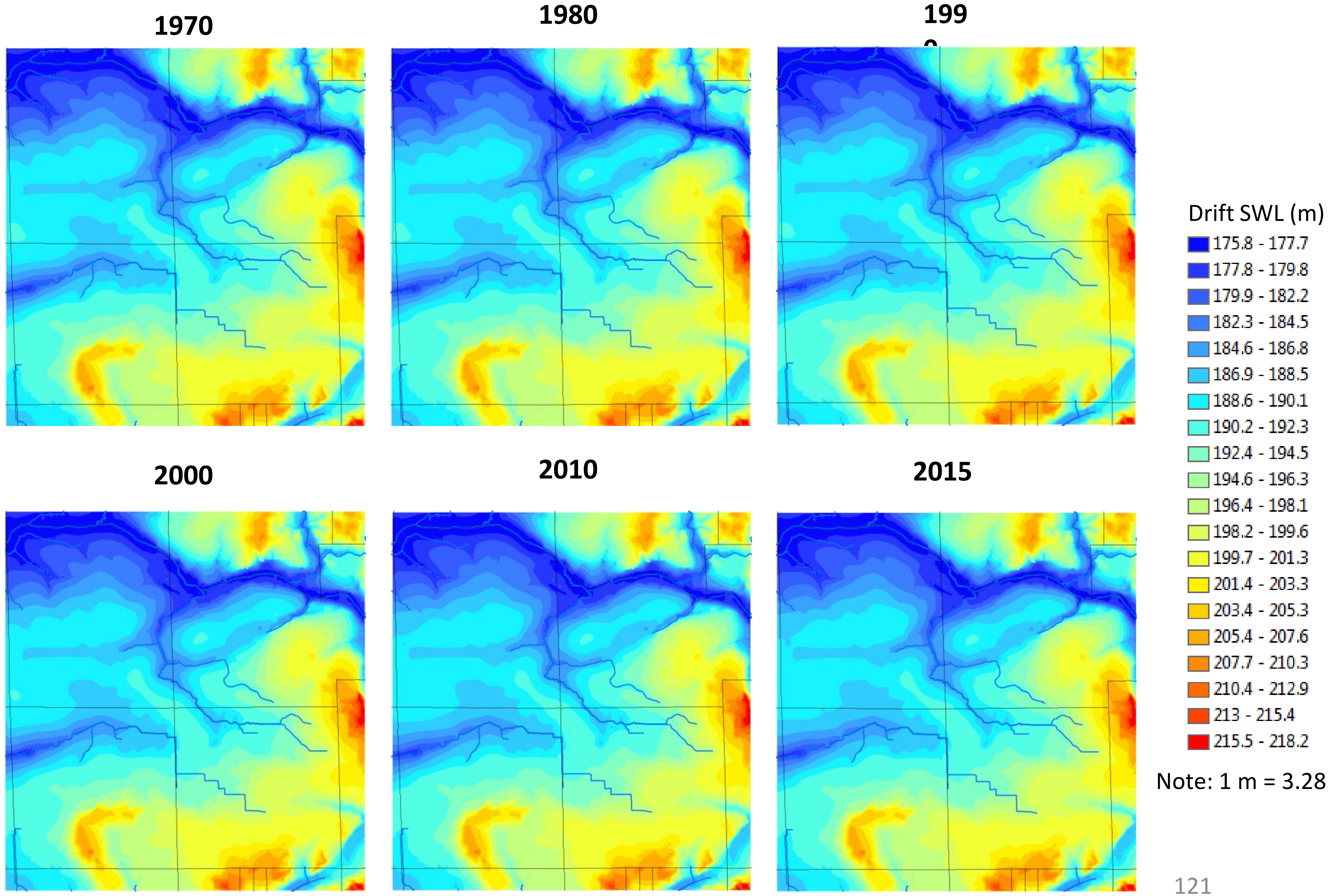






SUB-MODEL RESULTS

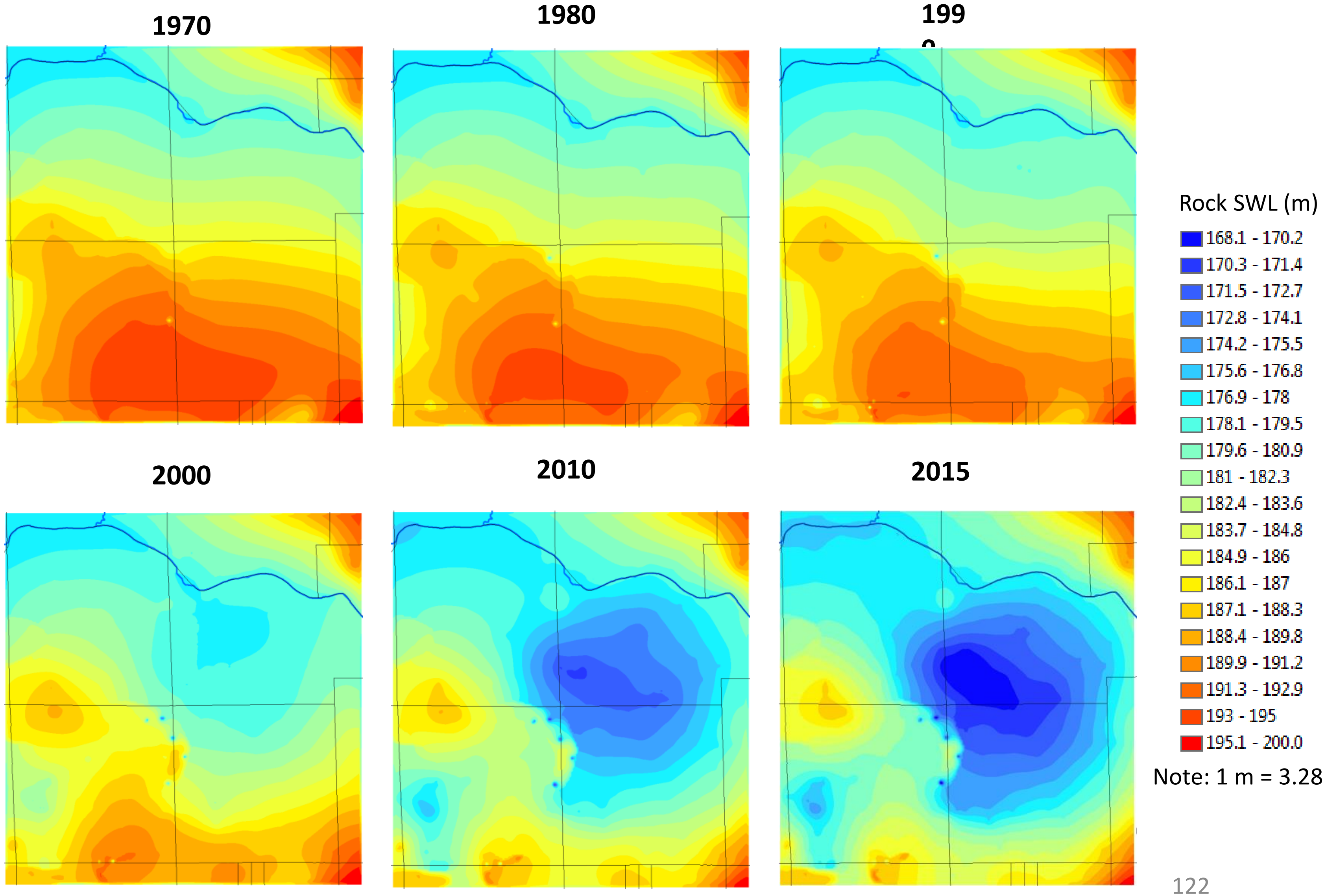
Shown here are the submodel SWLs for the glacial aquifer. Similarly to the countywide model, very few large-scale changes in glacial SWLs has occurred over the past 50 years.



Note: 1 m = 3.28 ft.

Bedrock SWL Dynamics

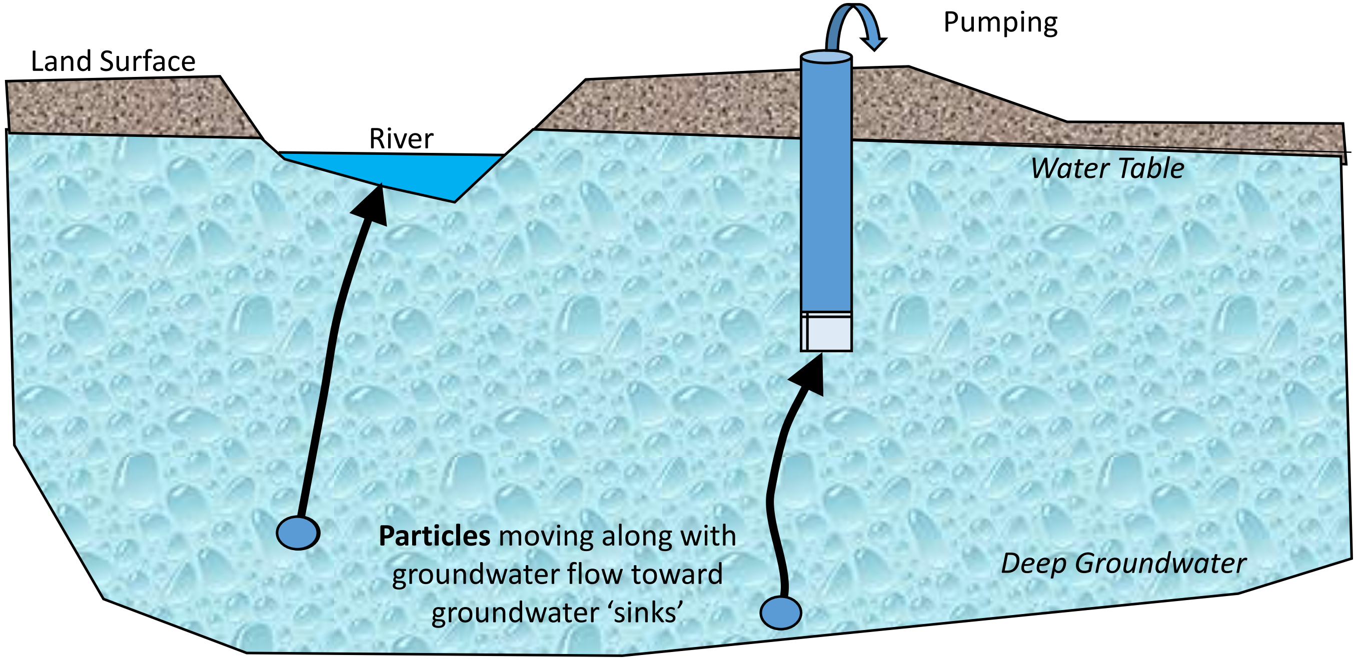
Shown here are the submodel simulated SWLs for the bedrock aquifer. The results are consistent with the countywide model outputs, namely that significant SWL decline has occurred south of the Grand River in each of the four townships included in the submodel. Note the greater level of detailed provided by the submodel.



Note: 1 m = 3.28 ft.

3D VISUALIZATION OF DEEP GROUNDWATER FLOW

The simulated 3D flow field generated by the submodel was used to visualize the flow directions of the groundwater in central Ottawa County. In particular, a particle tracking technique was used to illustrate the flow paths of groundwater in the deepest parts of the aquifer system to determine if/where deeper and - as evidenced by the Cl analysis - more mineralized groundwater was upwelling toward discharge zones. This approach allows for placing tracer particles anywhere in the flow field and allowing them to move along with the groundwater flow as the simulation proceeds. Lines tracking the particle paths through space helps to visualize the 3D movement of groundwater at different locations in the model.



Particle Velocity and Porosity Values

The velocity, v, of the particle is related to the groundwater specific discharge, q, and the aquifer porosity, n:

$$v = \frac{q}{n}$$

The specific discharge depends on the head gradient and hydraulic conductivity values at a particular location in the model, while porosity was assigned based on a review of relevant literature. The table on the bottom-left provides the porosity assigned to the different geologic material types used in the model. The table on the bottom-right is gives the range of values of porosity described in Freeze and Cherry (1979) and McWhorter and Sunada (1977). Note that the values assigned to different material types in the model are consistent with the values reported in the literature.

Material Type	Assigned Porosity
AQ (all TP zones)	0.3
MAQ (all TP zones)	0.3
PCM (all TP zones)	0.1
CM (all TP zones)	0.1
Kmarsh,1	0.08
Kcold,1	0.05
K_{MI}	0.01
Kave,1	0.05
Kave,3	0.08
Kmarsh,2	0.05
Kcold,2	0.01
Kave,2	0.02

Porosity assigned in the submodel

Material Type	Porosity Range
Gravel	0.1 – 0.4
Sand	0.15 – 0.45
Silt	0.01 – 0.4
Clay	0.01 – 0.2
Sandstone	0.05 – 0.30
Limestone/dolomite	0.01 – 0.20
Siltstone	0.01 – 0.4

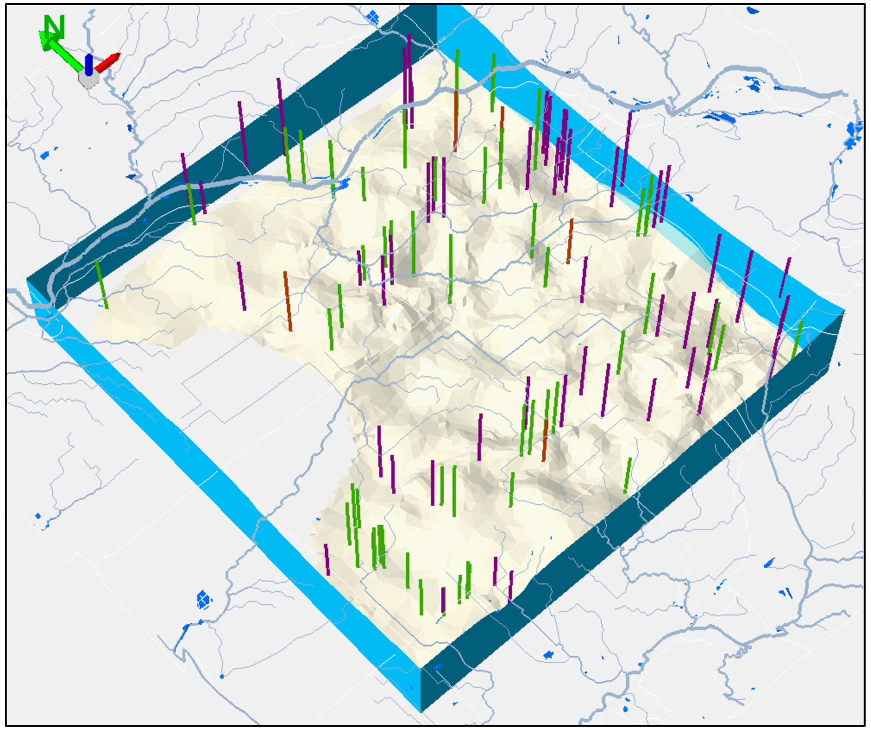
Porosity ranges reported in literature

Initial Particle Positions

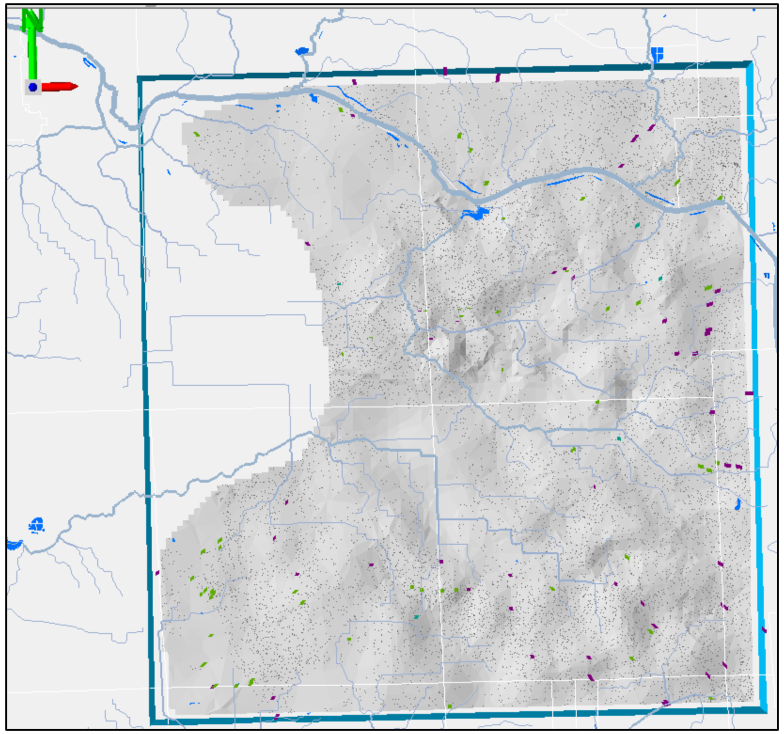
This slide presents the interpolated surface used for initializing particle positions. This surface was created by generating scatter points 10m (32.8 ft.) below all bedrock wells and interpolating between them. The locations of large-capacity wells are also shown. Domestic wells were omitted given the very large number of wells that would have been displayed.

Large-Capacity Well Type

- Irrigation
- Public Supply
- Industrial/Commercial



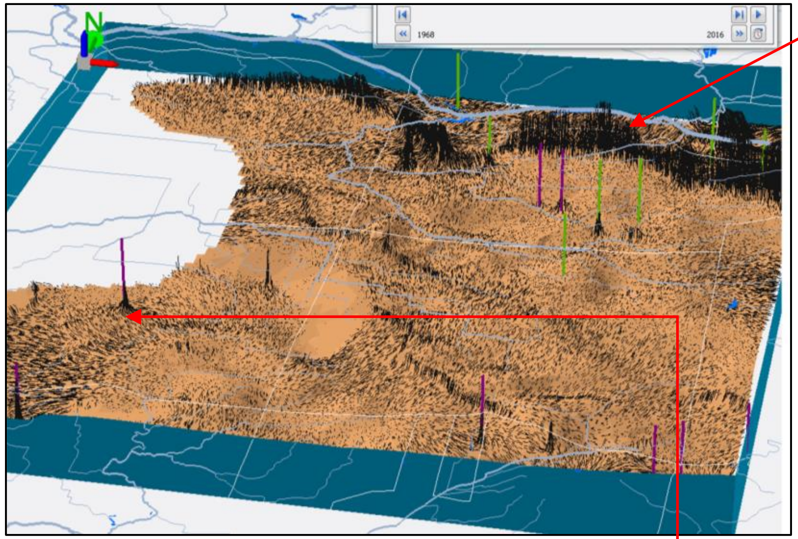
Interpolated Surface 10m below well screen bottom



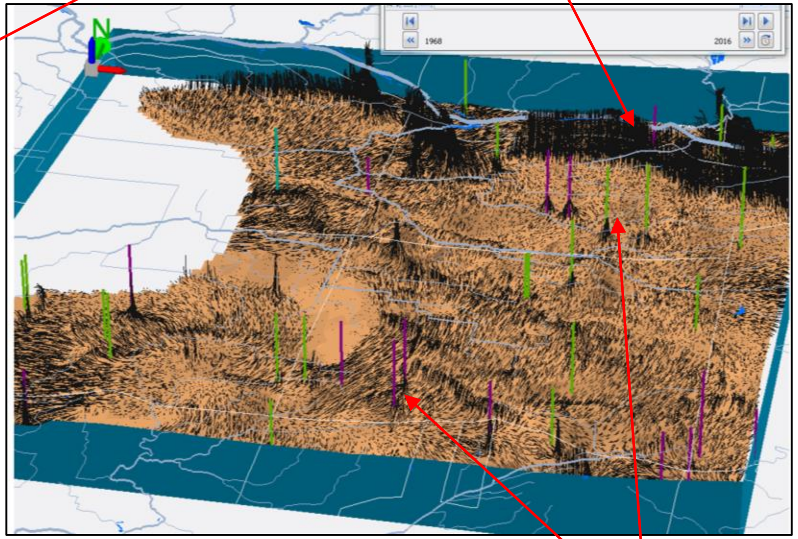
Plan-view of initial particle positions

Particle Tracking Results

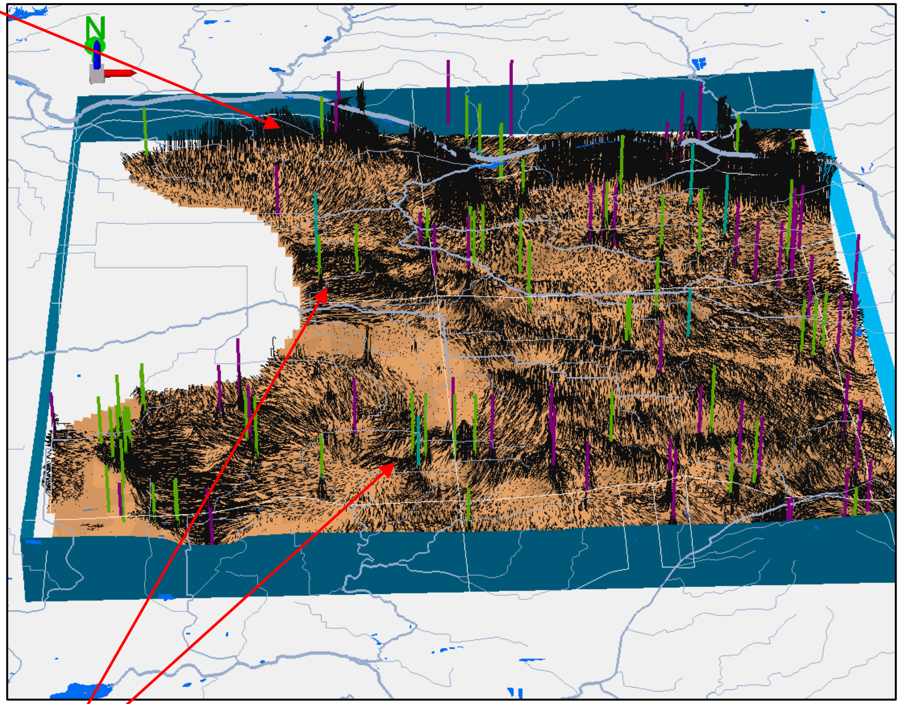
The results of the particle tracking are shown below. The path of the particles are indicated with solid black lines. Clearly, deep groundwater is upwelling to major pumping centers associated with large-capacity wells and clusters of small-capacity domestic wells. Deep upwelling to the Grand River can also be seen. This has important water quality implications since the analysis of chloride concentrations showed that salinity increases with depth in the central part of the aquifer system.



Flow paths after 20 years of simulation (1966-1986)



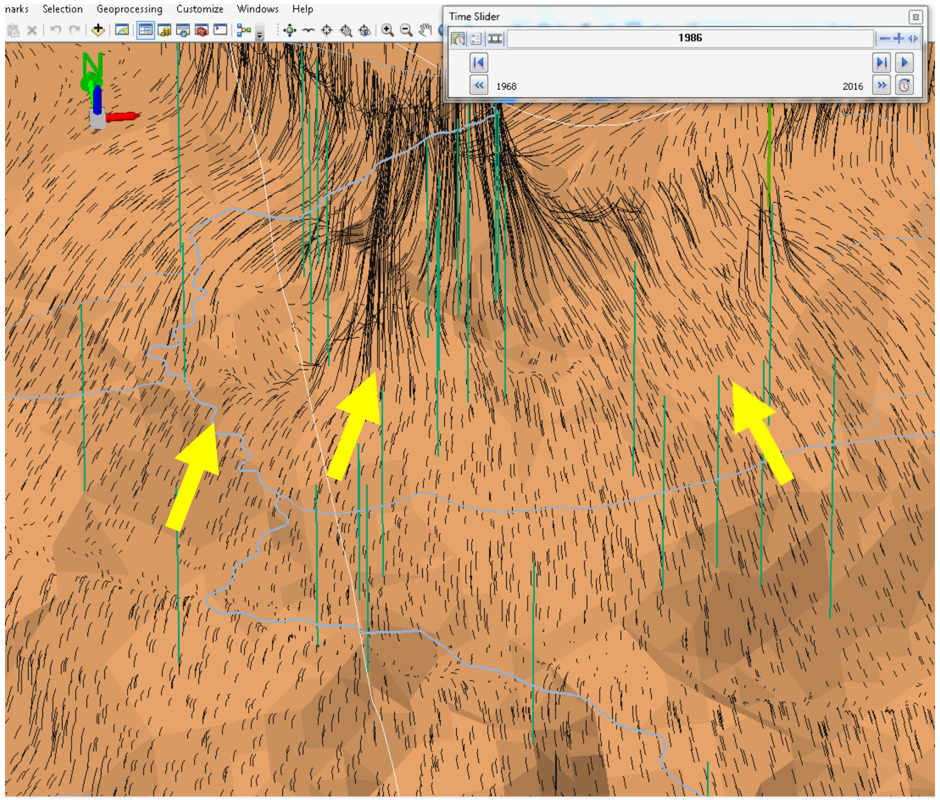
Flow paths after 35 years of simulation (1966-1986)



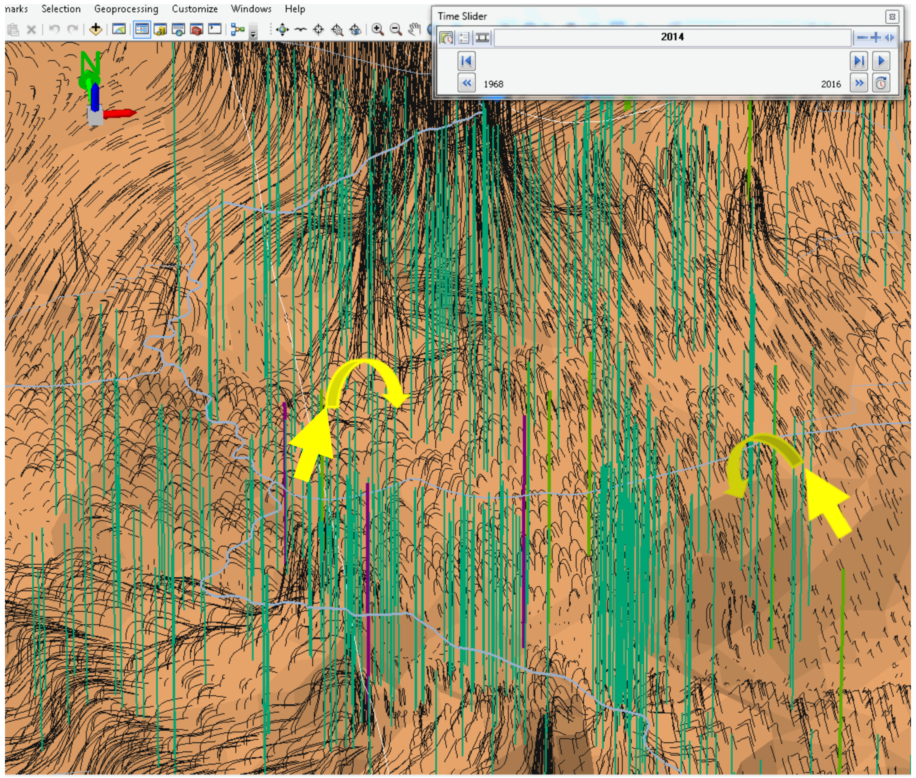
Flow paths after 50 years of simulation (1966-2015)

Pumping-Induced Changes to Flow Directions

The graphics below are a "zoom-in" of the particle tracking results in Allendale Twp. Close inspection shows that, as pumping has increased with time, flow directions have reversed from their natural course towards major pumping centers. This is consistent with the water balance analysis shown on slide 84, where discharge to the Grand River in Allendale Twp. was predicted to have significantly decease due to pumping south of the river.



Flow paths after 20 years of simulation (1966-1986)

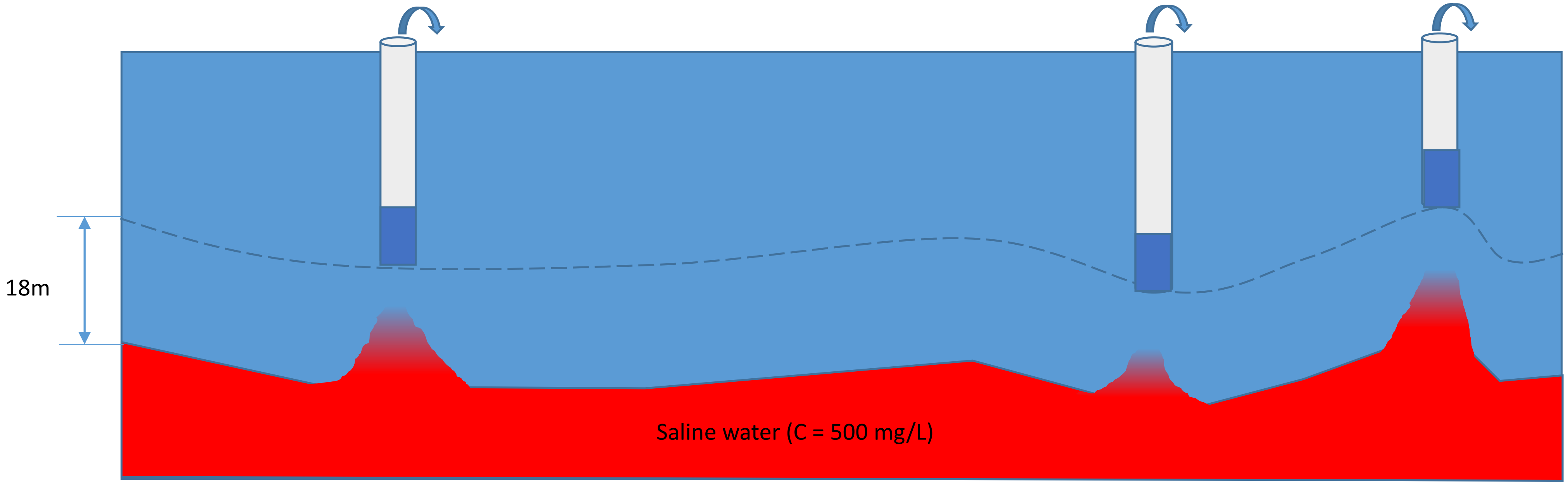


Flow paths after 50 years of simulation (1966-2015)

Approach for Visualizing Cl Plume Upwelling

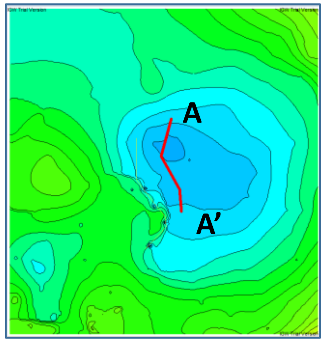
When performing Cl^- transport simulations, the nature of the source must be specified (continuous, time-varying, “instantaneous”, etc.). Determining the nature of the Cl^- source is difficult and requires data on the deep bedrock not available in this study.

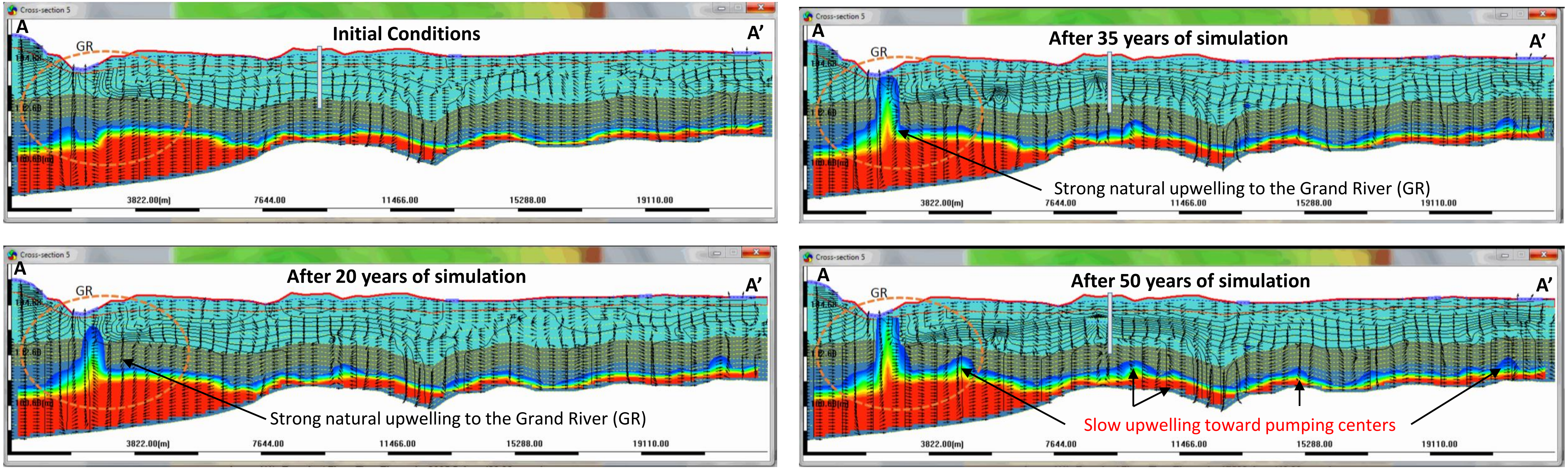
To visualize the response of Cl^- concentrations to the dynamic flow system, an idealized situation is presented first (to visualize upwelling in the vicinity of deep bedrock wells). The approach was to 1) assume a concentration (e.g., C=500 mg/L) at a surface that is 18m below well screen bottom; and 2) treat the surface as as continuous source (i.e., upward movement does not impact concentration at or below the hypothesized surface). The simulated flow field from the submodel was used for the analysis.



Illustrative Cross-sections of Flow and Cl Dynamics

This slide presents an illustrative cross section of the idealized Cl transport described on the previous slide. Note the strong upwelling to the Grand River, which was also seen in the particle tracking. Slow upwelling towards pumping centers can also be seen.



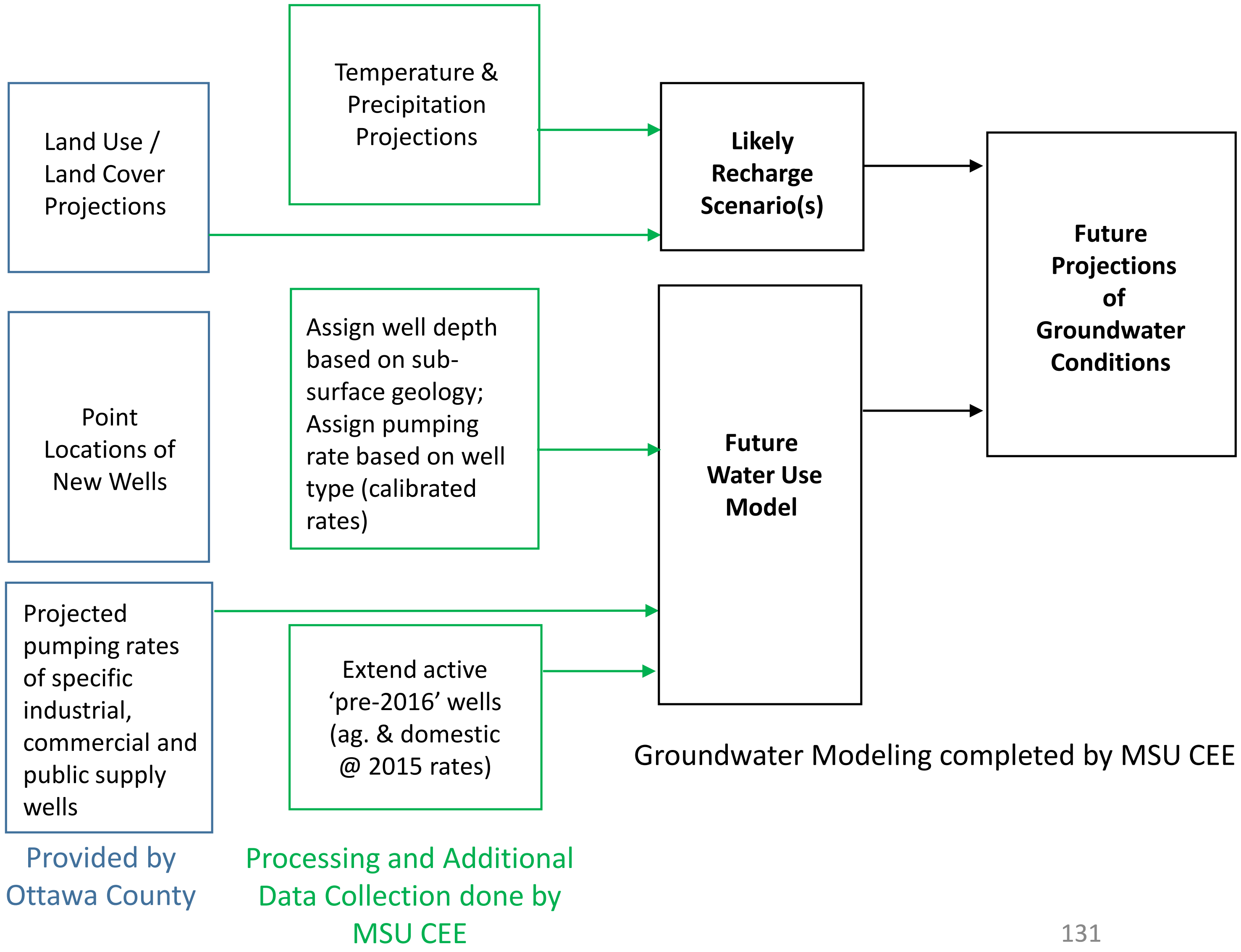


PROJECTIONS OF FUTURE GROUNDWATER CONDITIONS

PROCESS FOR ESTIMATING FUTURE CONDITIONS

The calibrated groundwater flow model was applied to estimate groundwater conditions 5, 10, and 20 years into the future (2016-2036). The future simulations were informed by best estimates of projected land use/ land cover (LULC) and groundwater withdrawals determined from development plans provided by the Ottawa County Planning and Performance Improvement Department (PPID). Long-term temperature and precipitation observations from the National Climate Data Center were analyzed to estimate temperature and precipitation patterns needed to project future recharge conditions.

The chart shown here illustrates the work-flow of preparing projections provided by Ottawa County into future recharge and water use models needed for the groundwater model. Each component is explained in more detail in the following slides.



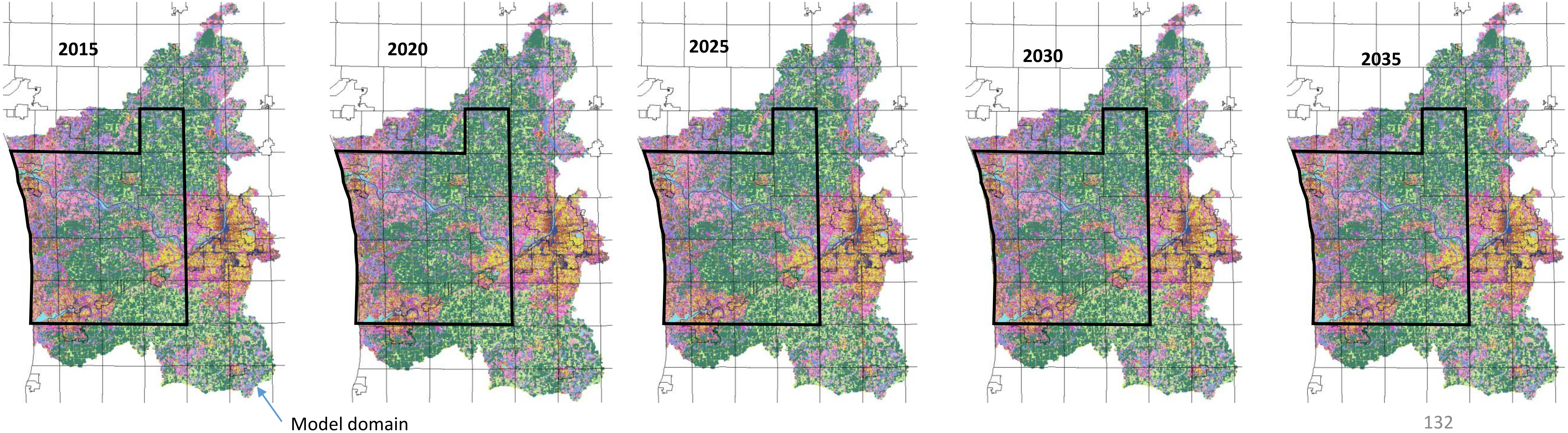
Land Use / Land Cover Projections

Ottawa County PPID worked with township-level officials and decision-makers to carefully plan zoning and land use for the next 20 years. This information was converted into county-wide spatial maps of LULC for every five years for the 2015-2035 time period (see below). These maps were converted into input for the transient future recharge modeling. Changes in LULC for areas of the model outside of Ottawa County were not estimated.

Note that the projected LULC is not expected to undergo significant large-scale changes during the next 20 years. This includes the amount of land dedicated to agricultural activities, although this can be difficult to estimate given the number of socio-economic and biophysical factors controlling crop production. The modeling of future water use therefore used a simple treatment of continuing the 2015 irrigation well pumping configuration (rates and locations) *ad infinitum* (without change through 2036) – see slide 143.

Land Use / Land Cover

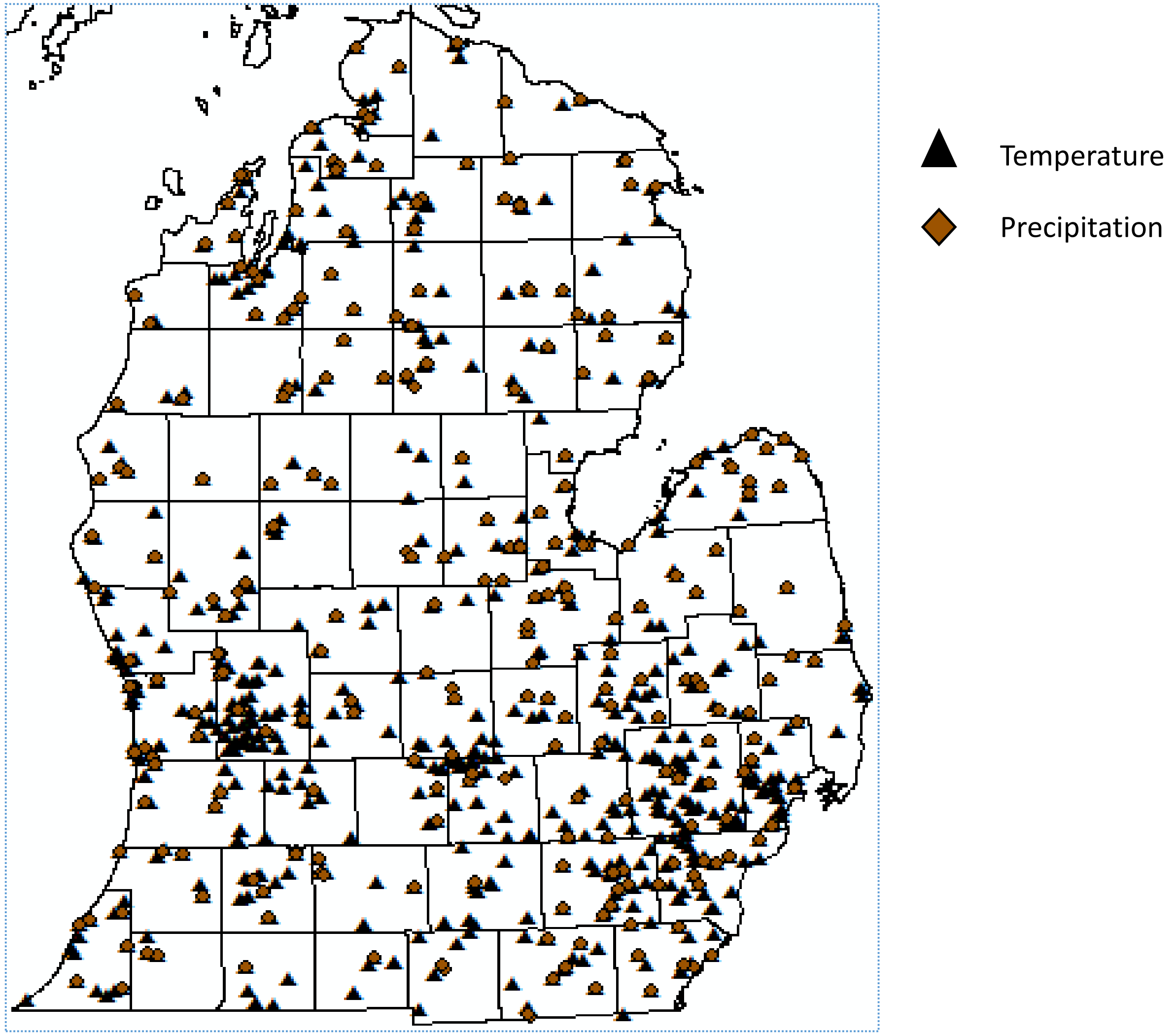
- Open water
- Developed/Open Space
- Developed/Low Intensity
- Developed/Medium Intensity
- Developed/High Intensity
- Barren Land (Rock/Sand/Clay)
- Deciduous Forest
- Evergreen Forest
- Mixed Forest
- Shrub/Scrub
- Grassland/Herbaceous
- Pasture/Hay
- Cultivated Crops
- Woody Wetlands
- Emergent Herbaceous Wetlands



Temperature and Precipitation Trends

The National Climatic Data Center operates 351 temperature stations and 857 precipitation throughout the Lower Peninsula of Michigan (see graphic on right). Many of these locations have detailed data going back decades, although spatial density has improved with time. Analysis of historical observations temperature and precipitation allowed for identifying long-term trends that could be used to inform future estimates of temperature and precipitation. In particular, 10-year annual averages using data from 1972-2012 were calculated. Then, a linear regression was applied to the 10-year averaged to provide a "slope" for projecting future estimates (see the next three slides). This analysis was recently completed by an MSU CEE doctoral student (see Zhang, 2014).

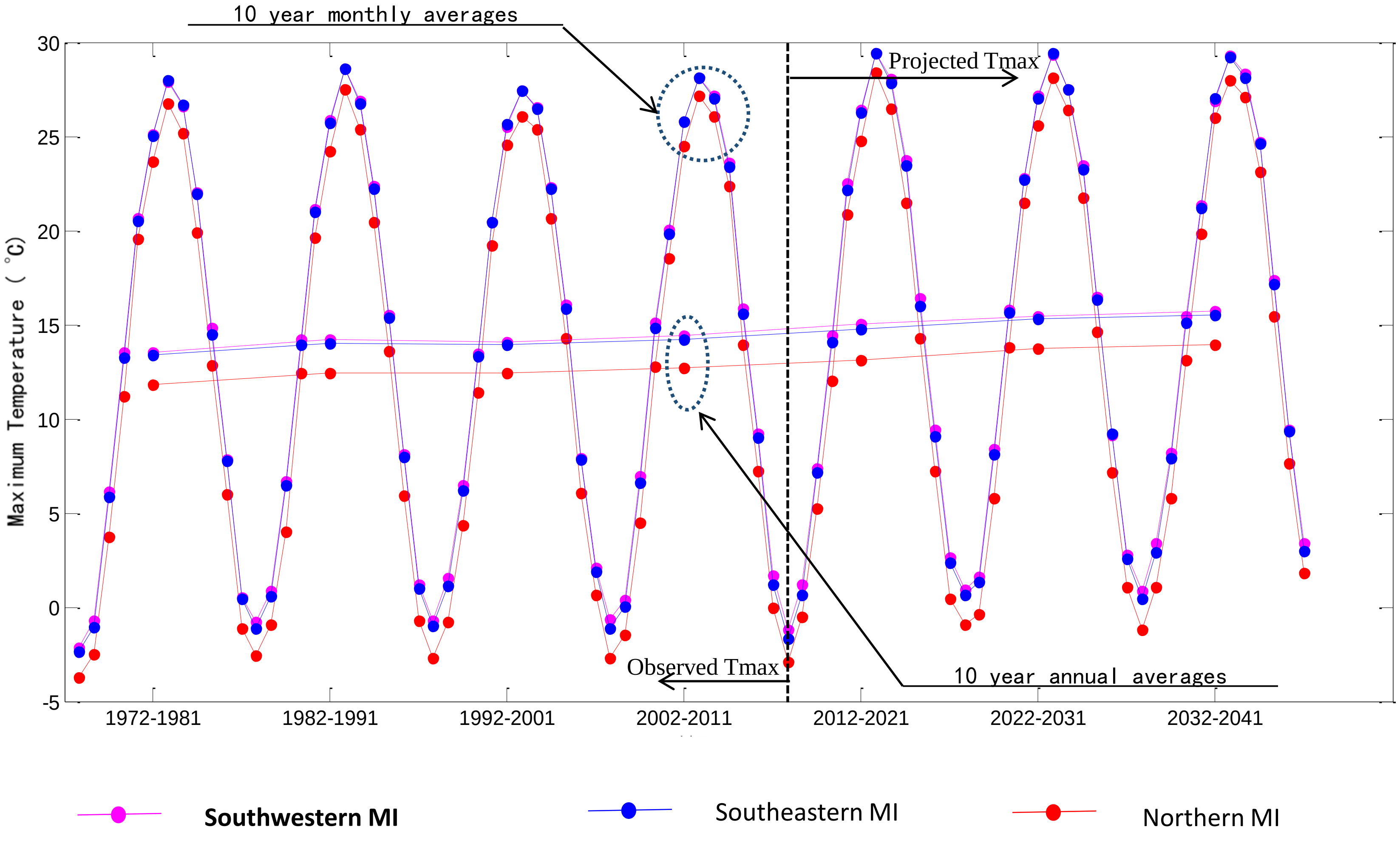
The statewide datasets were divided into three subsets based on spatial density of stations/gages so that trends could be identified separately for northern Michigan, southwestern Michigan, and southeastern Michigan.



Maximum Temperature Trend Projection

Rather than average daily temperature, the recharge model requires maximum and minimum temperatures as input. This slide presents the results from the long-term analysis of maximum temperature observations. Two sets of curves are presented for each dataset: the 10-year monthly averages (the curves with large variability) and the 10-year annual averages (the "flat" curves). Note that temperatures are consistently higher in southern Michigan than in northern Michigan, which is not surprising.

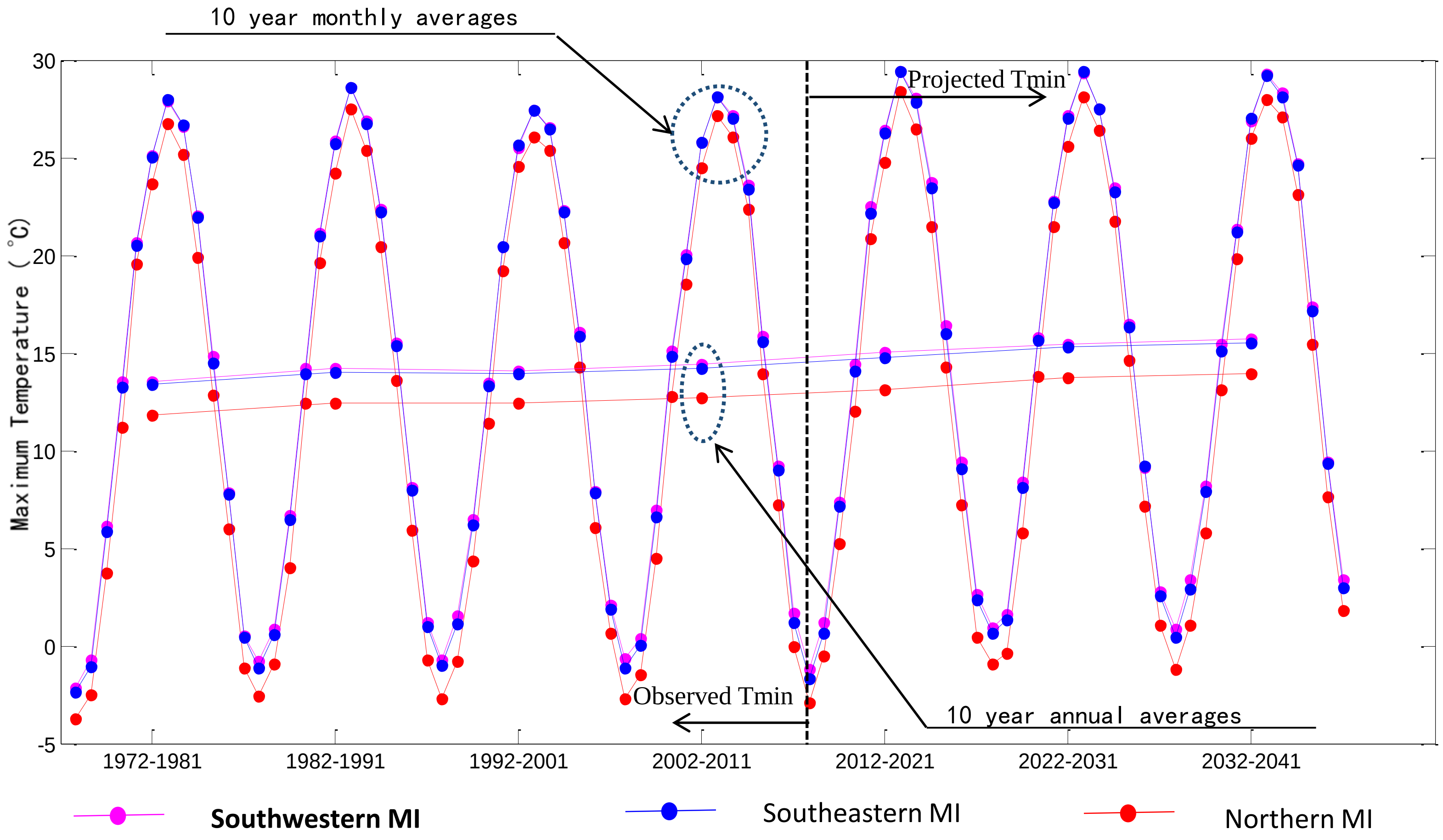
The analysis revealed a warming trend for southwestern Michigan of 0.228° C per decade. This trend was applied for adjusting "recycled" PRISM data from the past decade (2006-2016) to generate daily temperature data for 2016-2036 using the Delta. In this approach, the day-by-day temperature variations are repeated in the future simulation, but each temperature is offset using the trend from the analysis of historical data, the magnitude of the offset depending on how far into the future we wish to estimate.



Tmax Trend:
+0.228 °C every 10 years

Minimum Temperature Trend Projection

This slide presents the results from the long-term analysis of minimum temperature observations. A warming trend of 0.190° per decade was detected for southwestern Michigan, was and applied to produce adjusted PRISM datasets of minimum air temperature in the way described on the previous slide.

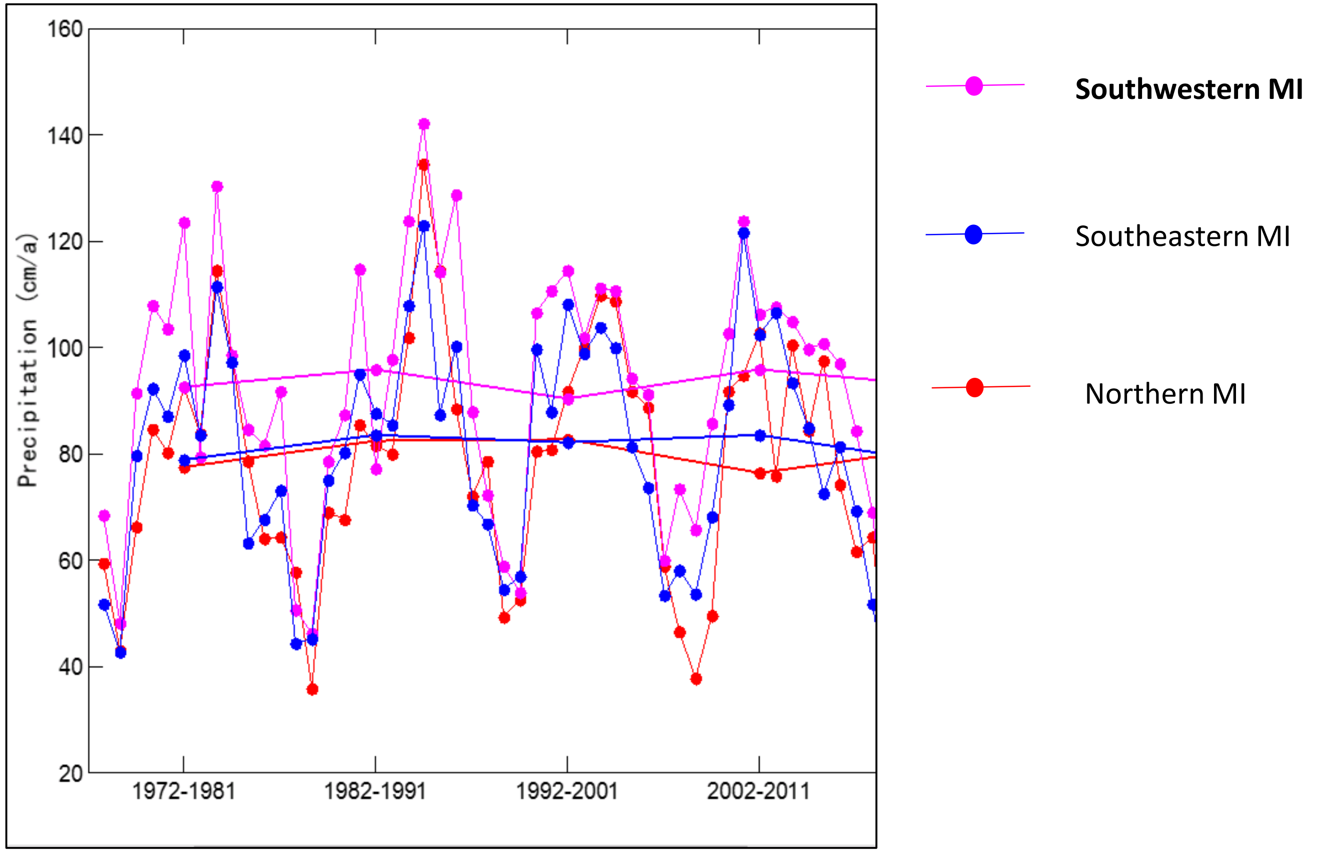


Tmin Trend:
+0.190 °C every 10 years

Long-term Precipitation Trend

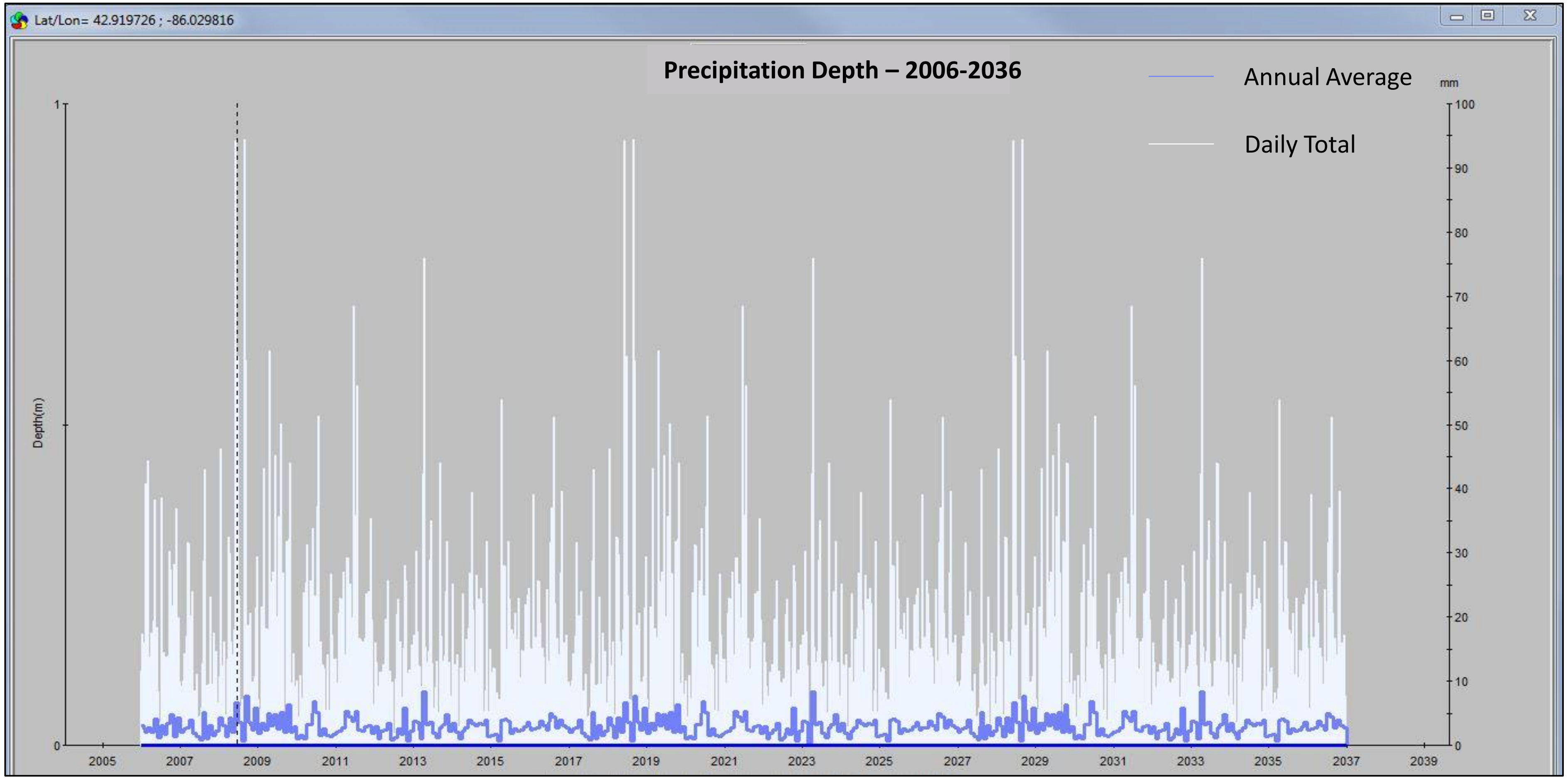
This slide presents the results from the long-term analysis of minimum precipitation observations. No clear trend was detected for southwestern Michigan, although it was clear that southwestern Michigan receives more precipitation than southeastern and northern Michigan.

Because there was clear long-term trend, precipitation patterns from the last decade (2006-2016) were simply recycled *without* using an offset (see next slide).



‘Recycled’ Precipitation Trends

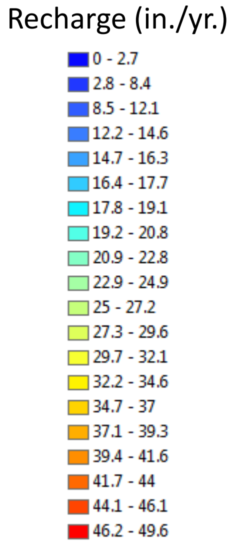
This plot shows an example of the daily total and annual average precipitation depth at a single location in the model for the time period used as a basis for recycling (2006-2016) and the time period of future simulation (2017-2036).

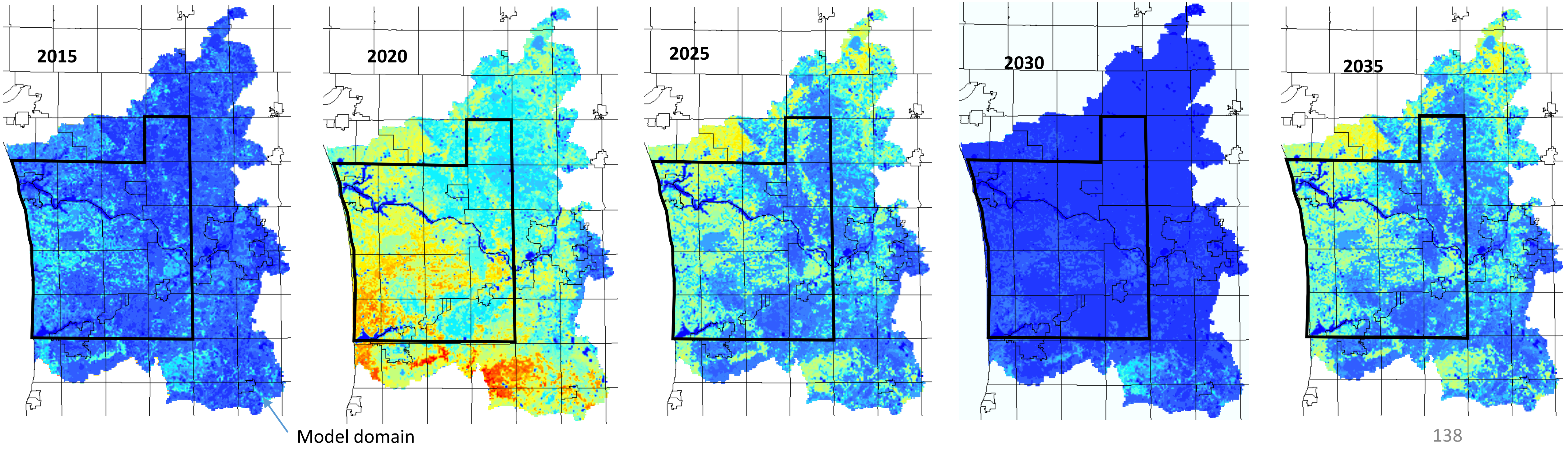


FUTURE RECHARGE PROJECTIONS

The output from the future recharge simulation was spatial maps of daily recharge, which were then computed into annual averages required for input to the groundwater model which utilized yearly time-steps. The results for 2015-2035 are shown every 5 years in the graphics below. Note that, although there is significant year-to-year variability, the spatial distribution of recharge is generally consistent across years, i.e., the areas where recharge is relatively high and where recharge is relatively low are consistent across time. The differences in magnitudes across different years is a result of year-to-year variations in weather patterns, whereas the consistency of the spatial distribution is the result of a lack large-scale changes in LULC projected for 2015-2035.

A separate recharge model that treated recycled temperature variations *without* an offset (similarly to the treatment of precipitation projections) was developed to determine the impact of future warming. The results were very similar to the results presented below (which did use an offset). Similarly, we used both future recharge scenarios as inputs to the groundwater model and observed very little difference in the flow model outputs. Therefore, the warming trend in air temperatures is not expected to significant impact recharge dynamics in Ottawa County.



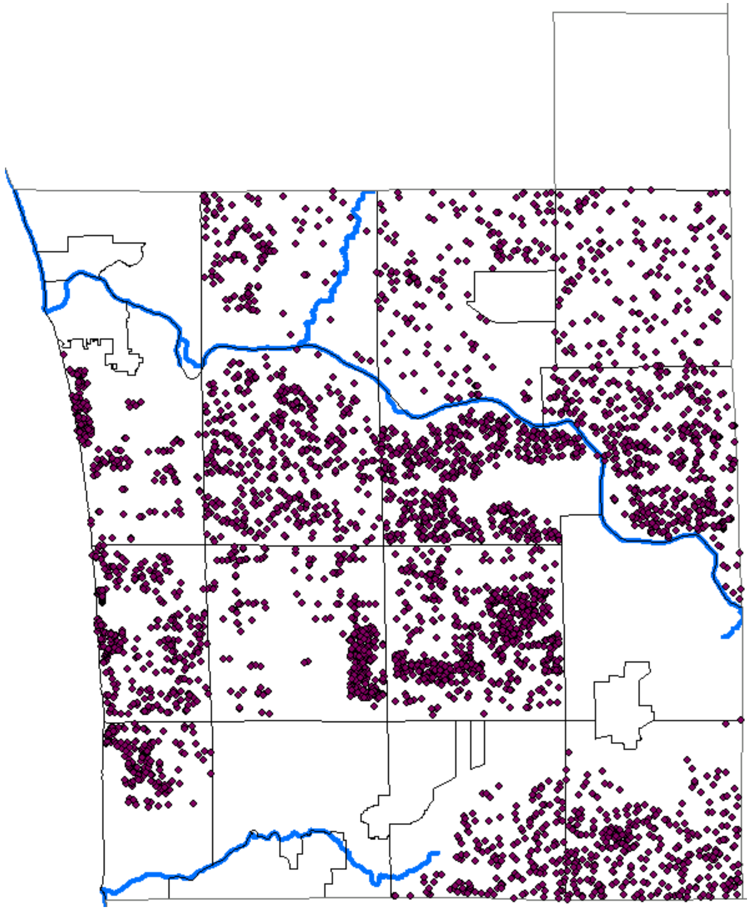


Processing Projections of New Wells

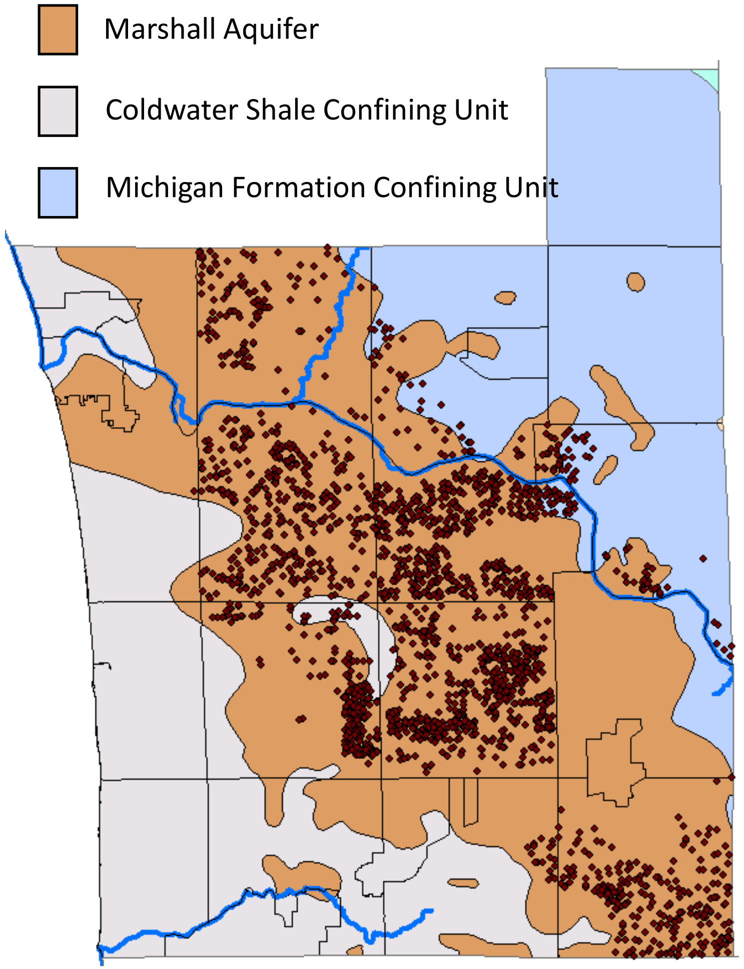
Ottawa County PPID provided two important sets of information required for modeling future groundwater use: 1) projected pumping rates of specific industrial, commercial and public supply wells; and 2) locations of 3800 new water wells (see left graphic) based on detailed zoning and infrastructure planning completed at the township level. Information regarding well type and expected time period of installation (2015-2020, 2021-2025, or 2026-2035) were included for each well.

The aquifer from (and depth at) which the new wells extract groundwater is important and must be provided as input the 3D groundwater flow model. The subsurface geology, mapped during the county-wide Geologic Modeling (see slides 50-59), was used as a guide for determining depth to each well provided by Ottawa County PPID.

The first step was to determine which wells must go into the bedrock. In other words, we needed to determine: where is the glacial aquifer likely not productive (because of extensive clay), but also where the Marshall aquifer is accessible below? The wells that satisfied these criteria were added to the fractured bedrock layer. Their locations are shown in the right graphic in this slide. Of course, in some of the locations (e.g., Jamestown Twp.), is it possible that productive "pockets" of the glacial aquifer will be encountered. However, as shown in upcoming slides, the areas where new wells are expected to impact bedrock SWLs in in areas where extensive clay is present (central Ottawa County).



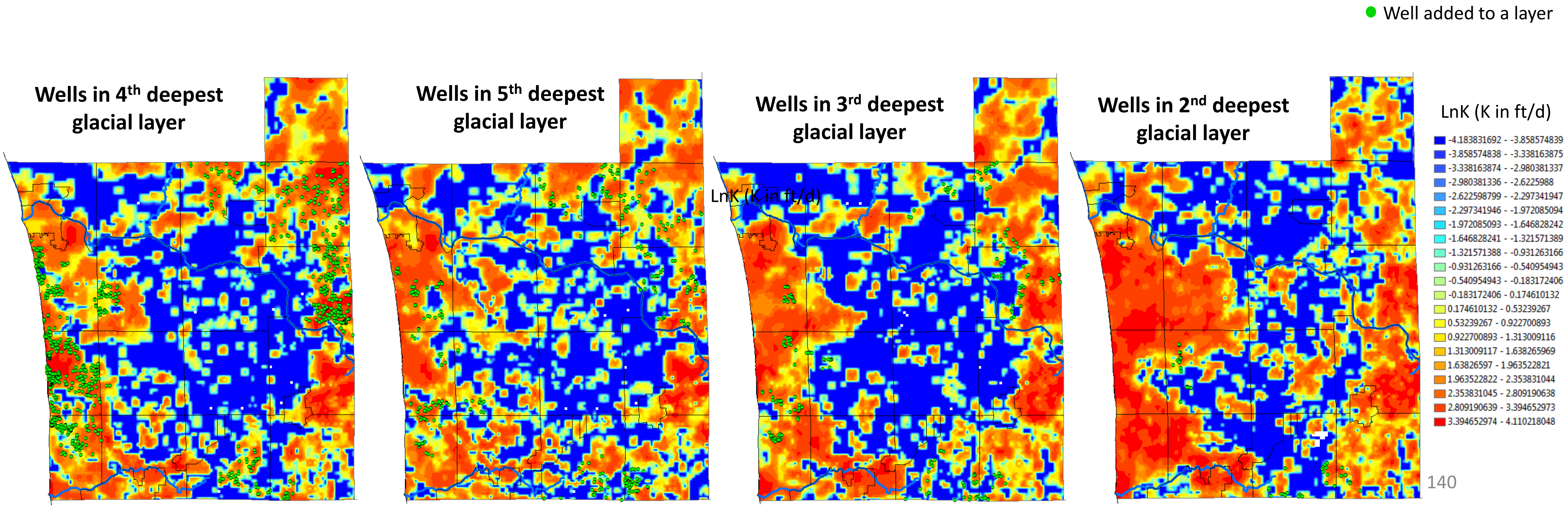
Projected New Wells Provided By Ottawa County Planning and Performance



Sub-set of wells assigned to the bedrock aquifer

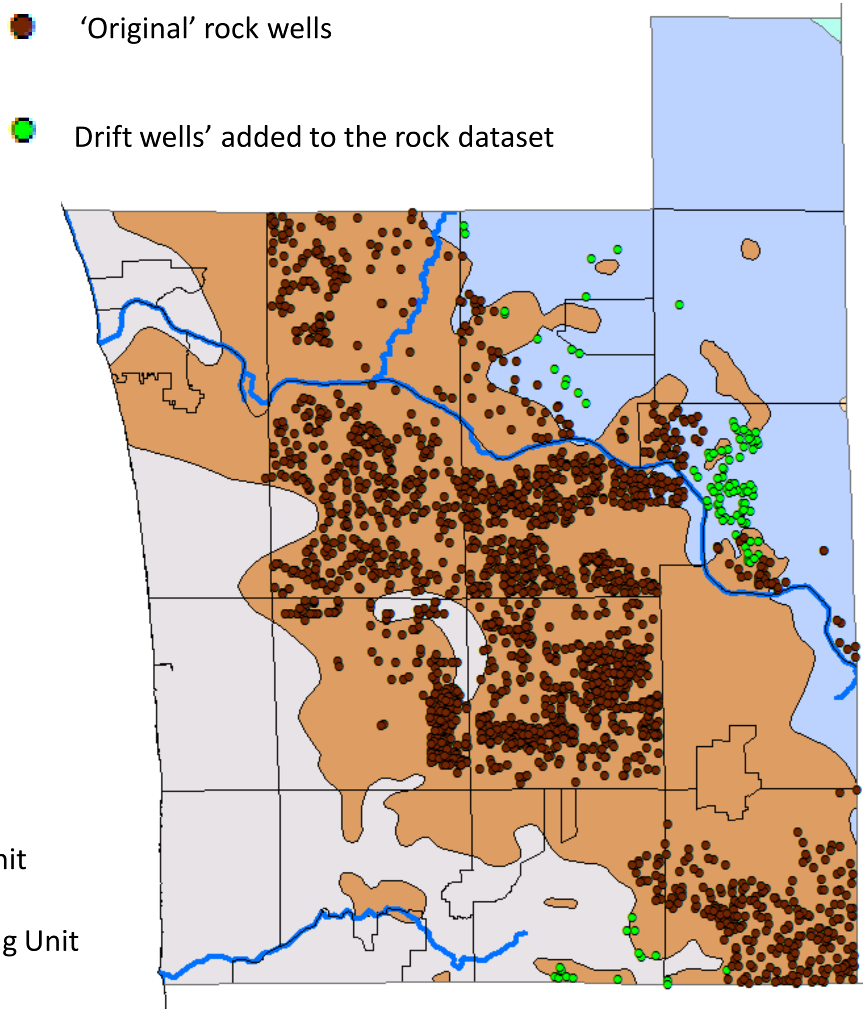
Assigning Depths to Glacial Aquifer Wells

After assigning wells to the bedrock aquifer, the remaining wells were assigned to one of the five glacial layers utilized in the countywide flow model. The hydraulic conductivity distributions from the five glacial layers were used to determine which layer was most appropriate for well screen location. First – considering that wells will go deep enough to avoid surface contamination and/or water table fluctuations/drawdown but no deeper (to save costs) – wells were overlaid to the K map of the 4th deepest glacial layer. Wells that fell in places of high expected yield (high K values) were assigned to the 4th glacial layer. The remaining wells were then overlaid to the 5th deepest layer, and the process was repeated. Any wells that were in locations of low K in the 4th and 5th deepest glacial layers were forced to go to a shallower glacial layer (layer 3 or layer 2, depending on the K distribution). The wells assigned to each glacial layer are shown below.



Wells Added the Bedrock Subset

After performing the analyses detailed on the previous two slides, there were some well locations that failed to coincide with an area of high expected yield in any of the glacial layers. Thus, these wells were added to the underlying bedrock aquifer. The locations of the wells added to the 'original bedrock' well dataset are shown as green circles in the graphic . The wells added in the northeast will need to penetrate through the Michigan Formation (confining unit), while the wells in the south will need to tap fractured bedrock along Coldwater Shale/Marshall formation interface.



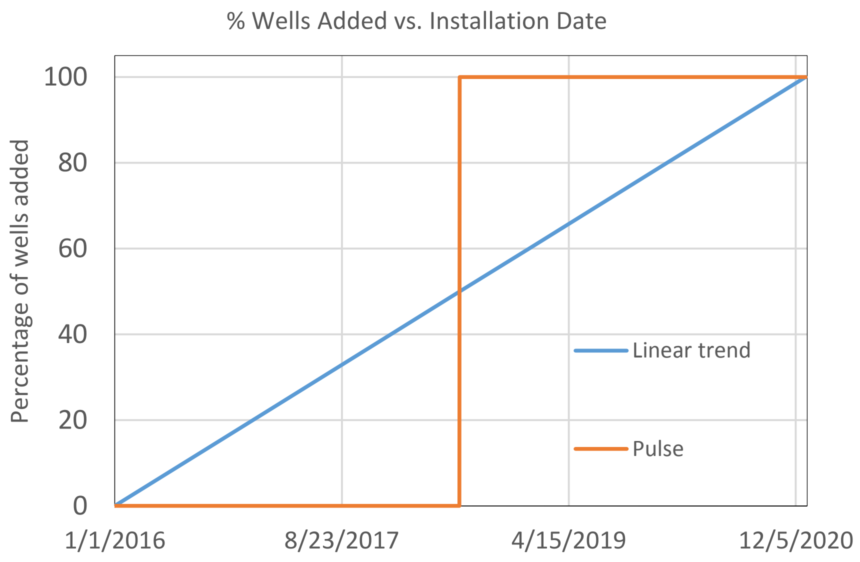
Marshall Aquifer

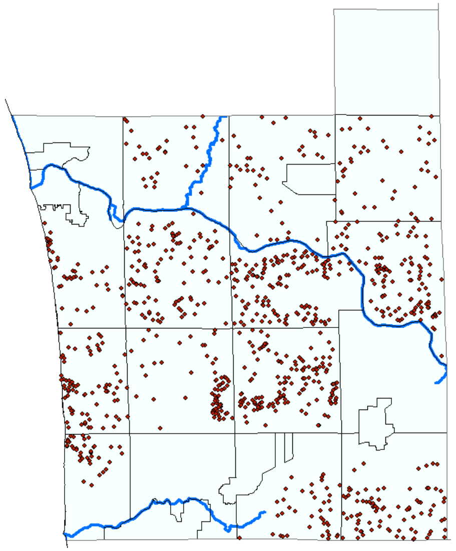
Coldwater Shale Confining Unit

Michigan Formation Confining Unit

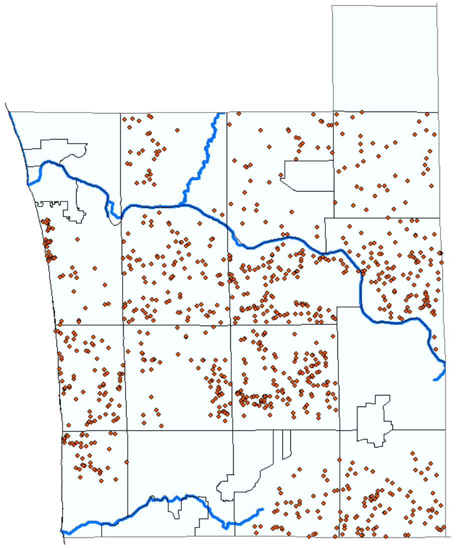
Assigning Installation Dates

It was necessary to convert the estimated time period of installation (e.g., 2015-2020) to a specific installation date for input to the groundwater flow model. A reasonable assumption is that the well installation dates are distributed evenly across the estimated time period of installation (i.e., the percentage of wells added to the model during the time period follows a linear trend – see the plot below). Without additional information, however, it is difficult to determine which wells (in which locations) to "turn on" at the appropriate date. A mathematically similar approach was used that added all wells at the half-way point of a time period of installation (a "pulse" treatment). This approach was deemed sufficient given that the key objective of the future modeling was to determine the impact of additional water use relative to 2015 conditions.

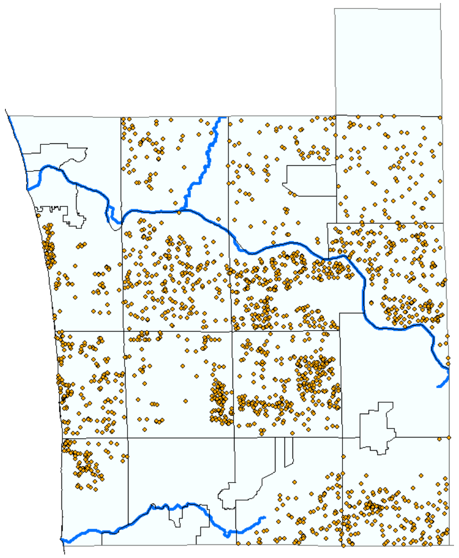




2016-2020



2020-2025

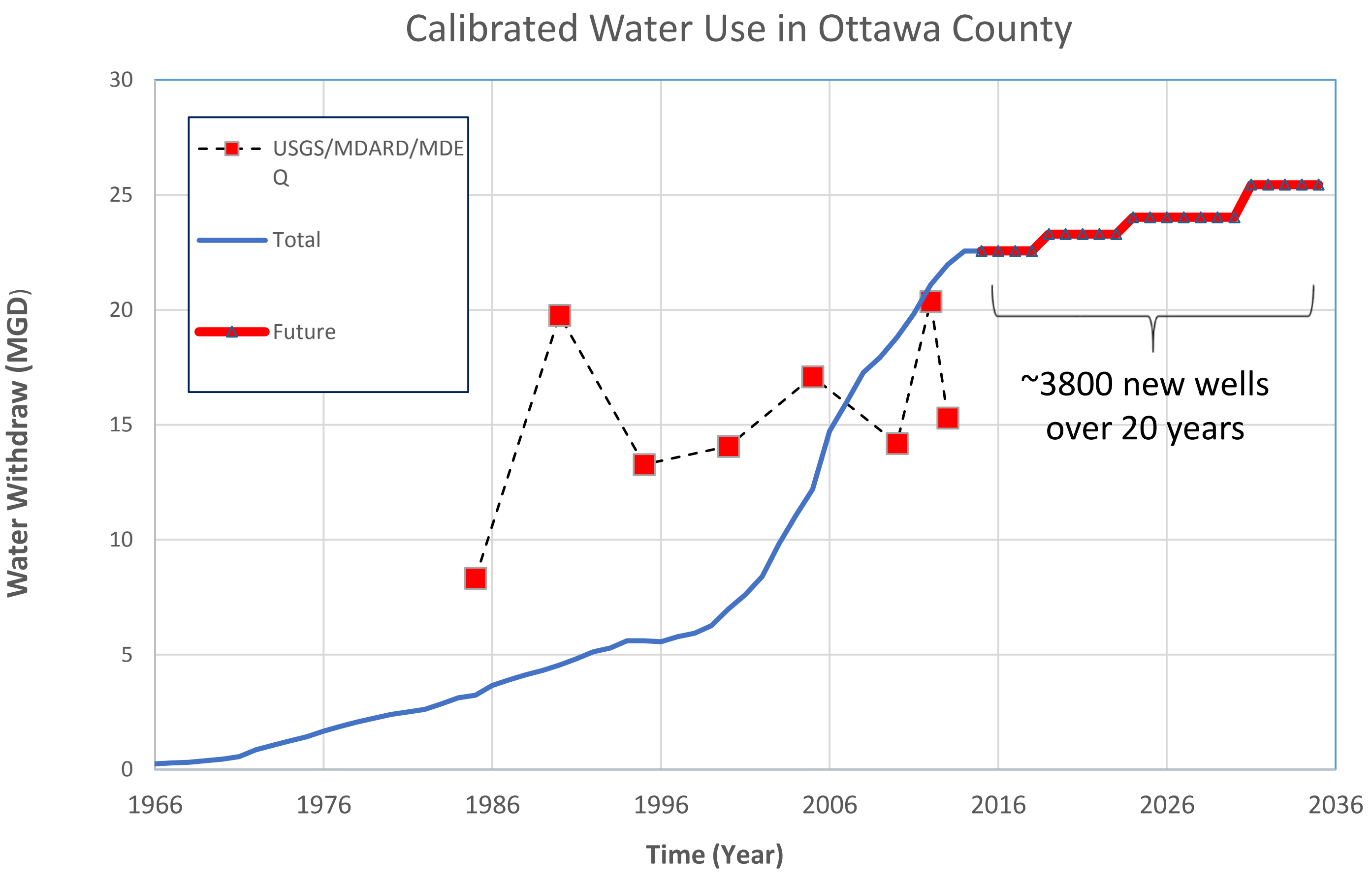


2025-2035

PROJECTED GROUNDWATER USE

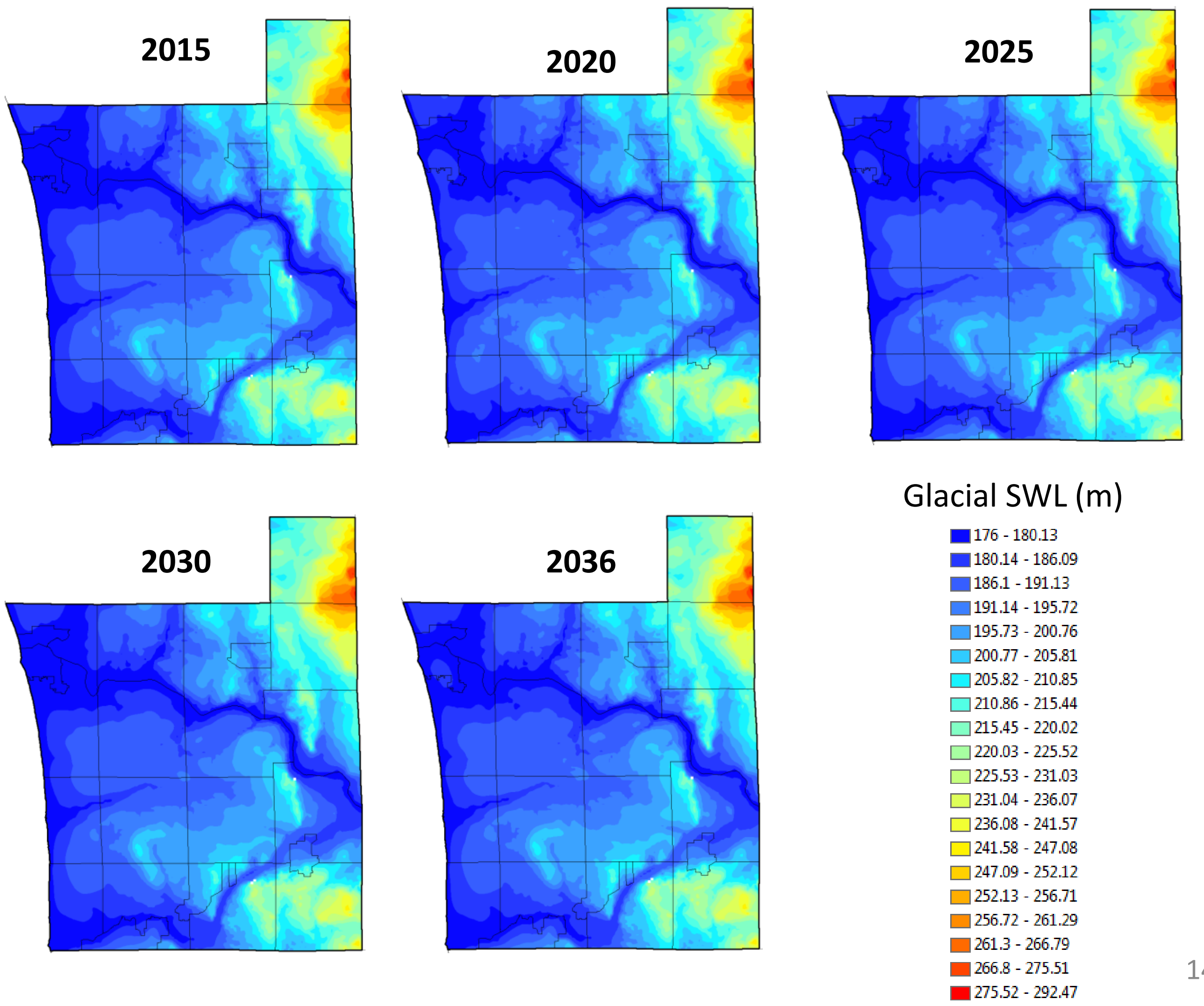
All domestic wells and irrigation wells operated at 2015 (calibrated) pumping rates , and any industrial/commercial or public supply wells that were included in the model - but which projected changes in pumping rates were not provided by Ottawa County PPID – continued operating at 2015 pumping rates.

A characterization of projected total countywide groundwater use is a helpful way to compare the future water use to past water use patterns. This slide shows the calibrated total water use (blue line in plot) and the future water use (red line with blue triangles) as a function of time. The results suggest that the rate of increase in groundwater withdrawals will decline over the next 20 years (i.e., the water use is "leveling off"). The expected increase in water use is primarily due to the expected increase in the number of domestic, small-capacity well withdrawals rather than changes in pumping rates of specific high capacity industrial/commercial and public supply wells (which may be significant locally, but not at a county-wide scale).



FUTURE SWL DYNAMICS

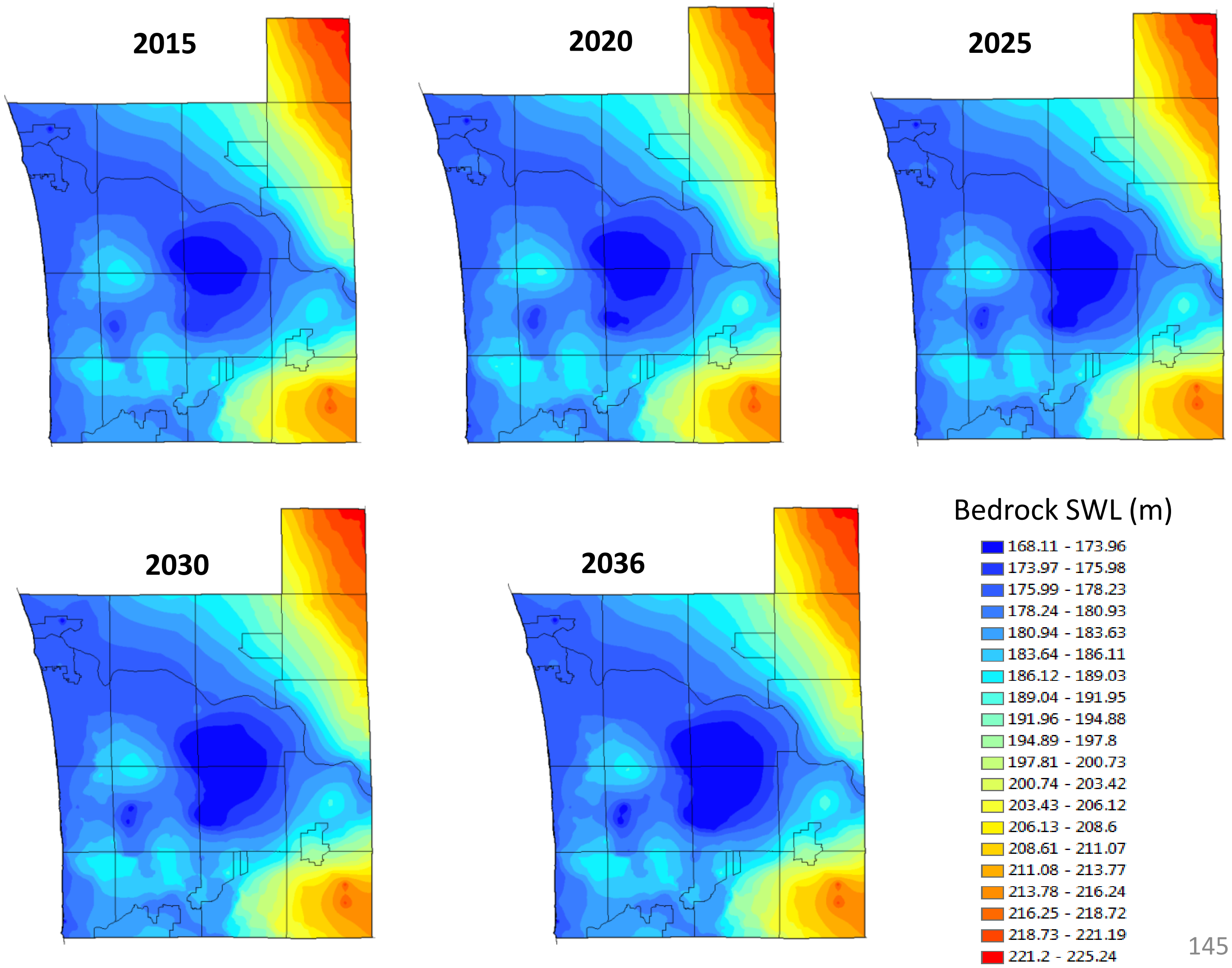
The future recharge scenario and water use model were used as input to the calibrated flow model to project flow conditions for the next 5, 10, 15 and 20 years (2016-2036). This slide presents the projected SWL distributions for the glacial aquifer. The results suggest that future wells withdrawals and expected recharge are not expected to significantly impact glacial SWLs, at least at the scales modeled in this study (300m x 300m).



Future SWL Dynamics – Bedrock Aquifer

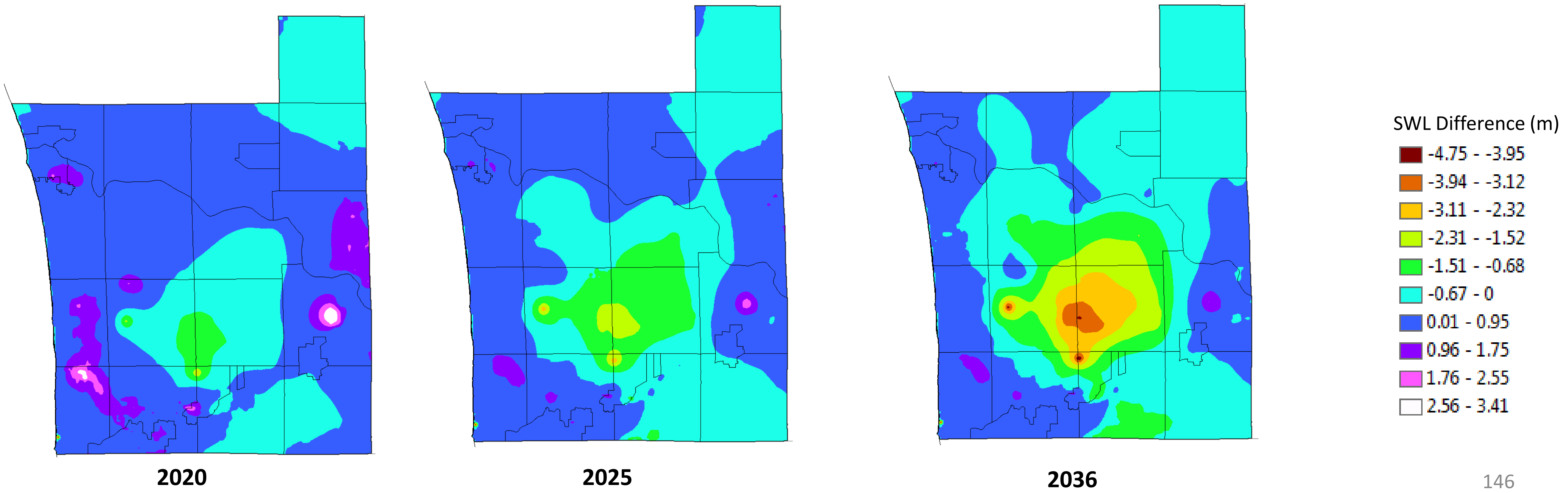
This slide presents projected SWL distributions for the bedrock aquifer. In contrast to the glacial aquifer, there are notable changes to the SWL distributions in the bedrock aquifer over time. In particular, decreases in SWL are predicted for west Olive Township, Blendon Township, and parts of Allendale, Zeeland, and Robinson Townships. Bedrock SWLs are not expected to undergo significant changes along the Lake Michigan coast or in the northeastern or southern portions of the County.

The next few slides quantify the changes in bedrock SWLs.



SWL Changes – Relative to 2015 SWLs

This slide presents spatial maps of the projected bedrock SWL change relative to the 2015 SWL distribution. The SWL difference was computed by subtracting the 2015 SWL value from the future SWL value for the given year of interest for each model cell (thus, negative SWL Difference values represent places where SWL decline is projected). The maps help to visualize the expected SWL changes in more detail. As mentioned on the previous slide, most of the significant SWL decline (>1.5 m) is expected to occur in the central portion of the County. The largest declines are expected to occur in west Blendon/east Olive Township and in west-central Olive Township.

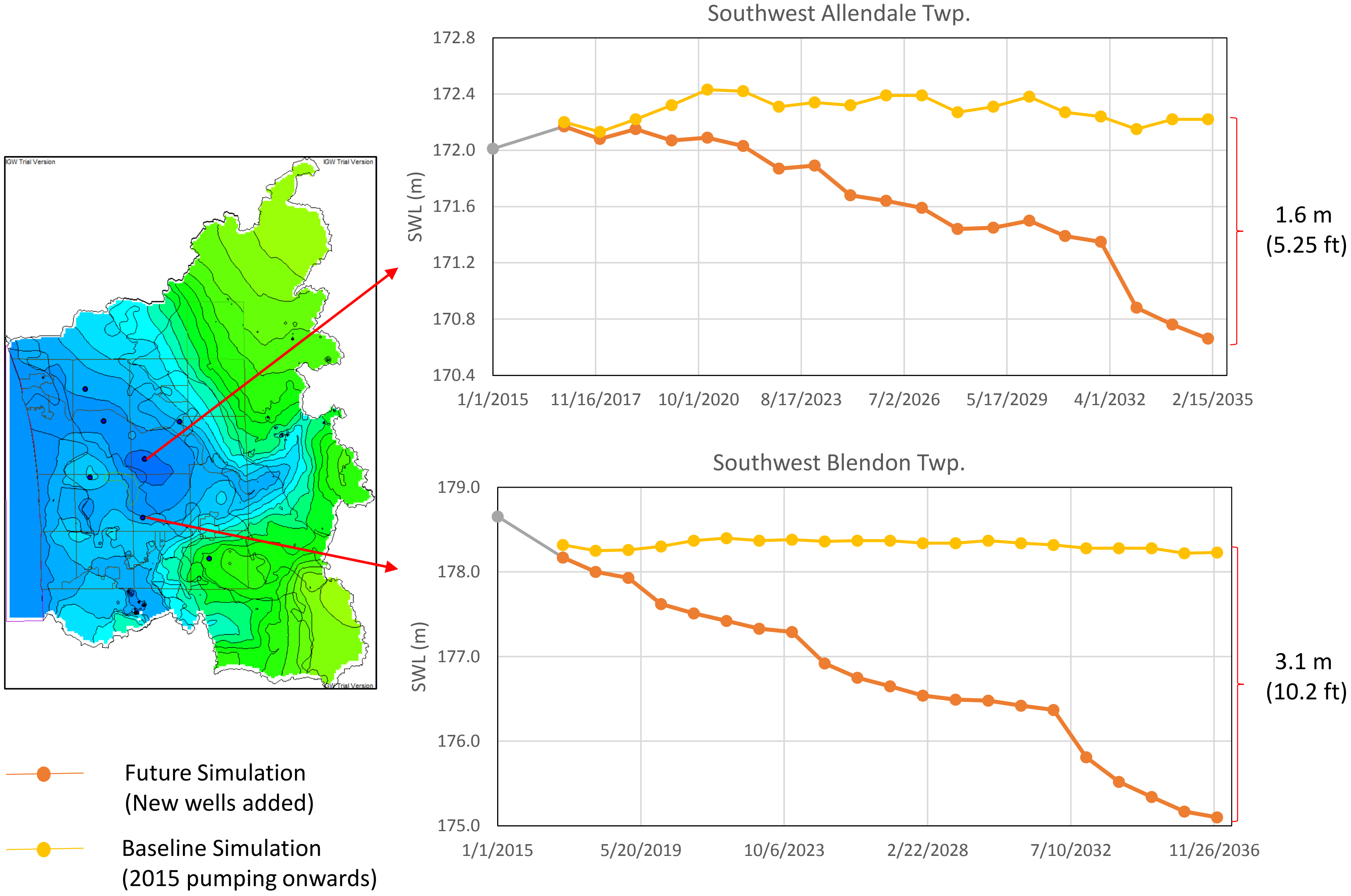


IMPACT OF ADDITIONAL PUMPING

To determine the impact of adding new wells to the aquifer system over the next 20 years, a “baseline” simulation was executed and compared to the future simulation. In the baseline model, new wells were not added for the 2016-2036 time period (i.e., the 2015 pumping configuration was applied ‘as is’ throughout the simulation). Both simulations used as input the future recharge estimates based on changes in LULC and projected temperature, and thus, and differences in their results can be attributed to additional groundwater withdrawals.

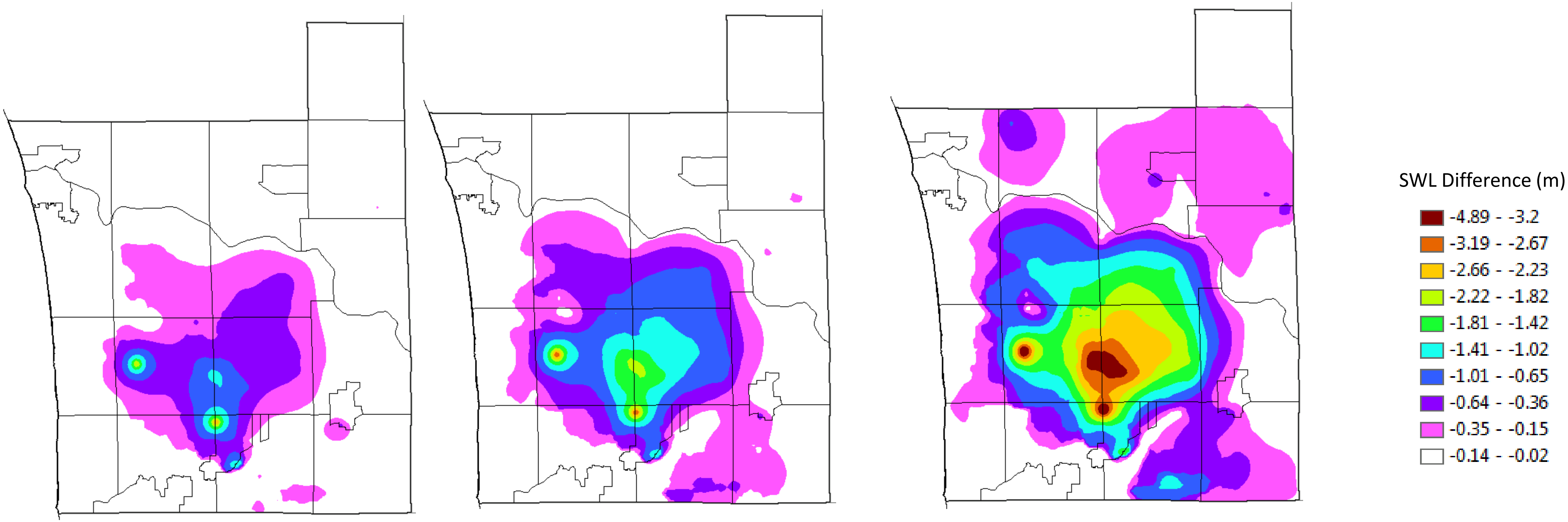
The plots shown here show the bedrock SWL output from each simulation for two point locations in central Ottawa County. As expected, the results are similar for the near future, but with time, additional pumping results in lower SWLs because of additional wells pumping the aquifer system. Also note that the SWL variability due to recharge – as expressed in the baseline simulation curves – is significantly less than the SWL decline caused by pumping in the bedrock aquifer.

Similar comparisons were made for the glacial aquifer, although the SWL differences due to pumping were consistently less than the variability due to recharge.



Impact Of Future Well Withdrawals – Spatial Maps

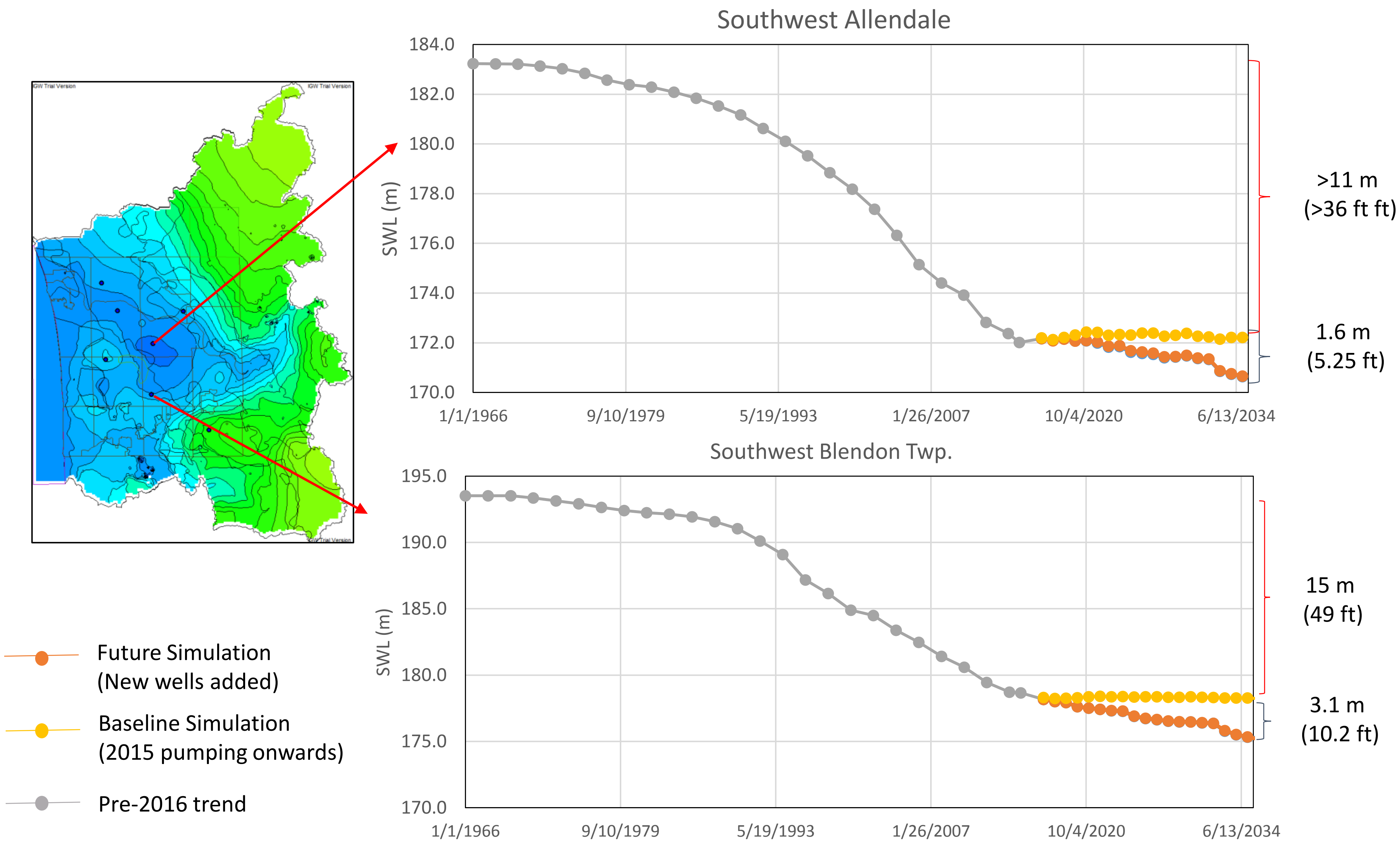
The simulation comparison outlined on the previous slide was completed for all model locations (bedrock aquifer) to generate spatial maps of the impact of pumping. These maps were generated for 5, 10, and 20 years into the future (see below). The SWL difference was computed by subtracting the baseline simulation SWL result from the future simulation SWL (negative numbers indicate SWL decline due to pumping). The maps indicate that the most significant decline due to pumping is likely to occur in Blendon and Olive Townships, while modest pumping-induced decline is expected for Robinson, Zeeland and Allendale Township.



2020 **2025** **2036**

Comparison: SWL Change Before & After 2016

While the projected increases in groundwater withdrawals are expected to result in SWL decline in parts of the bedrock aquifer, it is insightful to consider the impact relative to historical trends. The plots shown here are for the same two locations shown in Slide 147, but now include the historical (pre-2016) trend. Clearly, these plots suggest that SWL decline experienced over the previous 50 years (1966-2015) is much more than the SWL decline expected to occur over the next 20 years (2016-2036) based on projections of well buildouts provided by Ottawa County PPID.



Aquifer System “Stabilization”

The “flat” behavior of the baseline simulation curves shown in the previous slides suggests that the bedrock aquifer is able to stabilize relatively quickly once additional wells are no longer add to the system. (Note that there is always a delayed response (e.g., a few years) in the groundwater system to changes in pumping. In addition, the water table will fluctuate in response to natural changes in the environment (e.g., dynamic recharge), although the fluctuations are small compared to changes in groundwater levels across the system.)

The idea that groundwater system will eventually reach this “dynamic equilibrium” in the event that no additional well can be understood as follows:

- Once a network of wells begins operating, the water table (groundwater head) begins to decrease in response to the withdrawals.
- This decrease continues with time, but the surrounding groundwater system will slowly respond/adjust so that the rate of drawdown decreases. Eventually (e.g., after a few years), groundwater levels stabilize as pumping is fully compensated by changes in flow system (i.e., a new dynamic equilibrium is established).

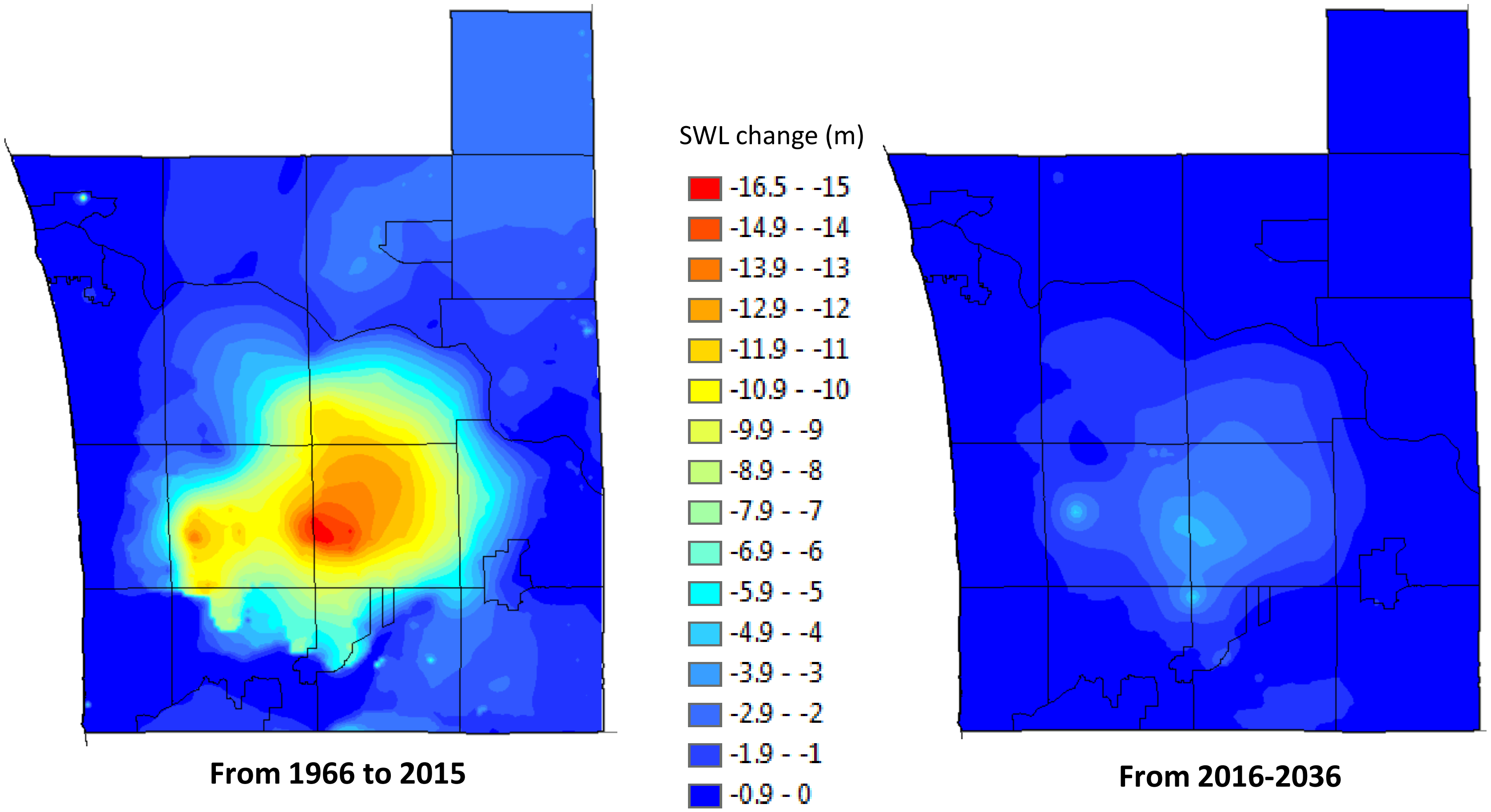
A groundwater system might compensate for withdrawals by inducing more infiltration of water from the surface (a lake or stream, for example), or by reducing flow downstream (e.g., to discharge points along major streams). Generally speaking, Ottawa County lies within in a major regional discharge zone, and although the clay layer of central Ottawa County was found to be very restrictive to the movement of groundwater, data from early portions of the study period (1960s and 1970s) show that bedrock groundwater discharges toward gaining streams (especially the Grand River), even though it is significantly less discharge than that contributed by the glacial aquifer. Thus, rather than inducing recharge from surface water bodies, increases in pumping have resulted in reduced discharge to surface water bodies. This impact is distributed throughout the dense/strong surface water network of Ottawa County and may thus not be easily noticed.

Township-by-township water balance analyses also suggested that some changes in lateral and vertical flows between parts of the aquifer system have compensated for increases in withdrawals (see the Calibrated Model Results in the Technical Report).

Drawdown Comparison: Before and After 2016

This slide presented extends the analysis of the previous slide to all locations in the bedrock layer of the groundwater model. The left-most graphic provides a spatial map of the SWL decline occurring during the 1966-2015 time period, while the right-most graphic shows the expected SWL decline over the next 20 years. The changes during the past 50 years are greater in magnitude and extent.

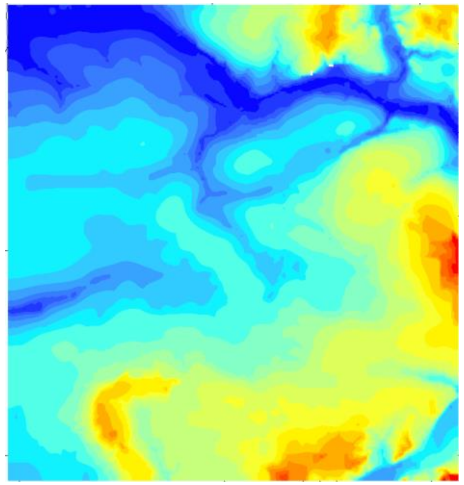
The analysis suggests that the rate of SWL will slow down, although SWLs will still be significantly less than “natural” (1966) SWLs in many parts of the bedrock aquifer. This has important implications for water quality: the low SWLs will continue to induce migration of Cl-laden water away from its natural path of discharge to the Grand River and its tributaries. This is also discussed on slides 126-127.



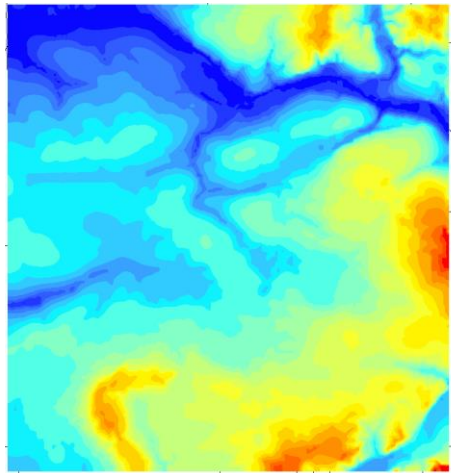
From 1966 to 2015 **From 2016-2036**

SUBMODEL SWL PROJECTIONS

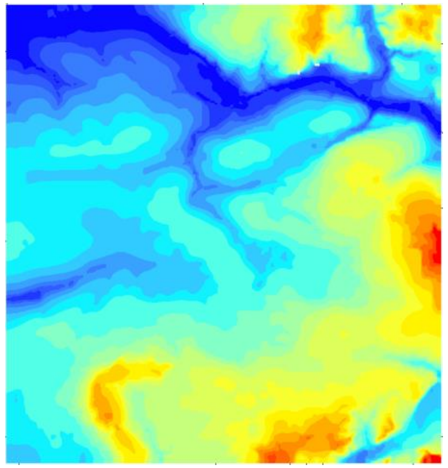
The future simulation was applied to the submodel area developed for the ‘hot-spot’ dynamics analysis to provide more details of SWL variability. This slide presents projected SWL results for the glacial aquifer at different times in the future. Similar to the countywide future simulation, it is difficult to notice any significant changes in glacial SWLs over the next 20 years. Note that, because of the extensive clay layer present throughout the submodel, new wells were added to the bedrock aquifer, and thus the consistent SWL results across time suggests that the variability induced by dynamic recharge is much less than the spatial SWL variability.



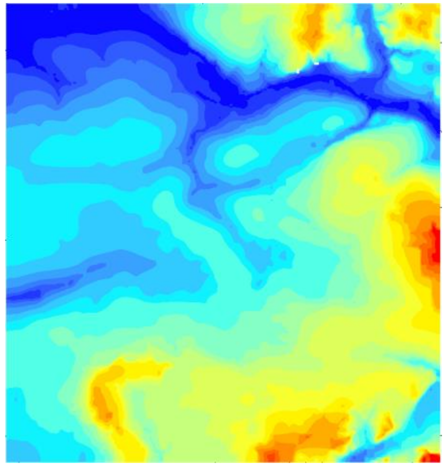
2016



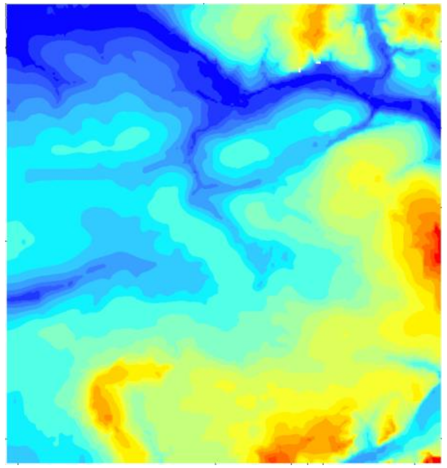
2020



2025



2030



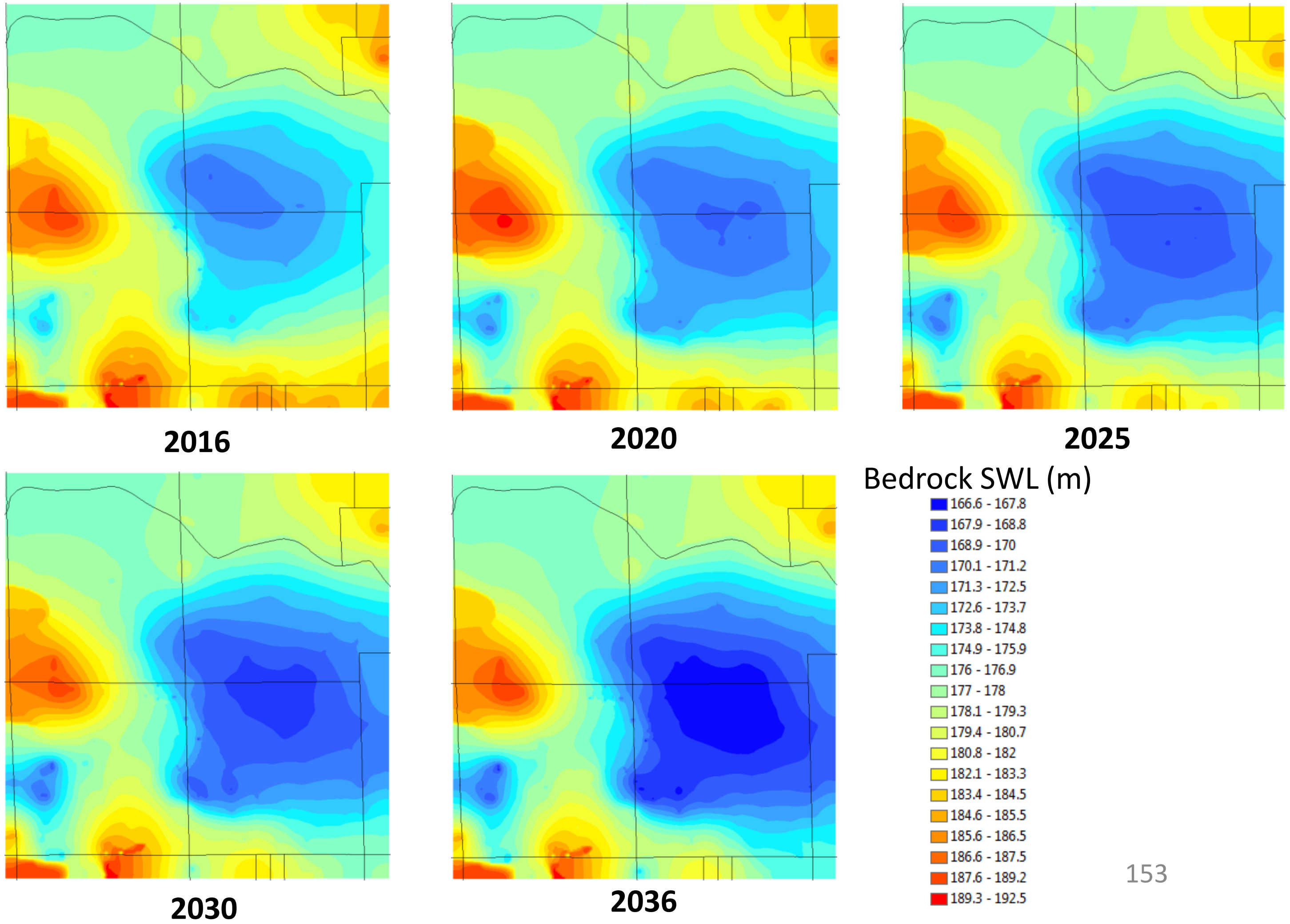
2036

Glacial SWL (m)

- 166.6 - 167.8
- 167.9 - 168.8
- 168.9 - 170
- 170.1 - 171.2
- 171.3 - 172.5
- 172.6 - 173.7
- 173.8 - 174.8
- 174.9 - 175.9
- 176 - 176.9
- 177 - 178
- 178.1 - 179.3
- 179.4 - 180.7
- 180.8 - 182
- 182.1 - 183.3
- 183.4 - 184.5
- 184.6 - 185.5
- 185.6 - 186.5
- 186.6 - 187.5
- 187.6 - 189.2
- 189.3 - 192.5

Submodel SWL Projections – Bedrock Aquifer

This slide presents projected submodel SWL results for the bedrock aquifer. Static water level decline can be seen in many parts of the submodel, with the most significant changes predicted to occur in west Olive Township and west-central Blendon Township. More modest changes are predicted to occur along the Olive Twp. – Robinson Twp. and Blendon Twp. – Zeeland Twp. borders.



Challenges of Quantifying Cl in the Future

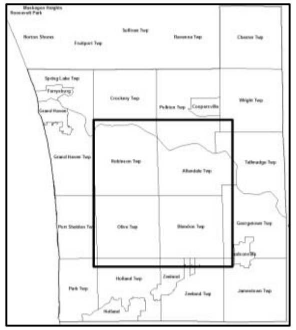
Simulating transport of solutes groundwater (in this case, Cl concentrations across space and over time) requires: 1) an accurate depiction of the dynamic flow field that is controlled by the geology and stress framework (e.g. recharge and pumping); and 2) characterization of the nature of the source (i.e., how the source concentration changes over time and/or space).

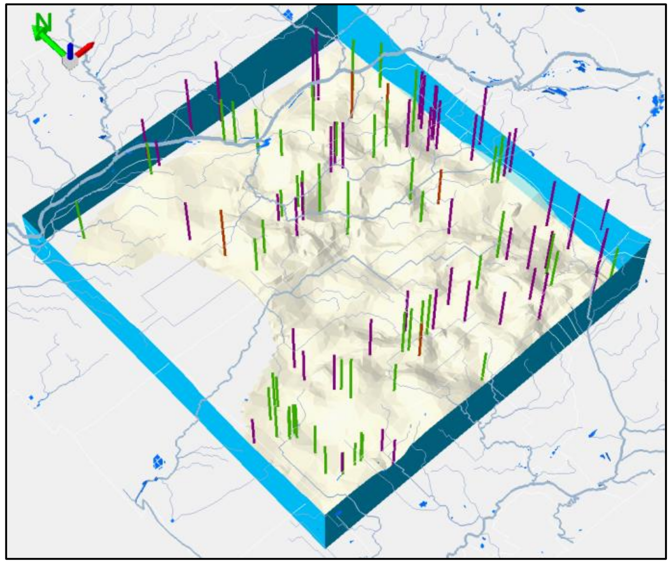
We are confident that the calibrated flow model is able to reasonably simulate the 3D flow field based on the projections of groundwater use, climate trends, etc. We are also confident that we captured the 3D variability of the “shallow” Cl plume that is impacting water wells in Ottawa County. The shallow plume is being “fed” by the deeper pool of brines down-dip of the part of the bedrock aquifer being used by water wells in Ottawa County. Because water wells were the sole source of Cl data used in this study, little/no information was available to characterize the deep source. This lack of information about the deep source feeding the shallow Cl plume means that the results of the chloride transport may be wrong/misleading.

Note that, in spite of this challenge, we did seek to better understand water quality implications of the modeling results by performing 3D particle tracking of deep bedrock groundwater flow for future conditions (see next slide).

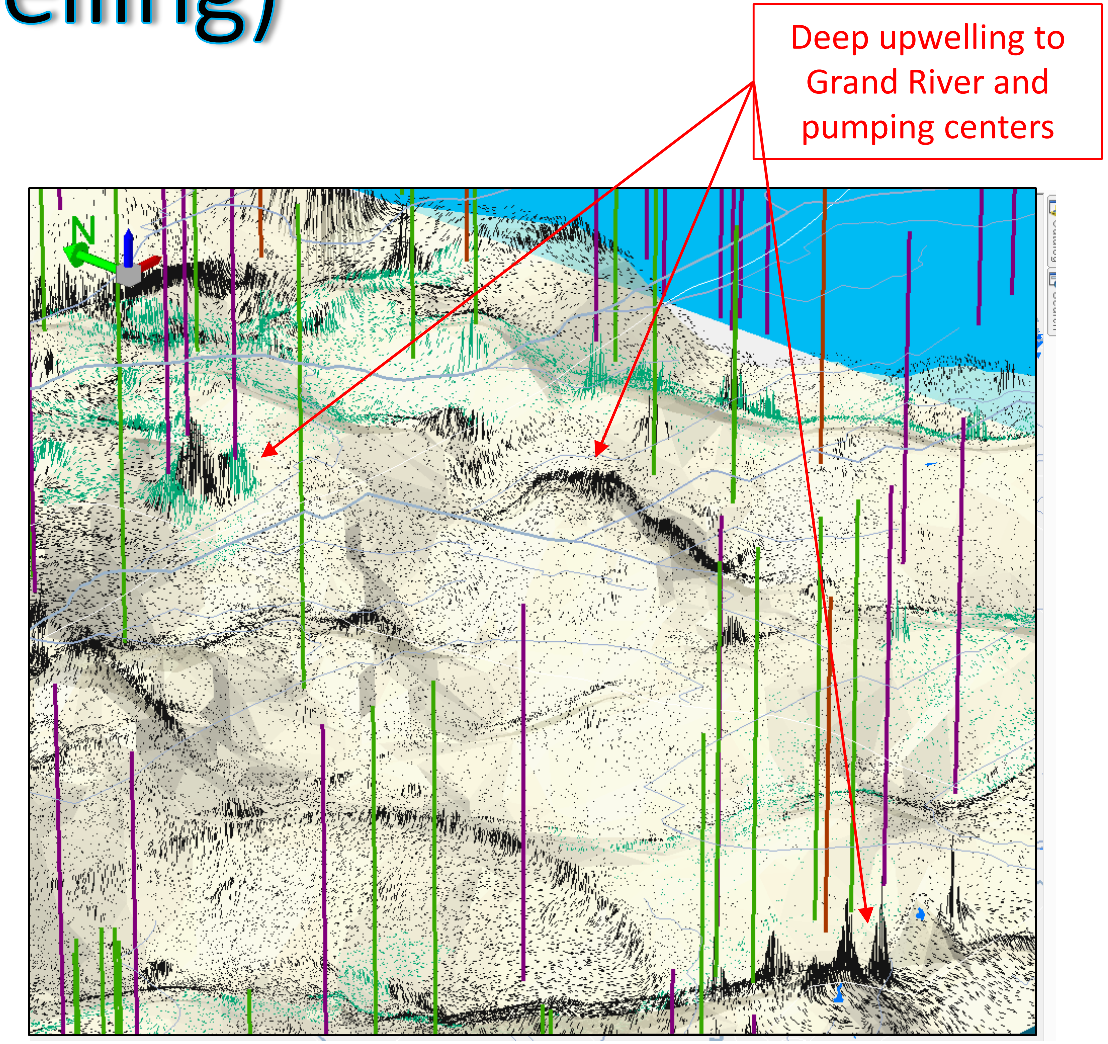
Sub-modeling To Visualize 3D flow (Deep Upwelling)

The 3D particle tracking approach described on slide 123 was applied to the future submodel simulation results. Shown below is the particle release surface with the high-capacity wells present in the submodel. On the right are the particle flow paths after 20 years of simulation. Upwelling of deeper groundwater to pumping centers and the Grand River can clearly be seen. This water contains high Cl concentrations and may be problematic from a water quality perspective, depending on the potential use of groundwater (e.g., for crop production).





“Particle Release Surface”
(18 m below bedrock wells)



Particle flow paths
(20 years of simulation)

SUMMARY OF FINDINGS FROM FUTURE MODELING

- Future recharge conditions and projected pumping is not expected to cause large-scale changes to SWLs in the glacial aquifer
- Increases in the number of wells will result in continued SWL decline in parts of the bedrock aquifer over the next 20 years
- However, this decline is much less than the SWL decline for the 1966-2015 time period (rate of SWL decline is slowing down)
- Deep upwelling of saline water will still impact water quality, and thus deep rock wells in “hot-spot” should consider the intended use of the water (i.e., one should ask: what is the acceptable Cl concentration?) or the use of an alternative water supply.

SUGGESTIONS FOR FUTURE MONITORING

Reflections on Phase II Data Availability and Flow Model Calibration

The core mandate of this project was to quantify the sustainability of the county-wide aquifer system. Sustainability – although experienced locally – is controlled by the overall, long-term system dynamics – how the characteristics of the system (e.g., groundwater levels) change over space and time in response to the geologic setting and system stresses (e.g., changes in recharge and groundwater pumping). Process-based computer simulations of groundwater systems make it possible to characterize how the system changes at different locations and times of interest, but require calibration (or "fine-tuning") through comparison of simulated outputs with real-world observations.

As mentioned on slide 44, ideally numerous monitoring wells distributed relatively evenly throughout the aquifer would be used to collect time-series of groundwater levels for flow model calibration. Indeed, in many long-term studies of aquifer systems, e.g., regional investigations by the U.S. Geological Survey (USGS), monitoring well networks are established and operated for several/many years so that long-term groundwater level data are available for model calibration. In Ottawa County, however, no USGS monitoring wells were available, and water level data available from scattered MDEQ Environmental Sites of Concern were almost exclusively related to point-measurements of the shallow water table over a limited time period (i.e., several weeks or months). Moreover, given the budget constraints and the fact that the modeling and analysis was to be completed in a few years, it was not feasible to establish a new monitoring network for the purposes of the study.

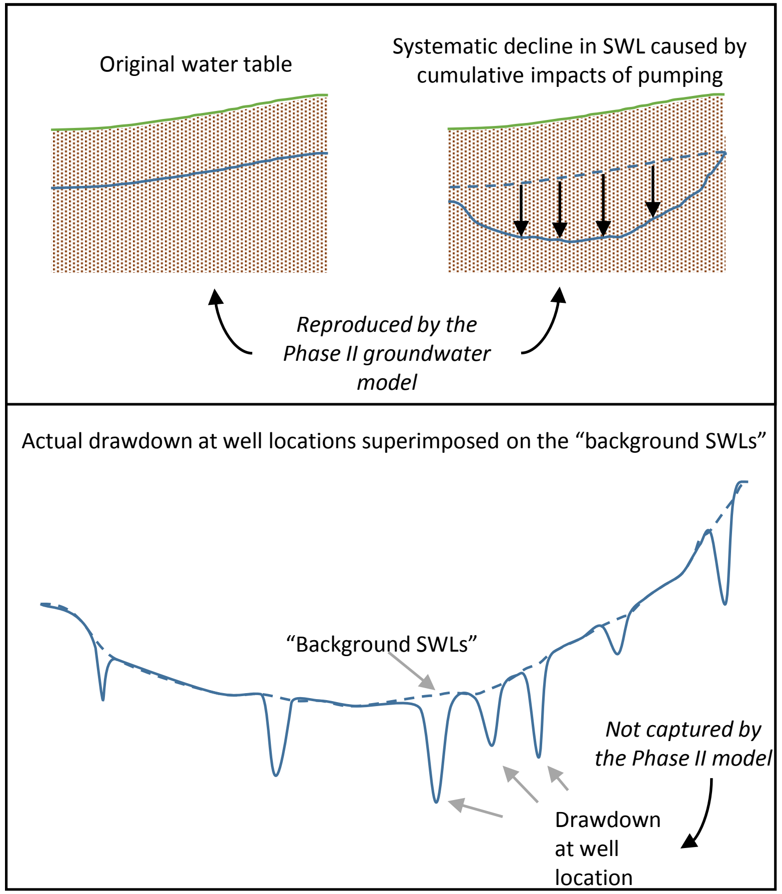
It is for these reasons that thousands of SWL measurements – made at single points in time but distributed throughout the aquifer system – were used to calibrate the county-wide groundwater model. By aggregating many SWL taken at different times within a relatively small area (e.g., for an entire township), it was possible to detect systematic changes in groundwater levels that would be observed with a single monitoring well. This is because in many cases the decreases in groundwater levels that have occurred over the past 50 years are larger than the SWL variability caused by spatial aggregation of observation data and noise in the measurements themselves. Thus, this approach was not only effective for the purposes of quantifying SWL changes controlling the sustainability of the county-wide aquifer system, but necessary given limited resources available for new data collection.

Challenges of Estimating Future Sustainability

There are, however, *limitations* in the modeling approach used in Phase II worth noting. First – although the SWL dataset allowed for ‘township-by-township’ analysis of water level changes, the substantial SWL variability caused by measurement error, temporal variations, and spatial inaccuracies makes its difficult to verify model predictions at smaller (sub-township scales). Second - even the regional model is able to detect/replicate systematic decline in the groundwater elevations, the drawdown at a single well is in reality larger than what is being simulated by the groundwater model. This is because:

a. in order to construct a model that can be executed with available computational resources - the model uses a cell size of 300m (countywide) or 100m (submodel). The use of "representative" cells for a contiguous area tends to smooth out the sharp changes in SWLs near a well; and
b. the wells in our model use long-term “effective rates” (as if the pumping was spread out over an entire year). In reality, wells pumping at rates higher than the effective rates for discrete amounts of time. During the pumping period, the drawdown will be larger than the “background” drawdown characterized by the groundwater model (see graphic on right).

For these reasons, it is difficult to determine precisely when a particular well (current or future) faces groundwater sustainability issues, such as a lack of water available at the well screen location (“dry wells”).



SUGGESTED FUTURE ANALYSIS: COUNTYWIDE WELL-SCALE PREDICTION

Estimating timelines for well sustainability requires answering: will groundwater continue to be available at the well screen elevation of a current or future well? The best way to address this in a quantitative manner is to map sustainable yield at the well-scale, across the entire county. This work would be focused on providing guidance on "limiting situations" of groundwater levels – those that occur when groundwater pumping is at its largest and recharge is lowest (i.e., during the dry season). The analysis would be complemented by continued monitoring of groundwater levels and salinity (see slide 162) to refine local understanding and inform management. The specific tasks include:

A. Countywide (300m) mapping of "background" SWLs during dry season, present day and over time (through 2036):

- Develop realistic irrigation pumping rates based on seasonal variability
- Run the groundwater model at a finer temporal resolution to capture seasonal variability in SWLs
- Map dry season SWLs across the county

B. Countywide (300m) determination of available drawdown, present day and over time (through 2036)

- Analyze water well logs and other sources of information to determine and map useable aquifer bedrock thickness; map useable glacial aquifer thickness
- Map available drawdown based on background SWLs and useable aquifer thickness

C. Countywide, plot-scale (e.g., 100 ft) mapping of sustainable yield at based on water quantity

- Estimate drawdown at well-scale (i.e., at the well borehole location) for different well types (e.g., domestic, public supply, etc.) using analytical solutions and local aquifer parameters (e.g., useable aquifer thickness, transmissivity).
- Superimpose analytical solutions on background SWLs to generate plot-scale predictions
- Determine and map sustainable yield based on comparison of available drawdown and plot-scale groundwater levels

Groundwater use may also be limited by water quality (high chloride concentrations), and thus an additional task is suggested:

D. Countywide, plot-scale mapping of sustainable yield based on chloride concentrations
- Map elevation where groundwater is of a particular Cl^- concentration (e.g., 250 mg/L) using the results from the 3D spatial interpolation of Cl concentrations (Phase II)
- Determining sustainable yield based on comparison of plot-scale groundwater levels and elevations where groundwater is of a particular Cl^- concentration

Finally, because the Phase I study noted the occurrence of elevated nitrate concentrations in parts of the aquifer system, is it suggested that a task related to nitrates is included:

E. Countywide, plot-scale mapping of sustainable yield based on nitrate concentrations
- 2D spatial interpolation of nitrate concentrations (from WaterChem database)
- Determining sustainable yield based on comparison of plot-scale groundwater levels and spatial occurrence of elevated nitrate concentrations

Reflections on Phase II Data Availability and Water Quality Characterization

The quantification of water quality (chloride concentrations) changes across time proved difficult to address.

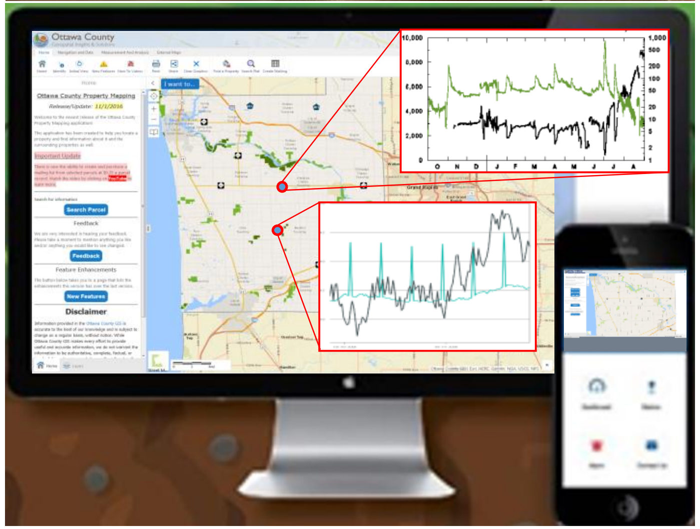
Obviously, field-collected samples represent present-day conditions and provide no information on past Cl concentrations, and a distributed network of sensors collecting groundwater salinity data for different times did not exist prior to the study. In addition, collecting data over the project duration (i.e., a few years) would have been inconsistent with the goal of analyzing long-term (multi-decadal) changes in groundwater salinity that impacts sustainability. Therefore, the best option for the water quality analysis was to use many historical Cl measurements from water wells distributed across the county and from different past decades. This allowed for mapping Cl concentrations for different time periods (see, e.g., slide 114), but also for comparing Cl concentrations made at the same well for different times (e.g., by comparing field results to historical results). Importantly, the former analysis clearly demonstrated that a majority of the wells with elevated Cl concentrations (250 mg/L or more) have seen increases in concentrations with time. However, there was no consistent interval of analysis available (i.e., each comparison had its own unique set of sampling dates that may be very close or very far apart in time), and at lower concentrations, there appeared to be no clear decreasing or increasing trend – likely the result of the complex interplay between natural variability, anthropogenic sources, and the complex, dynamic 3D structure of the Cl plume.

These aspects related to water quality dynamics and data availability made it difficult to quantify i) the rate of salinization in the aquifer system at a given location or across a specific time period; and ii) the coupling between pumping and changes in Cl concentrations. Such characterization requires a network of strategically-placed water quality sensors delivering long-term measurements of groundwater salinity. The following slides provide suggestions on how to design such a network based on the calibrated flow model results and the analysis of Cl concentrations completed for this study.

SUPPLEMENTING THE PHASE II STUDY WITH CONTINUED MONITORING

Michigan State University CEE will provide two data-loggers purchased from Schlumbergers Water Services. These can be installed in pre-existing wells for automated, long-term monitoring of groundwater levels (water column pressure), temperature, and salinity (conductivity). An additional probe will be provided to compensate for changes in barometric pressure when determining groundwater levels. This will provide the detailed (daily) time-series information related to SWLs and Cl concentrations lacking in the Phase II study. Measured groundwater levels can be carefully analyzed for management purposes and compared to the projected SWLs simulated by the groundwater model (and well-scale predictions) to get a sense of the model uncertainty and refine analyses. Groundwater salinity can be carefully analyzed over the course of months and years to detect and seasonal or long-term trends that were not detected in the analysis of Cl^- concentrations.

It is important that – in addition to providing more details on SWL and Cl dynamics to supplement Phase II findings – the two locations chosen for continued monitoring yield as much useful information as possible for informing sustainable management of Ottawa County's groundwater resources. Based on this study, it is clear that the problems related to SWL decline and Cl concentrations are focused within the bedrock aquifer in the central portion of Ottawa County. Thus, it is suggested that the probes are installed in wells that are completed in the bedrock aquifer in this part of the county. To determine exactly where these wells would be best-placed, the following criteria were used to determine the two suggested locations:



1. Where are there significant changes in SWL expected, based on the past and future modeling results?
2. Where are the chloride concentrations clearly elevated due to brine upwelling to areas of significant drawdown due to groundwater pumping?

SUGGESTED MONITORING AREAS

This slide presents two general areas suggested for long-term monitoring of the bedrock aquifer. Both areas have been subject to significant drawdown over the past 50 years and yielded elevated/high Cl concentrations from the water quality analysis. The future modeling suggested Area 1 and Area 2 will experience ≈2m and ≈ 3.5m of drawdown in the bedrock aquifer, respectively, over the next 20 years due to increases in well withdrawals and relatively little recharge from above (because of the clay layer). With continuous time-series Cl and SWL data collected from these locations, it is possible to quantify the increase in Cl concentrations due to deep pumping.

The Marshall aquifer in Area 2 is thin and contains higher Cl concentrations and can be ideal for this type of analysis. On the other hand, Area 1 contains a portion of the Marshall aquifer that is relatively thicker and contains slightly lower Cl concentrations, and thus can be considered an 'emerging areas at risk' – where monitoring can help to determine if Cl-laden water is migrating due to pumping and where different management strategies can be explored through continuous monitoring.

Area 1

ΔSWL ≈ 2m

Rock Cl 200-300 mg/L

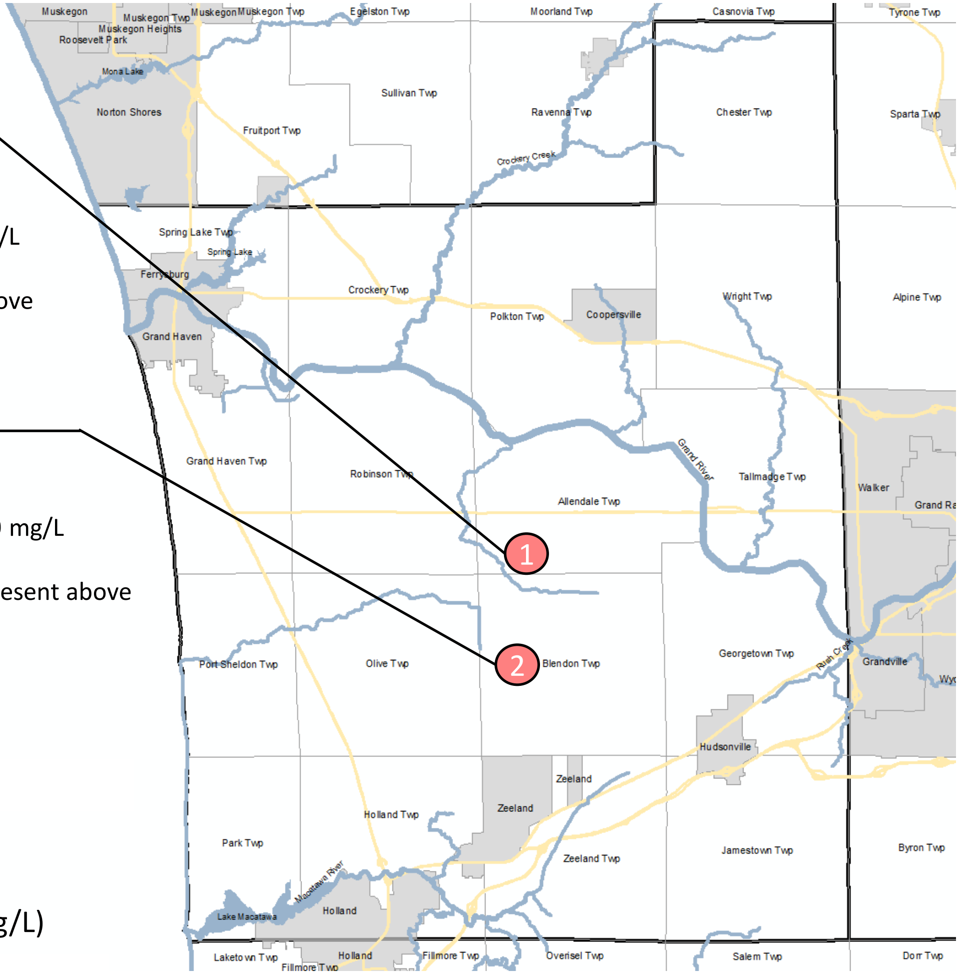
Continuous clay layer above

Area 2

ΔSWL ≈ -3.5 m

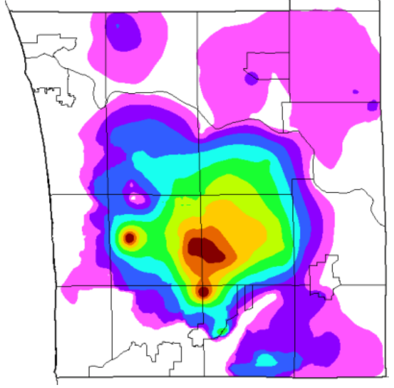
Rock Cl 300-650 mg/L

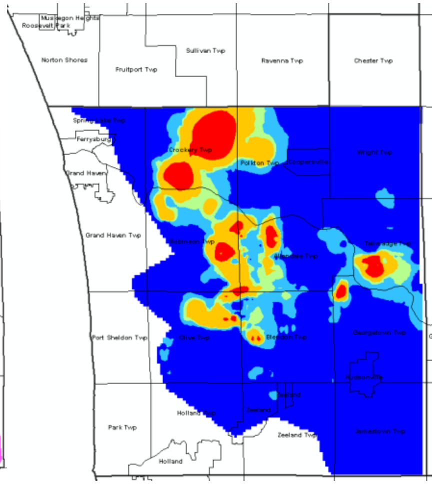
Thin bedrock; clay present above



ΔSWL (m)

- -4.89 - -3.2
- -3.19 - -2.67
- -2.66 - -2.23
- -2.22 - -1.82
- -1.81 - -1.42
- -1.41 - -1.02
- -1.01 - -0.65
- -0.64 - -0.36
- -0.35 - -0.15
- -0.14 - -0.02



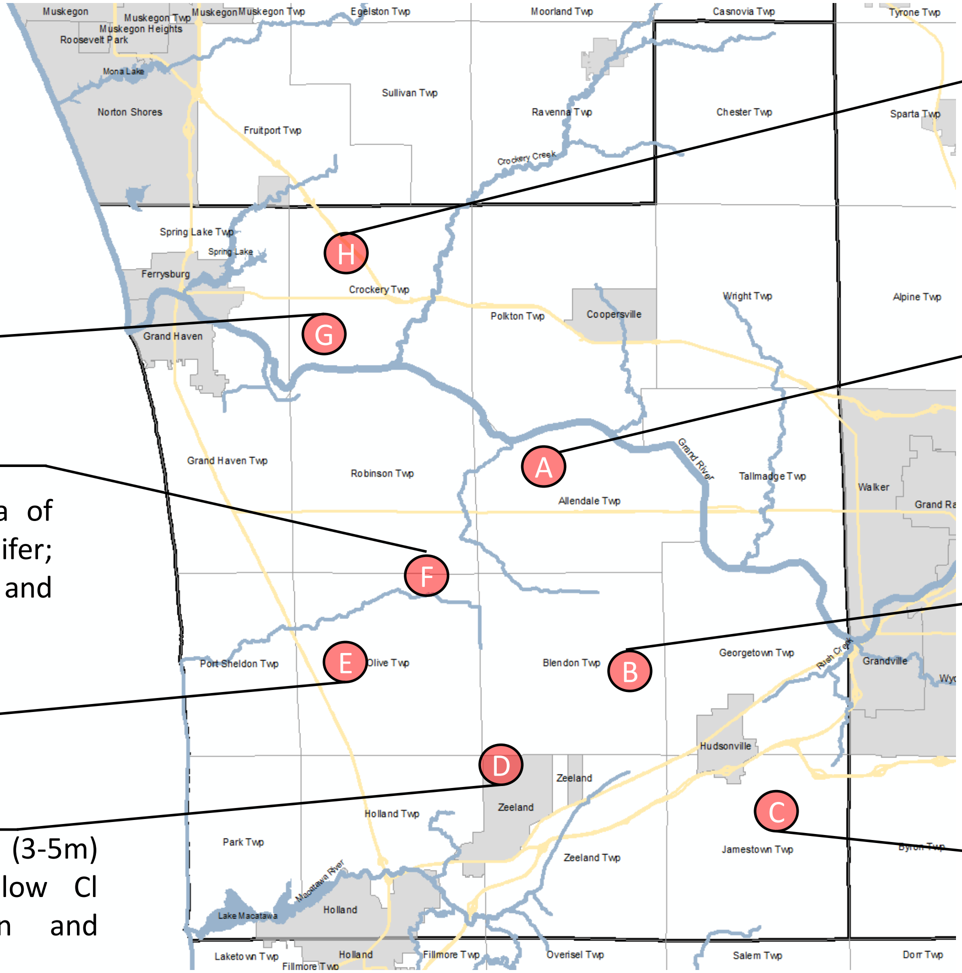


Rock Cl (mg/L)

- 2.2 – 100.0
- 100.1 – 200.0
- 200.1 – 250.0
- 250.1 – 500.0
- 500.1 – 1855.0

Additional Monitoring Areas to Consider

This final slide presents additional monitoring areas to consider in light of the findings from this study. Specific comments regarding the relevance of each area are include. Monitoring at these additional locations might be particularly useful for better understanding water quality (salinity) dynamics.



Area H

Small drawdown (≈ 1m) expected over the next 20 years; elevated Cl detected within area; high Cl detected to the east

Area A

Small drawdown (≈ 1m) expected over the next 20 years; high Cl detected in area; adjacent to section of Grand River impacted by pumping

Area G

Naturally-high Cl concentrations; no significant drawdown due to pumping expected
=> Monitor natural variations of SWL and Cl (e.g., due to seasonal changes in recharge)

Area F

Local recharge area of the bedrock aquifer; high Cl north, east, and south of area

Area B

Modest drawdown (≈ 2m) expected over the next 20 years; elevated Cl observed in and around area

***Area E**

Significant drawdown (≈4m) expected by 2036; high Cl to north and east of area
=> migration of Cl due to pumping? (similar to *Area 1* on previous slide).

Area D

Significant drawdown (3-5m) expected by 2036; low Cl concentrations within and around area

Area C

Important recharge area to the bedrock aquifer; low Cl concentrations

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