Allegan County Groundwater Study

Phase 1: Understanding the Big Picture

March 2, 2021

Submitted by:

Hydrosimulatics INC.

This report contains findings and explanations from the Allegan County Groundwater Study – Phase 1: Understanding the Big Picture, completed by Hydrosimulatics Inc. for Allegan County, Michigan. The project represents the first step of an overall effort to improve the management of water resources in Allegan County. In particular, the project provides a comprehensive review of groundwater conditions in the county, making innovative and critical use of existing data available from State of Michigan environmental / groundwater data storehouses. We downloaded, processed, and analyzed the available data to create a set of countywide maps and visualizations that can help to prioritize further data collection and analysis and inform groundwater management.

Findings from the Phase 1 project are organized into three Tasks:
- Task 1 – Geologic Modeling
- Task 2 – Water Quantity Analysis
- Task 3 – Water Quality Analysis

An executive summary is provided at the beginning of each Task section, followed by detailed maps, visualizations, and written explanations.

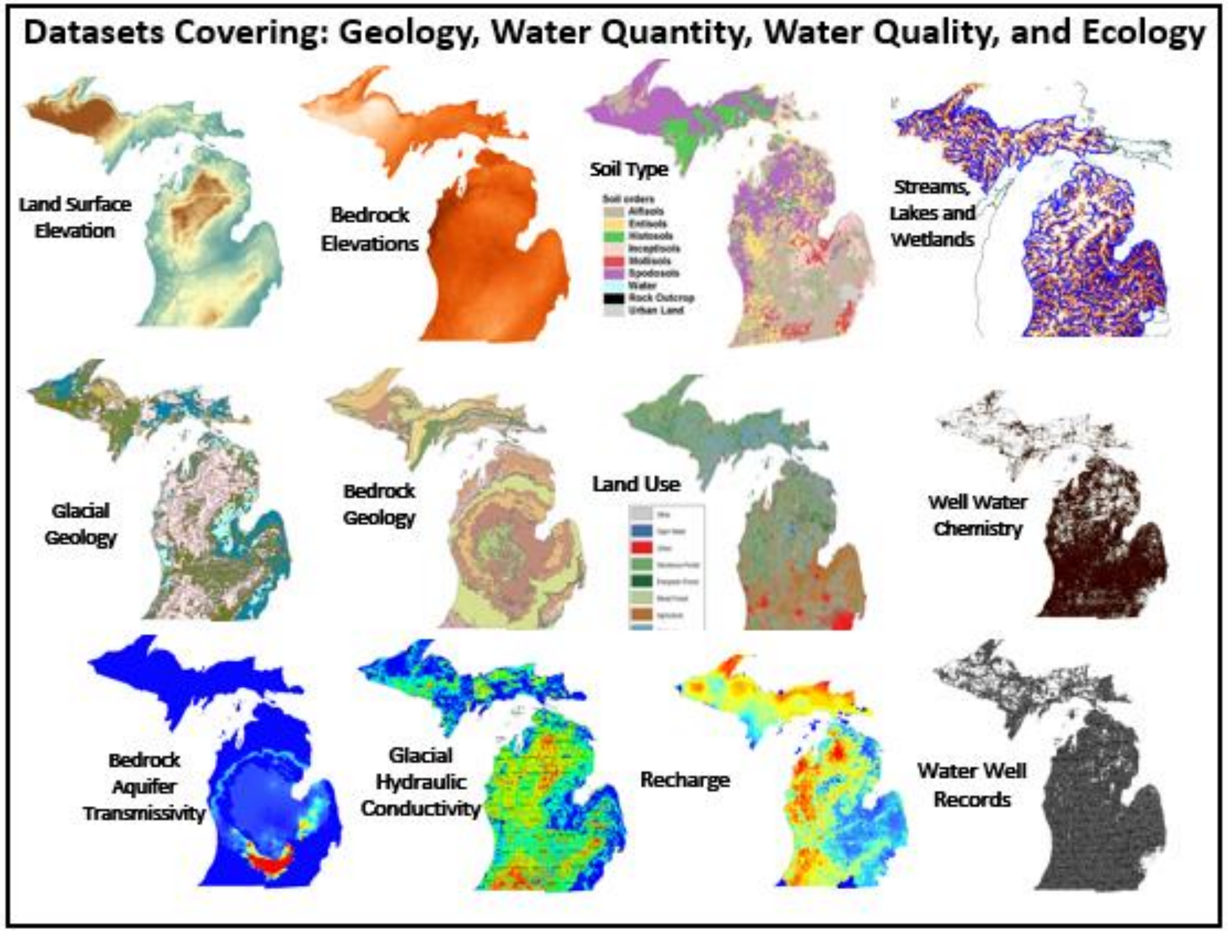
A related document, "Story of Allegan County's Groundwater – With a Focus on Management Implications", was provided to the County as a high-level summary of the Phase 1 study.

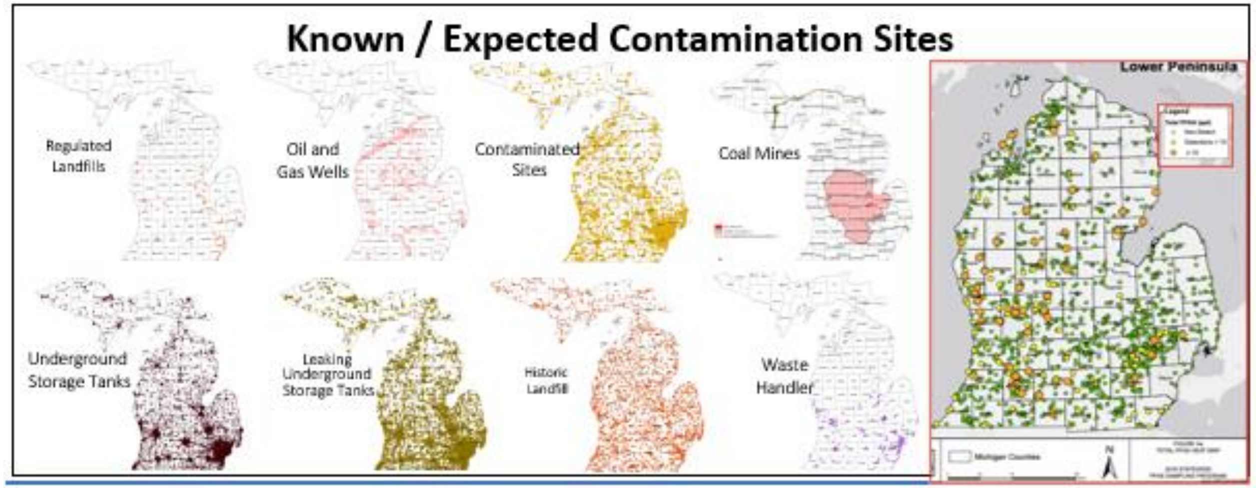
Contents

Statewide Groundwater Datasets

The State has made a significant contribution to the groundwater data availability in Michigan through legal mandates and institutional initiatives that ensure data accumulates automatically (and therefore very quickly). The Groundwater Inventory and Mapping project (GWIM) produced statewide hydrogeologic maps useful for site characterization, modeling and analysis. The *Wellogic* database initiated in 2000 contains hundreds of thousands of water well records containing physical groundwater information (Static Water Levels, borehole lithology). The *WaterChem* database contains water quality information from over 1 million samples collected from water wells and analyzed at the State of Michigan's Drinking Water Analysis Laboratory.

We made an effort to make full use of the statewide datasets for this Phase 1 project, in addition to other freely available spatial framework data (e.g., the USGS National Elevation Dataset, NED).

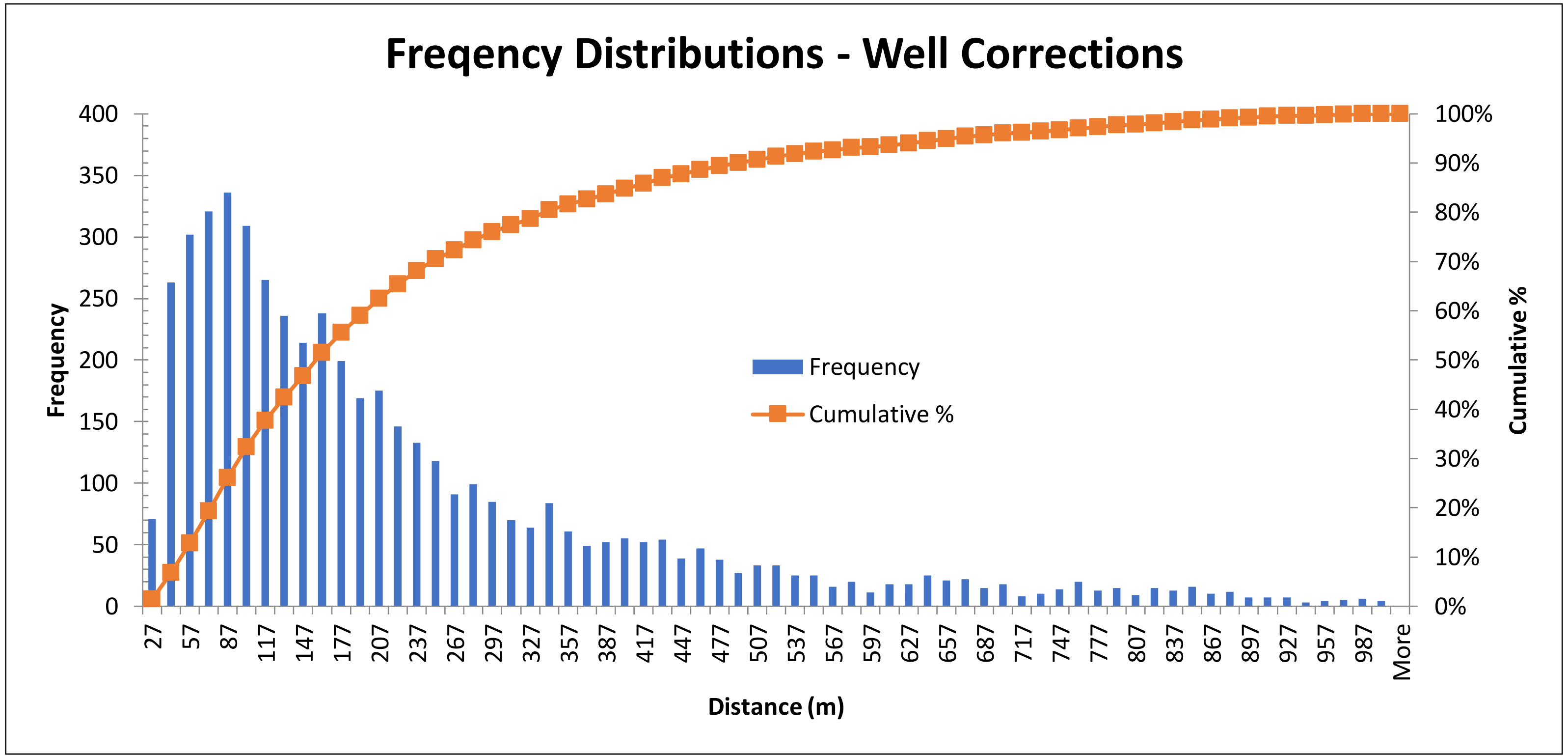




Well Location Correction

The statewide water well database, *Wellogic*, is continuously updated with new water well records as new wells are installed. We downloaded the complete Wellogic dataset for Allegan County in early August 2020 for our analysis. In fact, this was just after the Michigan Geological Survey (MGS) completed a review and validation (or correction, as needed) of the locations for all the current wells in for Allegan County in the *Wellogic* database. The wells that were found to be in the incorrect location were relocated using available information and spatial mapping.

We compared the new (corrected) locations to old locations of wells in a previous subset of Wellogic data (i.e., before well correction) to get a sense of “how large” the locational corrections were made during the analysis by MGS. The frequency distribution (histogram) and cumulative distribution function (CDF) of the well correction analysis is shown on the right.   Note that about 75% of the wells were corrected to a distance of less than 300m, and less than 10% were corrected by a distance of 500m or more.



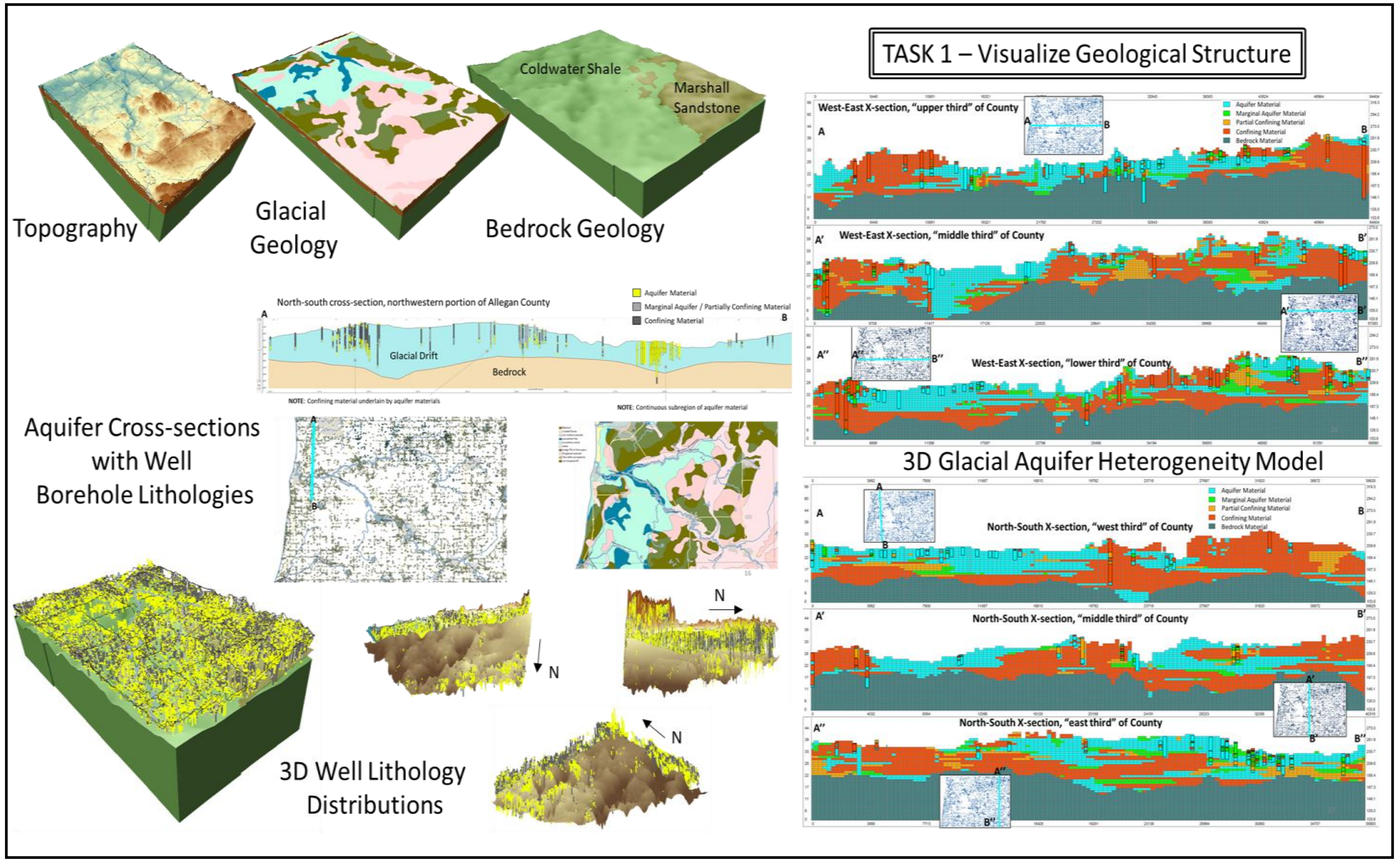
Allegan County Groundwater Study

Task 1 – Geologic Modeling

Hydrosimulatics INC.

Task 1 – Executive Summary

In Task 1, we processed, analyzed and visualized the shallow subsurface geological structure in Allegan County. We visualized in three-dimensions (3D) the large-scale topography, shallow glacial geology, and deeper bedrock geology. Borehole lithologies (soil and rock characteristics) from recently updated water wells records contained in the *Wellogic* statewide database were mapped and visualized. We then developed a countywide geological model with two distinct / parallel elements: a glacial geology model and a bedrock geology model. A sophisticated transition probability (TP) approach was used to model the glacial geology, whereas the bedrock was modeled using traditional 'layers and zones' generated from bedrock geology maps to identify aquifers and aquitard zones (Coldwater Shale – confining; Marshall Sandstone – aquifer; Michigan Formation – confining). The interface between the bedrock and glacial deposits (or 'bedrock top') was estimated / interpolated from lithologic information contained in the water well records. For the glacial layer, the entire county was discretized into 1,580,250 cells (215 and 147 cells in the x- and y-directions, respectively, and 50 cells in the vertical direction), providing a resolution of 250m (820 ft) horizontally and 3.5m (11.5ft) vertically. Lithologies in each cell were aggregated and equivalent lithological classes were assigned: AQ (aquifer material), MAQ (marginal aquifer material), PCM (partially confining material), and CM (confining material). Aquifer classes in cells with no data were statistically interpolated based on the transition probability (TP) approach. We experimented with many different statistical realizations for different assumptions about how horizontal and vertical variabilities are related to each other. We evaluated which realizations were able to best reproduce the large-scale glacial geology and the more detailed patterns in the observed lithology distributions. The set of parameters deemed most acceptable were then used to execute two hundred and fifty realizations to produce an ensemble mean model by assigning the most frequently occurring material at each grid cell.

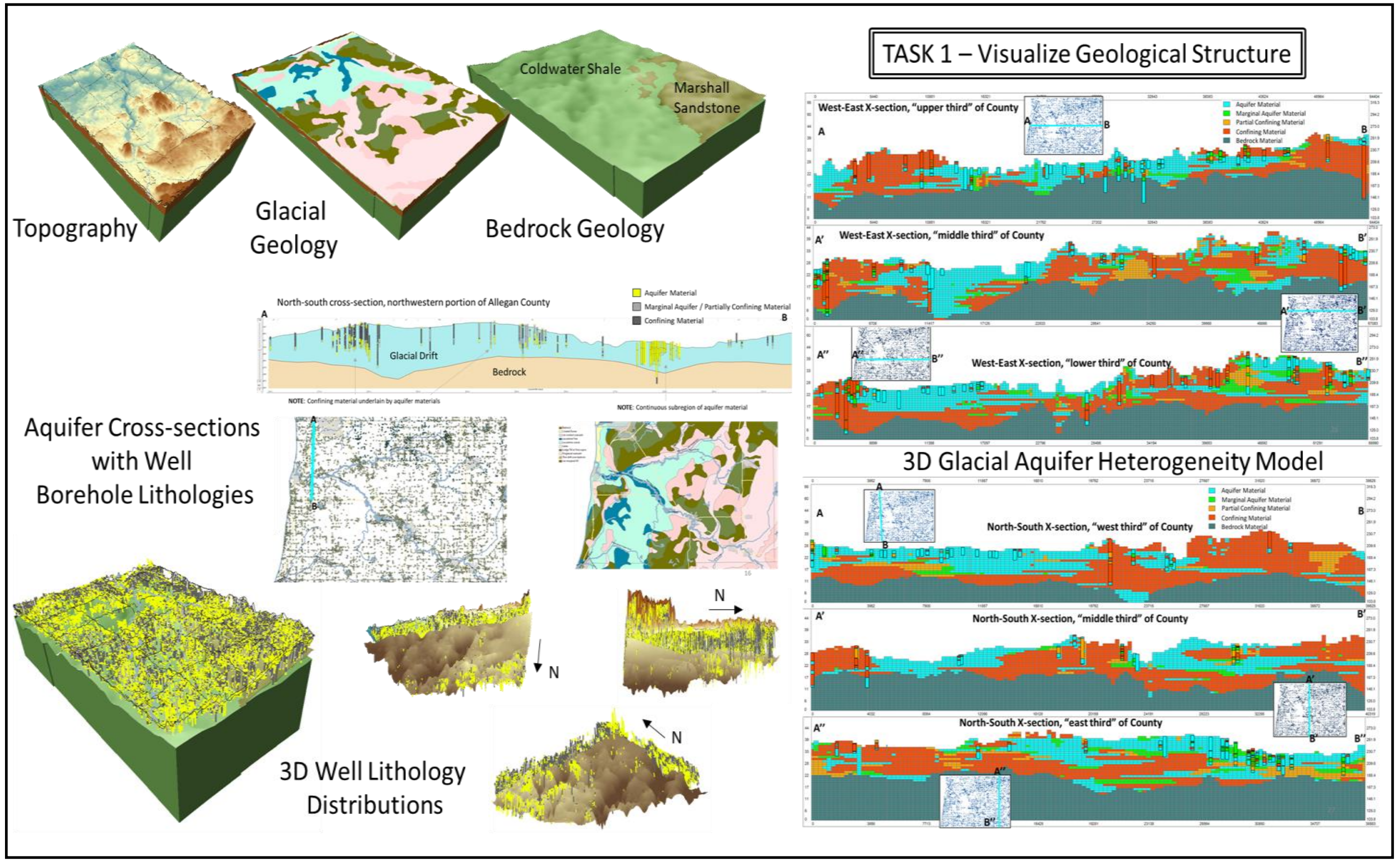


Task 1 – Executive Summary (cont'd)

The resulting highly informative 3D model reveals that the glacial geology in Allegan County is complex and heterogeneous – both aquifer and non-aquifer (confining) material exhibits strong spatial persistence, but there are no "perfect layers".

In particular, the model shows:

1. In the northwest, south-central, central and northeast portions of the county, there are relatively extensive/continuous shallow fine-grain tills (CM and PCM) underlain by coarser-grained materials (AQ and MAQ), or aquifer "pockets";
2. in the northeast, many wells pierce through the less permeable clays/silts (CM) to withdraw water from the Marshall Sandstone aquifer (AQ / MAQ) because layers of confining material are extensive and found throughout much of the depth of the glacial aquifer;
3. in the east, southeast, northeast, and in some central areas of the county, glacial outwash materials with significant vertical variability and lateral variability are present, with more permeable materials (AQ, MAQ) typically found near the surface – the ability to find significant yields of groundwater may vary significantly within short distances (or different depths); and
4. in the low-land areas, extensive, continuous lacustrine deposits are found, with both coarse (AQ / MAQ) and fine-grained materials (CM / PCM) present; in these areas is it common to have continuous shallow sand deposits (AQ /MAQ) underlain by clays/silts (CM / PCM), with some interbedding/fingering predicted by the TP model.



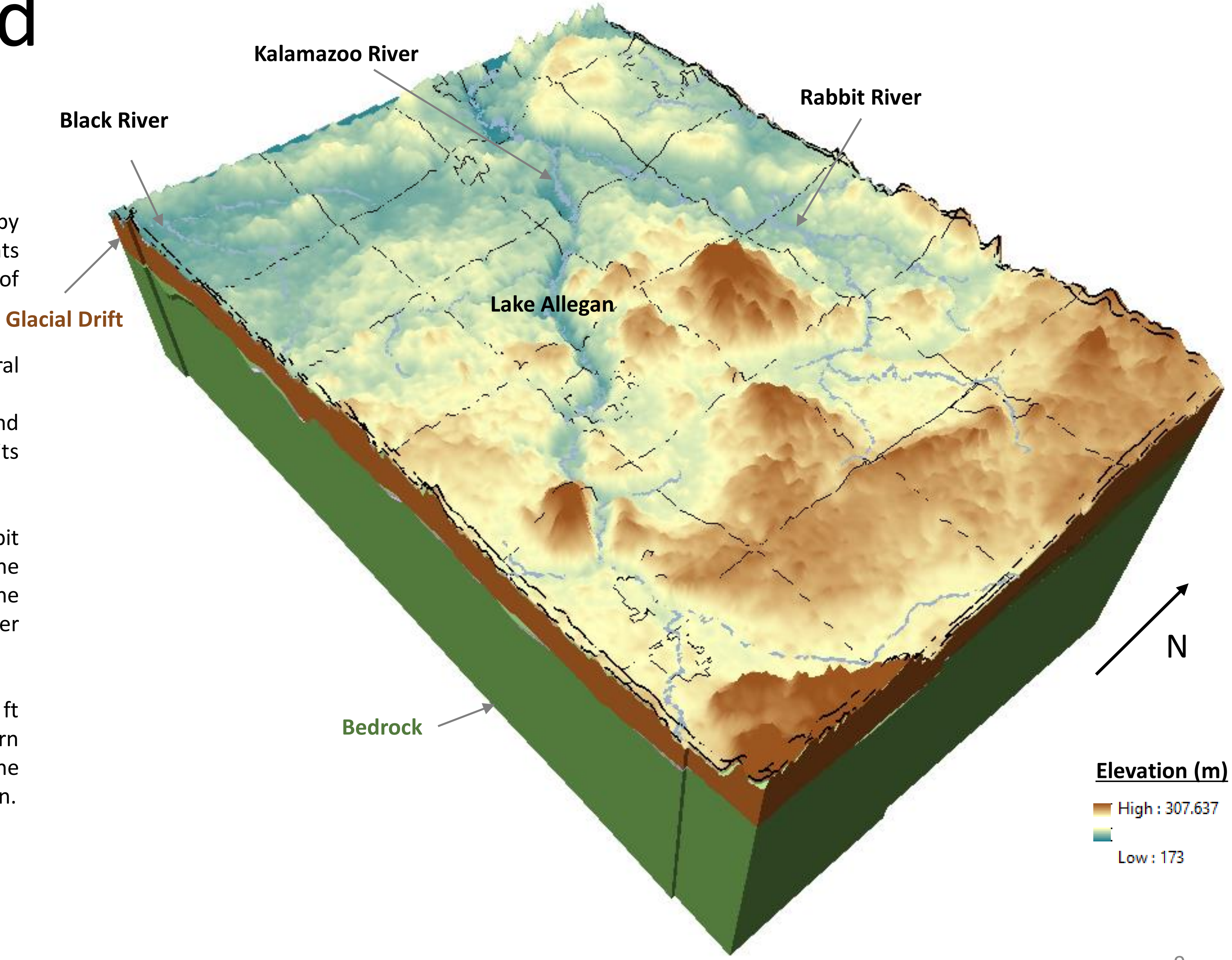
Topography and Major Rivers

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

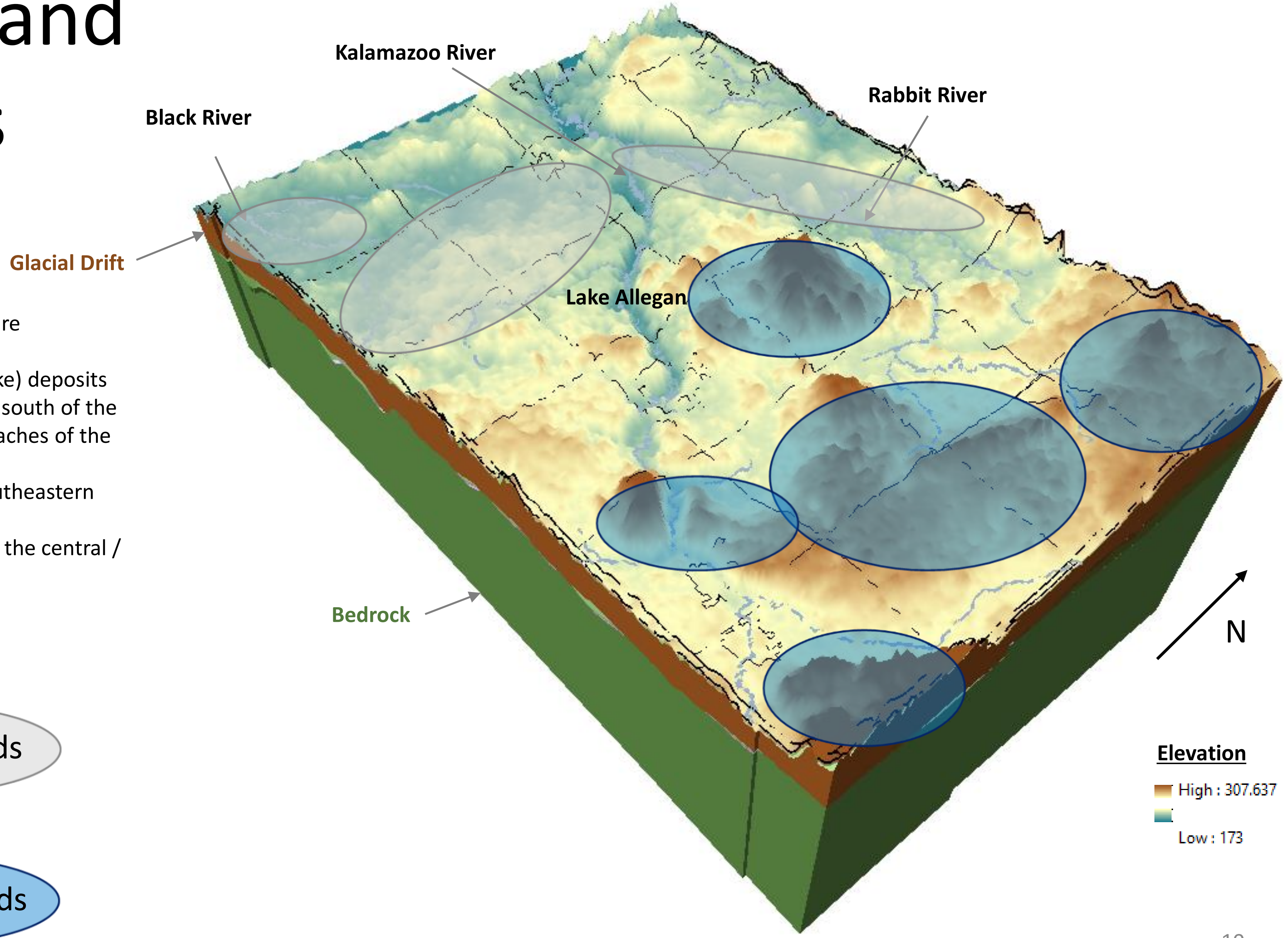
The land surface toward the eastern and central portions end of the County is fairly rugged, undulating, and dissected by the Kalamazoo River (and its tributaries) and the Rabbit River (and its tributaries).

The lower reaches of the Kalamazoo River and Rabbit River – and much of the southwestern portion of the county – are flanked by relatively flat areas, with the exception of the northern flank of the Kalamazoo River in the northwestern portion of the county.

The elevations in the County range from about 1,000 ft above mean sea level (amsl), at the southeastern corner in Gunplain Township, to about 570 feet at the confluence of the Kalamazoo River with Lake Michigan.



Topography and Major Rivers



Three well defined topographic divisions are recognized in the County:

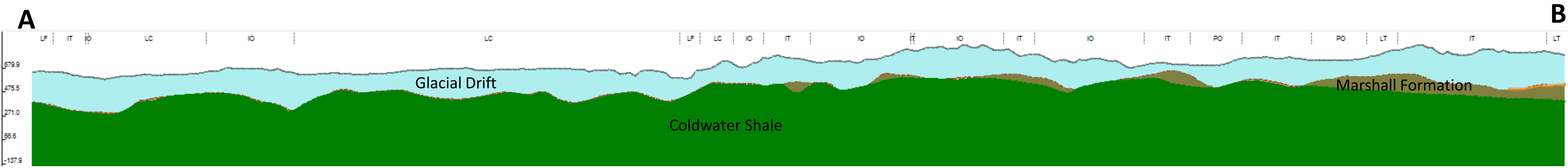
- A broad, low-lying plain of lacustrine (lake) deposits found in the western half of the County, south of the Kalamazoo River and along the lower reaches of the Rabbit River and Black River;
- Hilly upland areas in the eastern and southeastern portions of the County, and;
- Rolling hills of moderate relief dominate the central / north-central portion of the County.

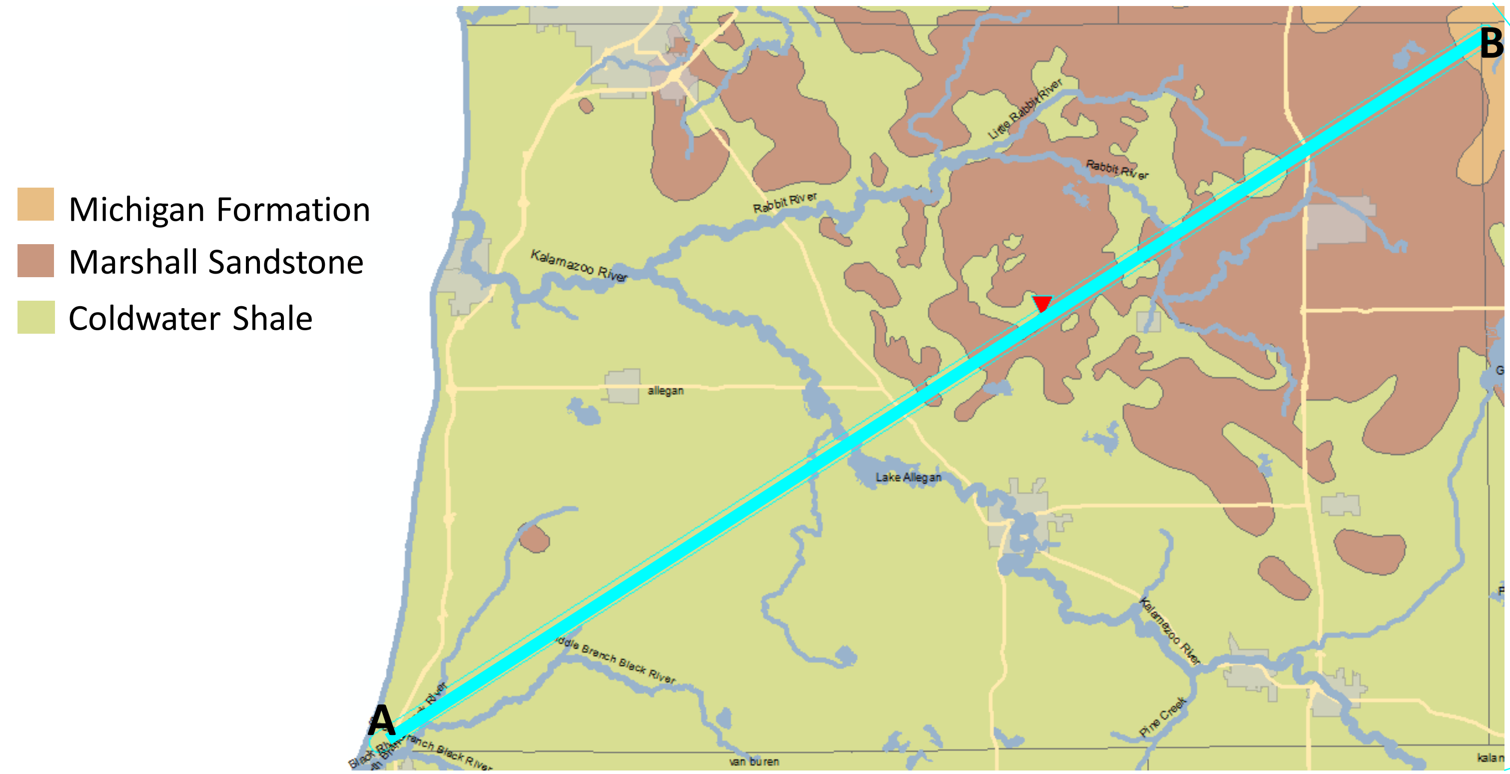
Allegan lowlands

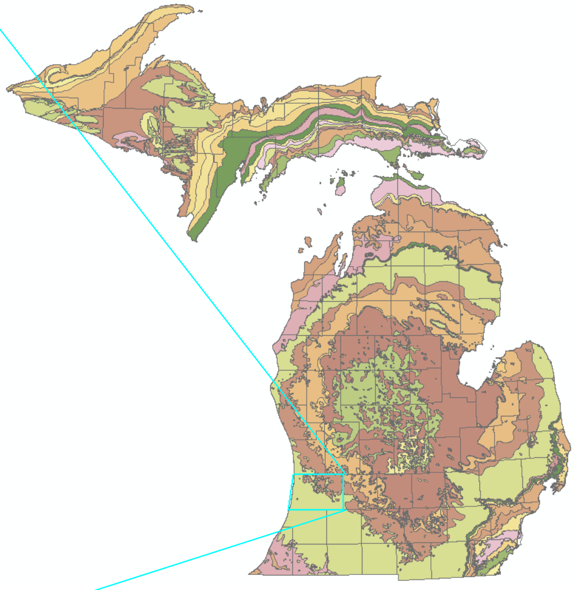
Allegan highlands

Aquifers

The County is underlain by multiple geological units, including a shallow, glacial aquifer and deep, fractured, bedrock formations. The glacial aquifer layer is composed of dunes, lacustrine deposits, outwash, and post-glacial alluvium, and till. The bedrock units under the glacial deposits include, from northeast to southwest, the Michigan Formation (very small areas in northeast corner), the Marshall Formation, and Coldwater Shale.



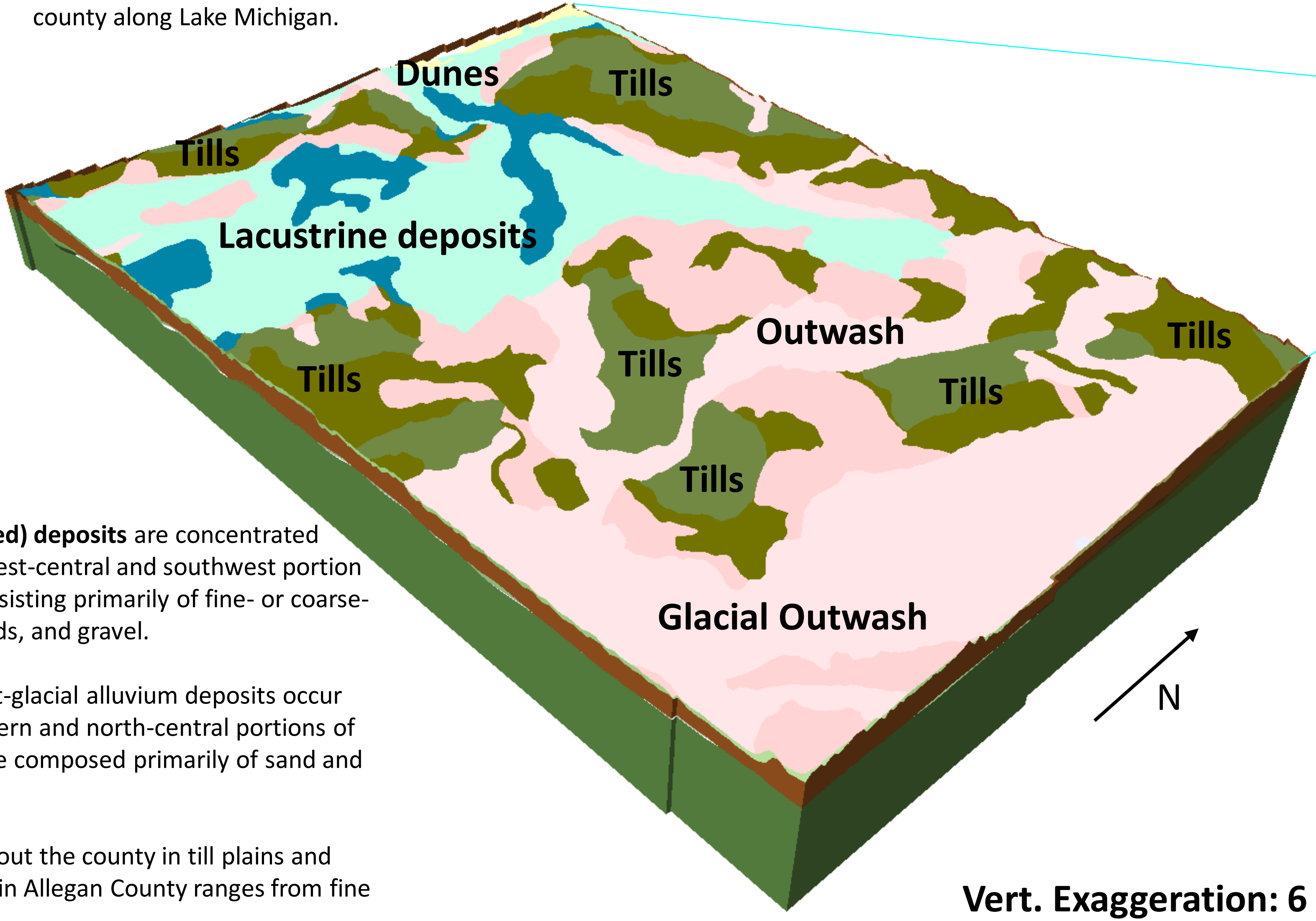




Michigan Bedrock Geology

Glacial Geology

Dune sand primarily exists in the western and northwestern edges of the county along Lake Michigan.



Lacustrine (lakebed) deposits are concentrated primarily in the west-central and southwest portion of the county, consisting primarily of fine- or coarse-grained clays, sands, and gravel.

Outwash and post-glacial alluvium deposits occur mostly in the eastern and north-central portions of the county and are composed primarily of sand and gravel.

Till exists throughout the county in till plains and moraines. The till in Allegan County ranges from fine to coarse grained.

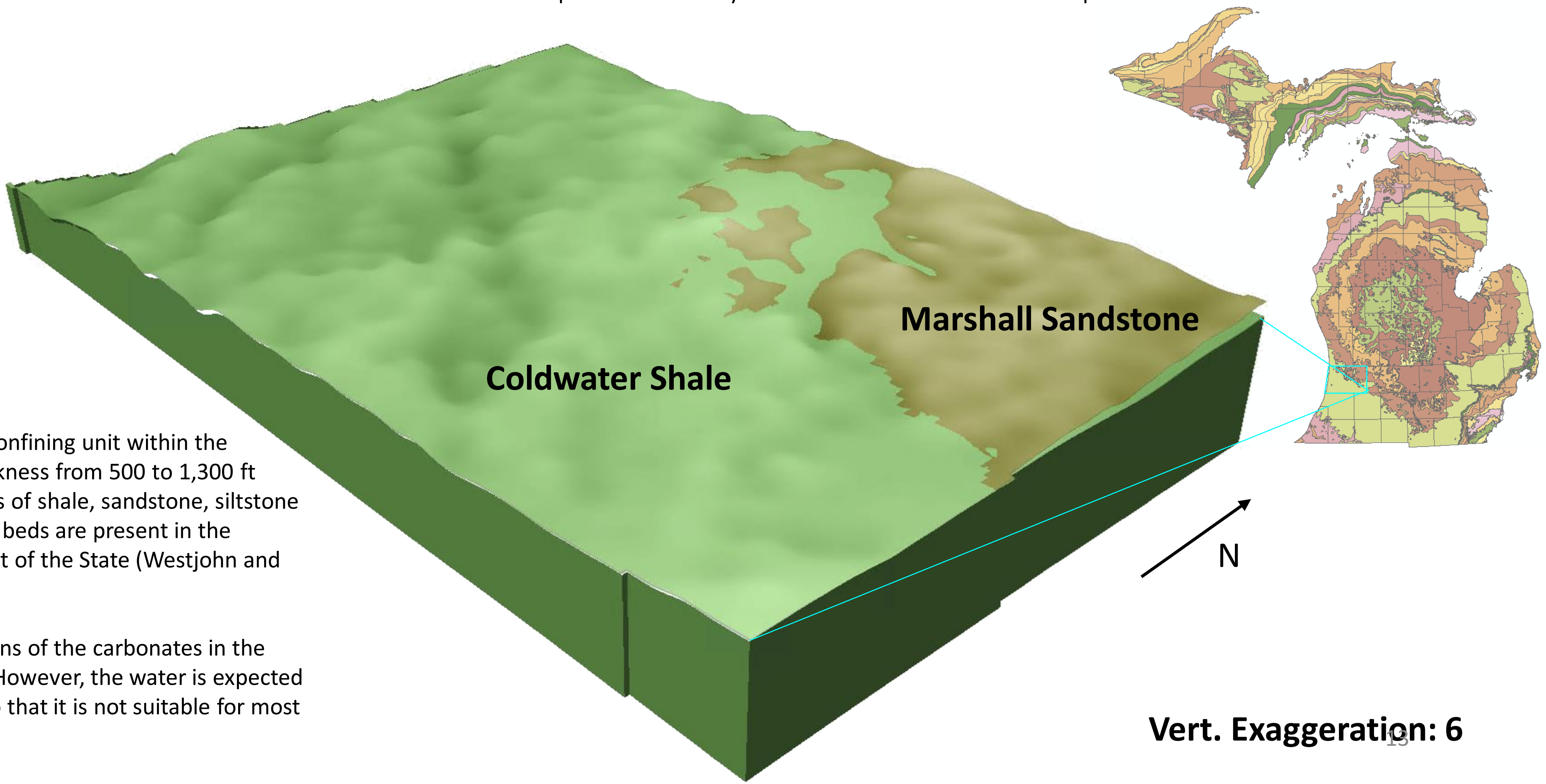
Vert. Exaggeration: 6

- Coastal Dunes
- Ice-contact outwash
- Lacustrine Fine
- Lacustrine coarse
- Lakes
- Lodge Till
- Proglacial outwash
- Thin drift over bedrock
- ice-marginal till

Bedrock Geology

The **Marshall Sandstone** formation subcrops diagonally beneath the northcentral and northeastern portion of Allegan County, trending from Fillmore and Overisel townships in the NW direction to Watson and Martin townships in the SE direction. Stratigraphically, the Marshall Formation overlies the Coldwater Shale and is overlain by the Michigan Formation (in the very northeast corner of the County).

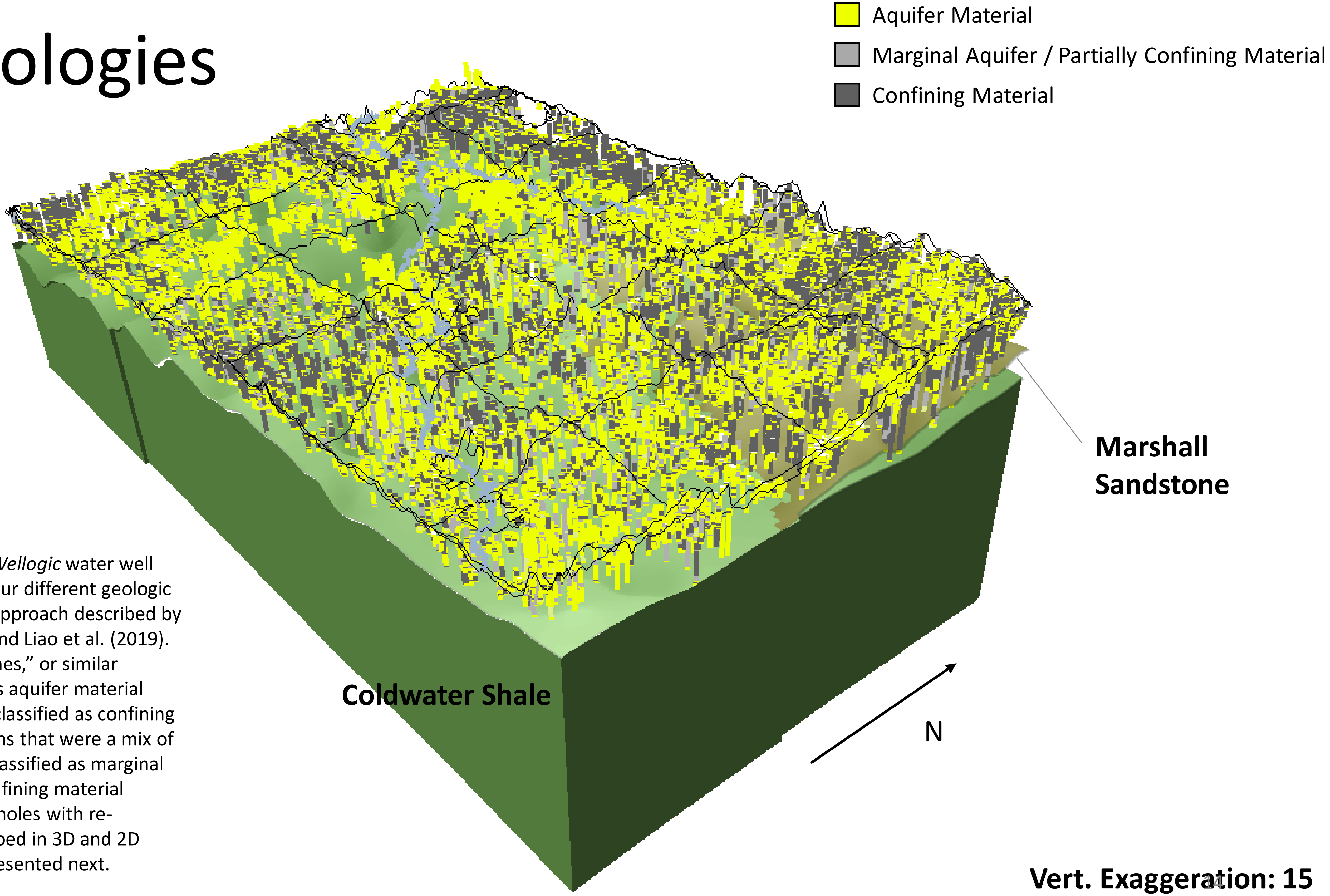
Along its subcrop contact with the Coldwater Shale, the Marshall Formation is thin; it thickens to the east and northeast. The top portion of the Marshall Formation is composed of fractured sandstone which is somewhat permeable and comprises the Marshall Aquifer. The Marshall Aquifer ranges in thickness from 75 to more than 200 ft within the state (Westjohn and Weaver, 1998), the maximum thickness within the county is estimated to be less than 175 ft (Apple and Reeves, 2007). Many wells in north-central and northeastern part of the County obtain water from the Marshall Aquifer.



The **Coldwater Shale** is a master confining unit within the Michigan Basin, and ranges in thickness from 500 to 1,300 ft thick. The Coldwater Shale consists of shale, sandstone, siltstone , and carbonates. More sandstone beds are present in the Coldwater Shale in the eastern part of the State (Westjohn and Weaver, 1998).

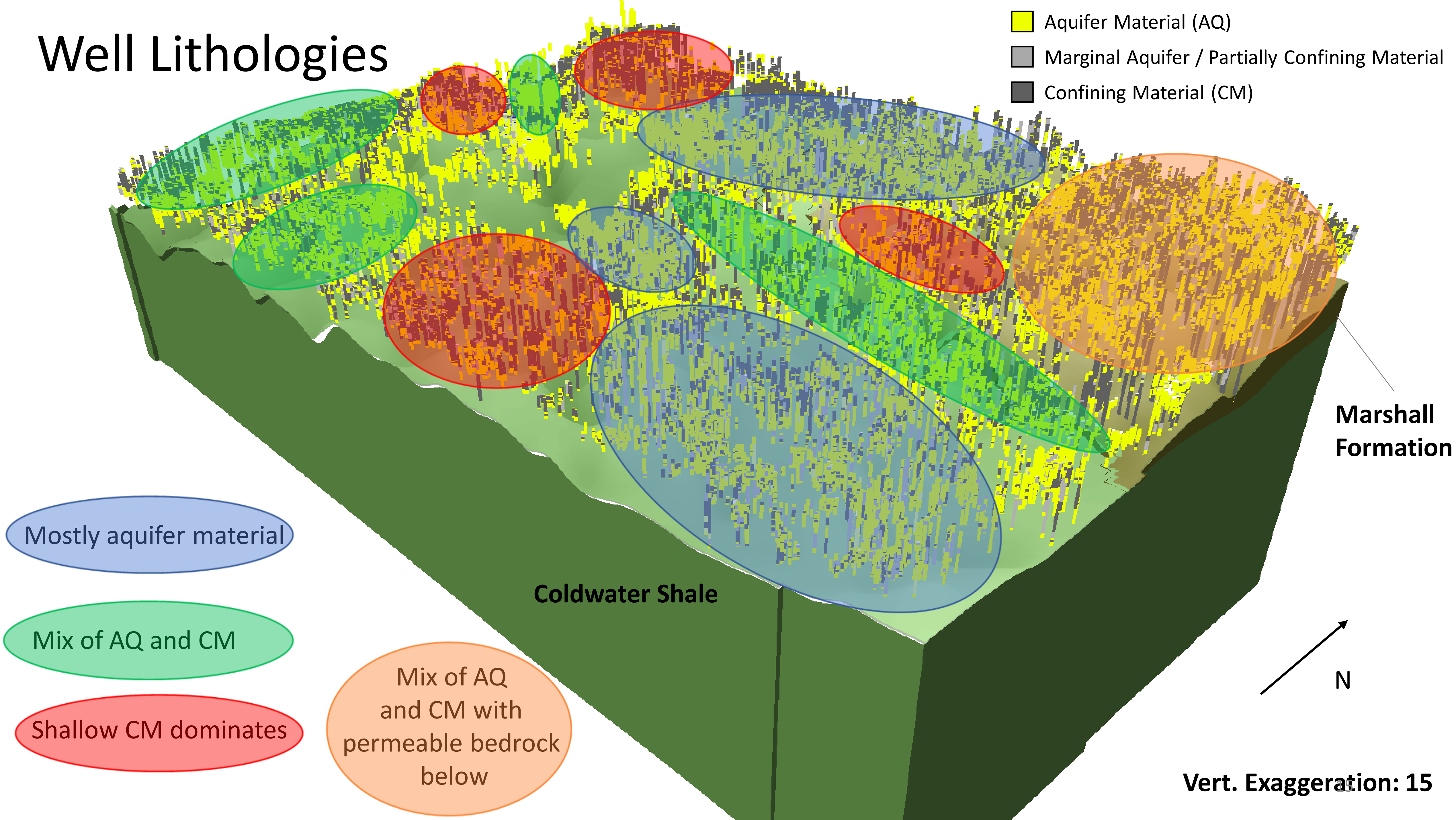
In Allegan County, fractured portions of the carbonates in the Coldwater Shale may yield water. However, the water is expected to be saline (highly mineralized) so that it is not suitable for most uses.

Well Lithologies

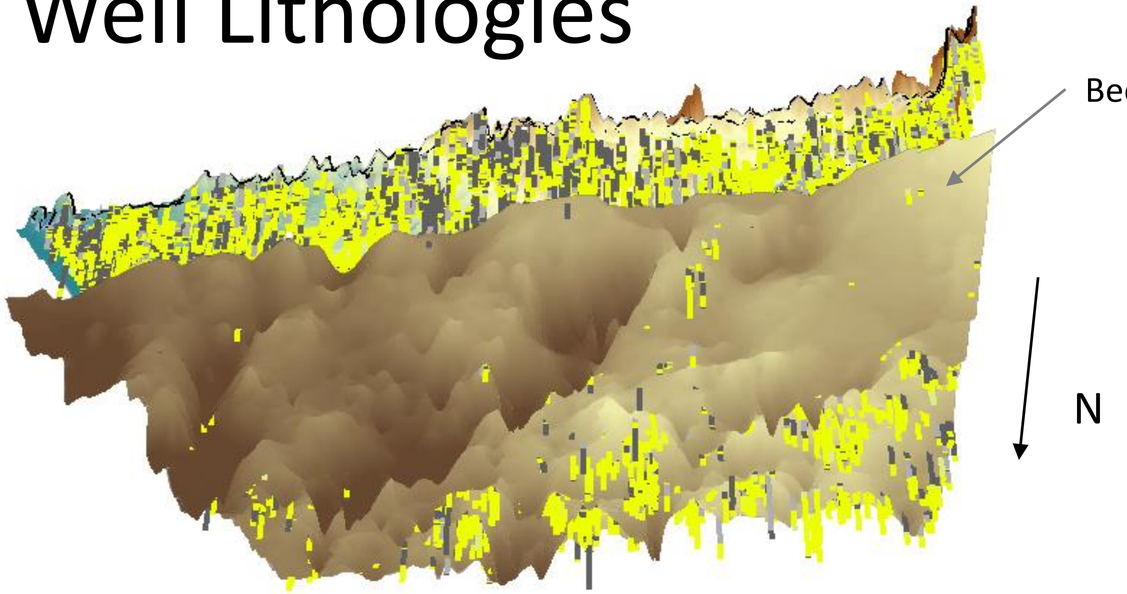


Lithologic descriptions from *Wellogic* water well records were classified into four different geologic material types following the approach described by Sampath et al. (2015, 2016) and Liao et al. (2019). “Sand,” “Gravel,” “Coarse stones,” or similar descriptions were classified as aquifer material (AQ); “Silt,” “Clay,” etc. were classified as confining material (CM); and descriptions that were a mix of AQ and CM materials, were classified as marginal aquifer (MAQ) or partially confining material (PCM), respectively. The boreholes with re-classified stratums were mapped in 3D and 2D (cross-sections), which are presented next.

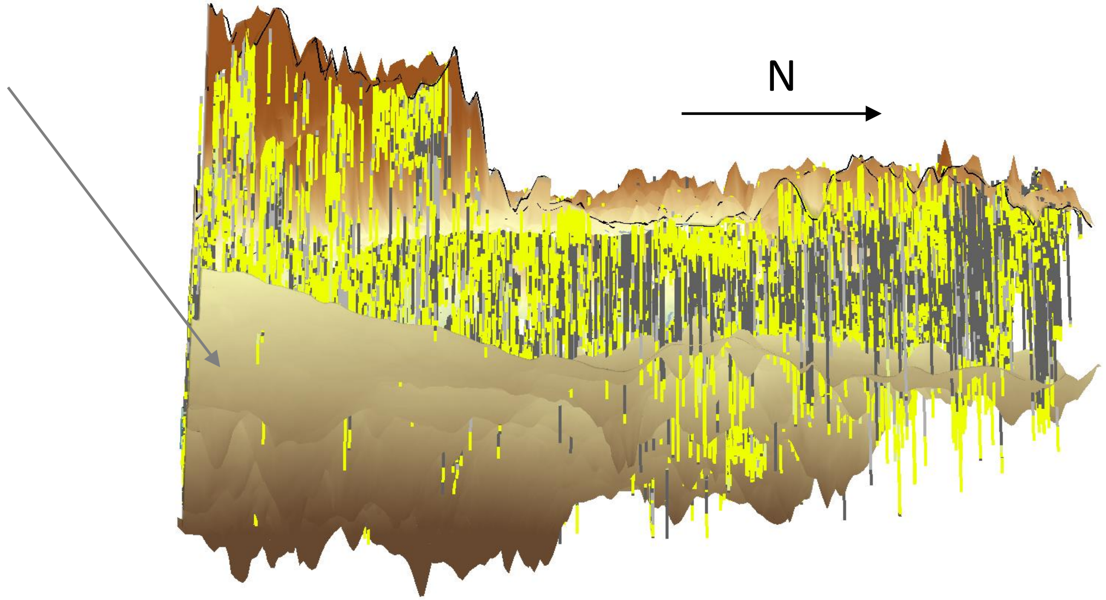
Well Lithologies



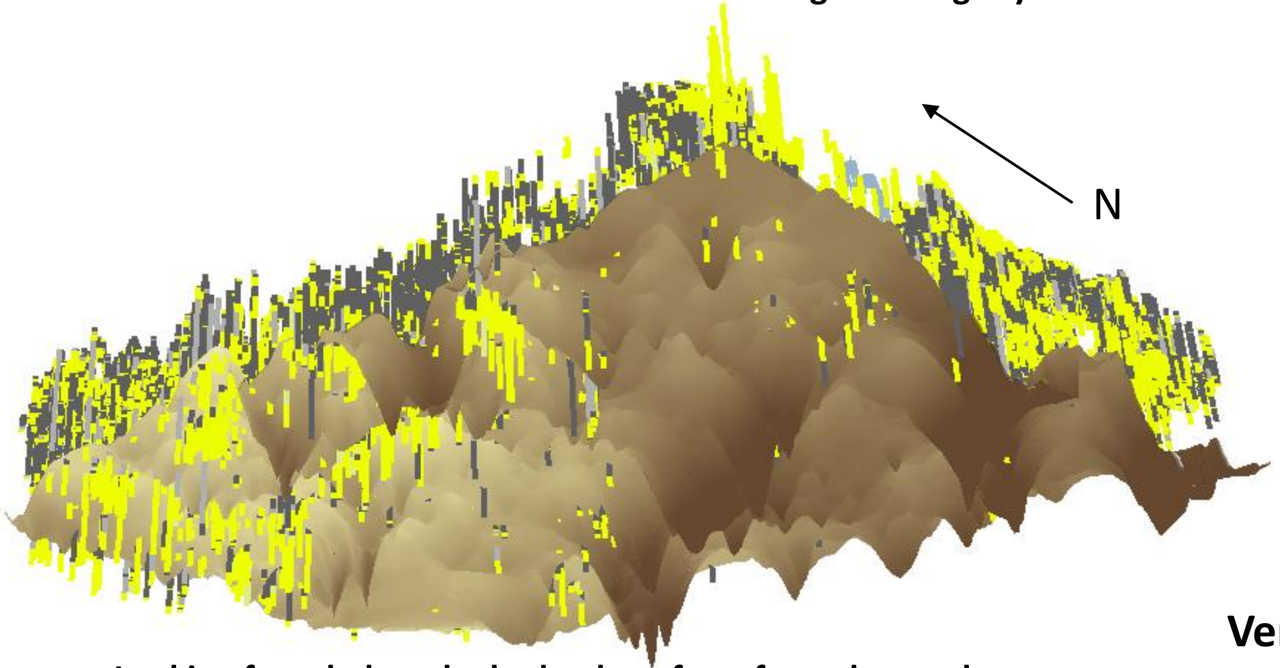
Well Lithologies



Looking from below the bedrock surface, from the south



Looking from slightly below the bedrock surface, from the east



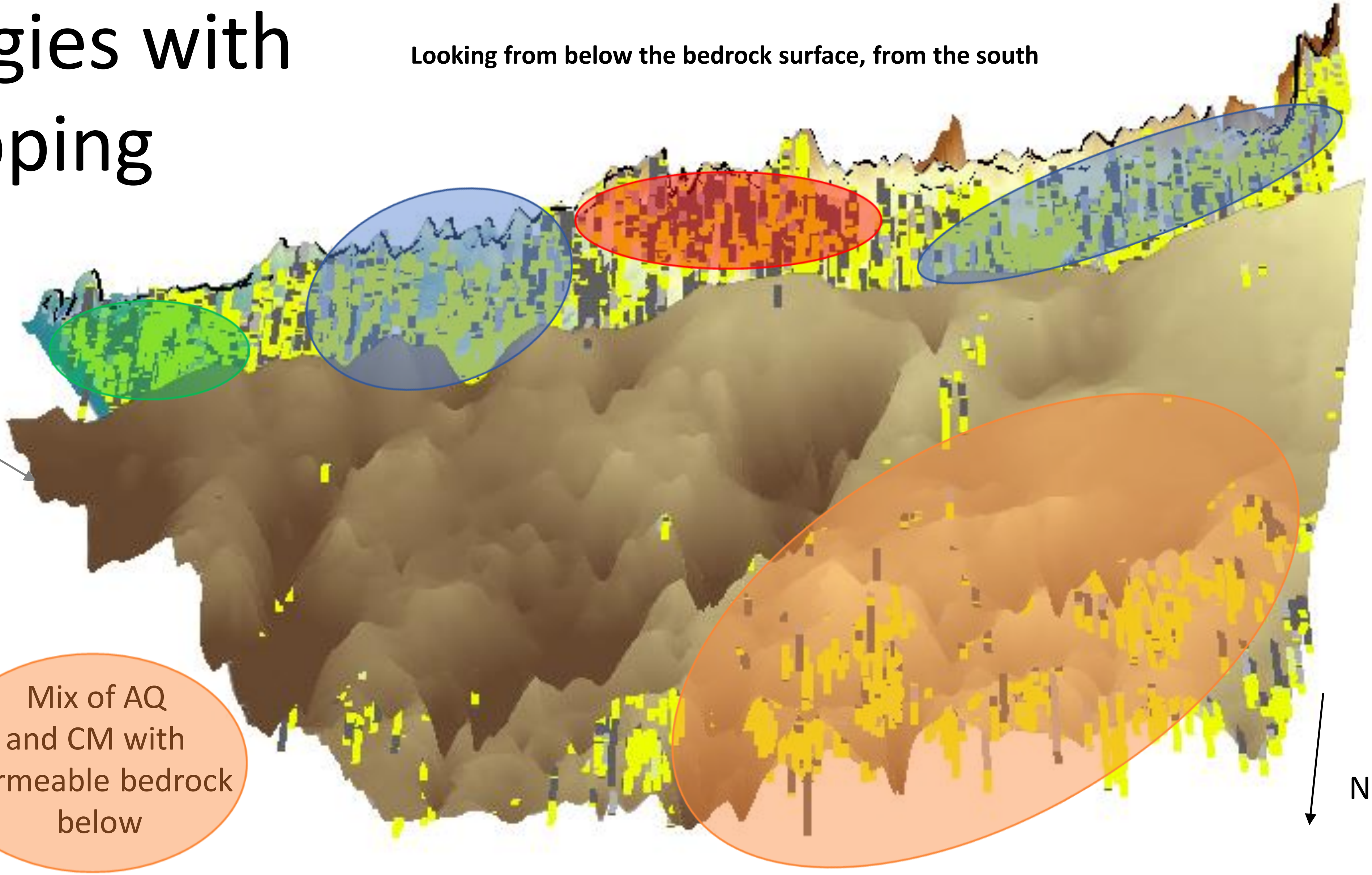
Looking from below the bedrock surface, from the northwest

- Aquifer Material (AQ)
- Marginal Aquifer / Partially Confining Material
- Confining Material (CM)

Vert. Exaggeration: 32

Well Lithologies with Aquifer Mapping

Looking from below the bedrock surface, from the south

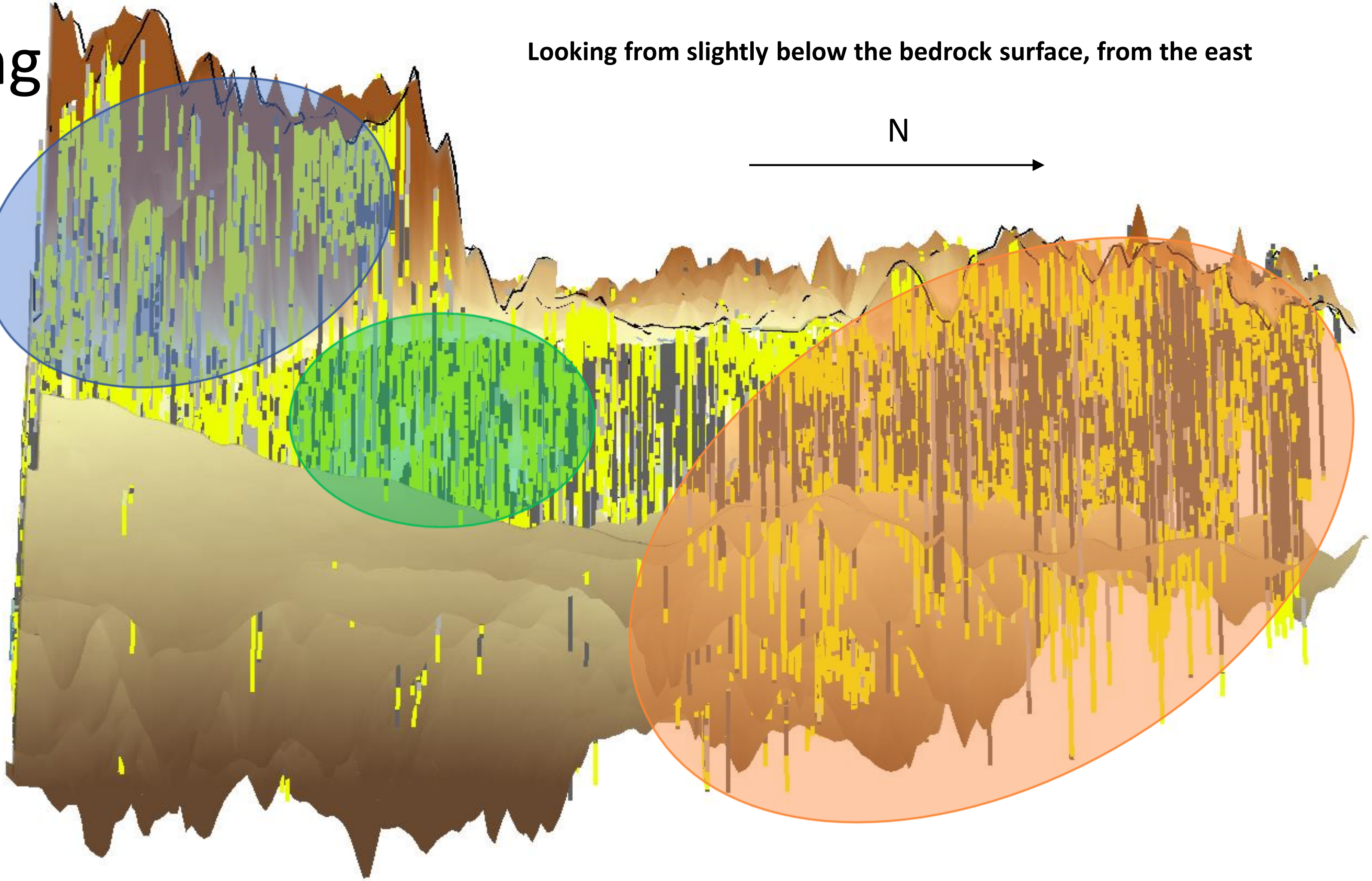


Vert. Exaggeration: 32

Well Lithologies with Aquifer Mapping

Looking from slightly below the bedrock surface, from the east

N



Mostly aquifer material

Mix of AQ and CM

Shallow CM dominates

Mix of AQ and CM with permeable bedrock below

Aquifer Material

Marginal Aquifer / Partially Confining Material

Confining Material

Vert. Exaggeration: 32

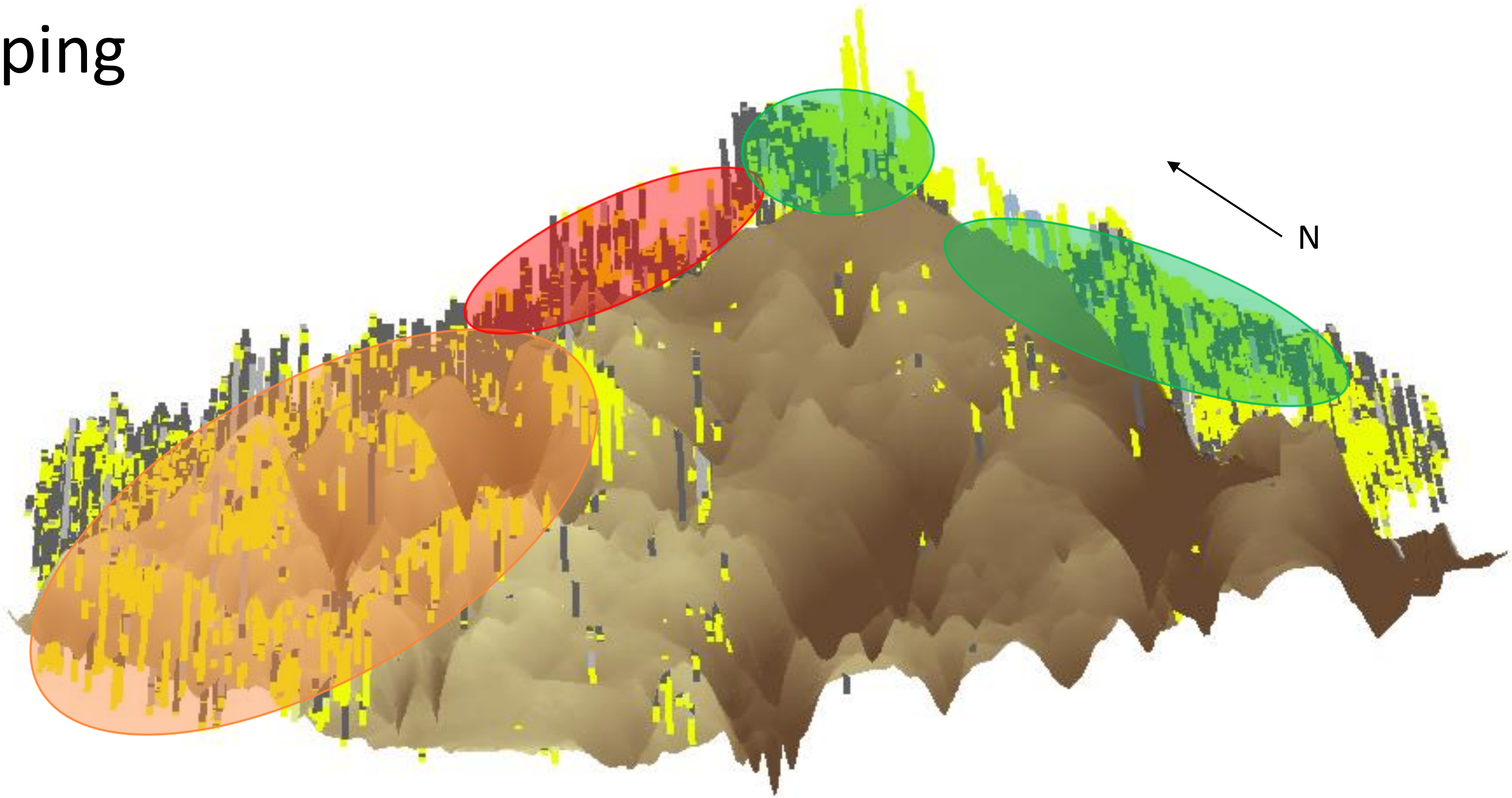
Well Lithologies with Aquifer Mapping

Mostly aquifer material

Mix of AQ and CM

Shallow CM dominates

Mix of AQ and CM with permeable bedrock below



Looking from below the bedrock surface, from the northwest

- Aquifer Material
- Marginal Aquifer / Partially Confining Material
- Confining Material

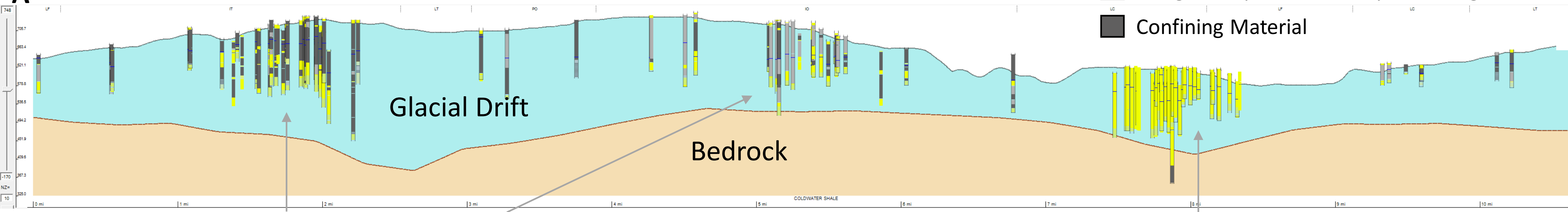
Aquifer Cross-sections with Well Lithologies

North-south cross-section, northwestern portion of Allegan County

Aquifer Material

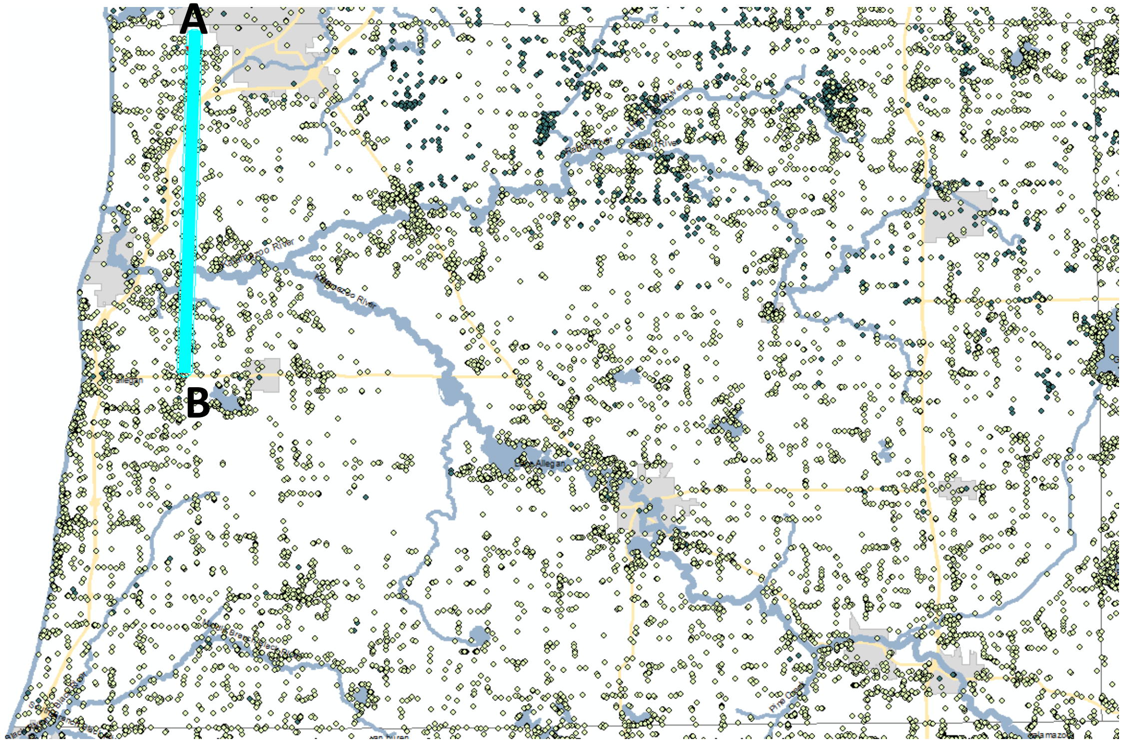
Marginal Aquifer / Partially Confining Material

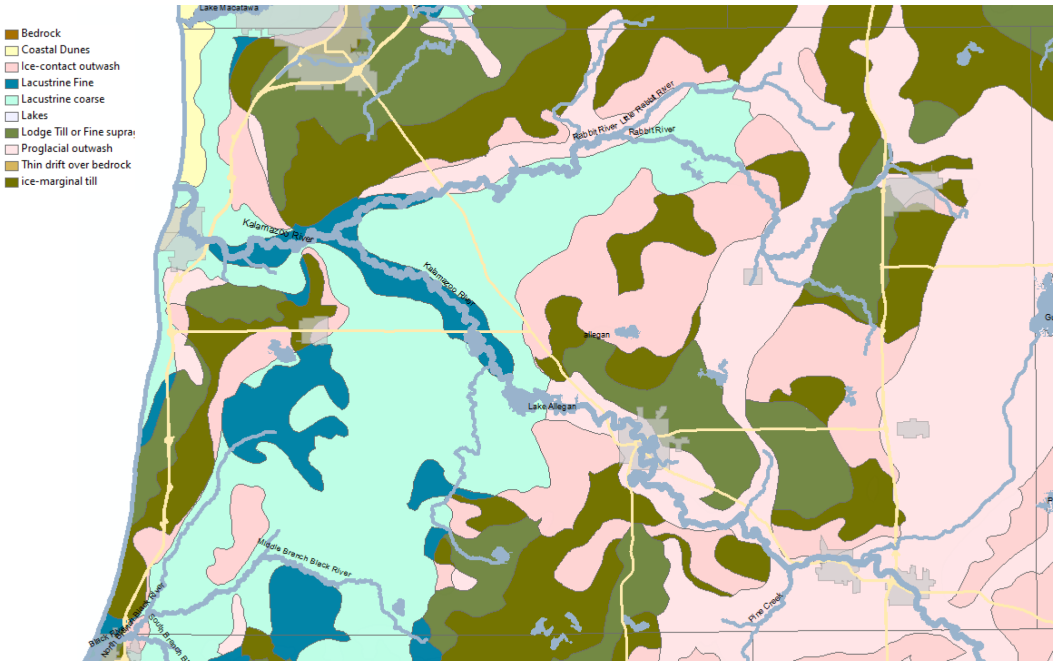
Confining Material



NOTE: Confining material underlain by aquifer materials

NOTE: Continuous subregion of aquifer material





Aquifer Cross-sections with Well Lithologies

North-south cross-section, southwestern portion of Allegan County

Aquifer Material

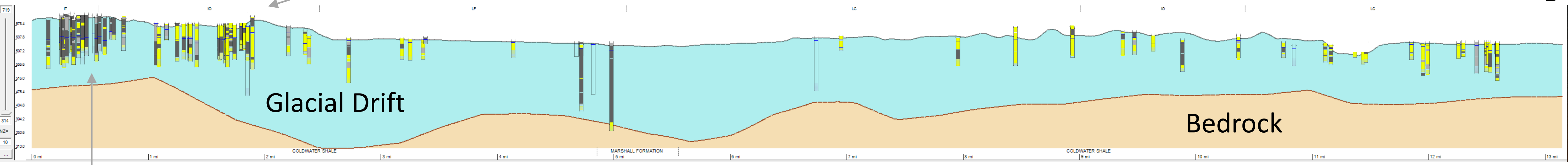
Marginal Aquifer / Partially Confining Material

Confining Material

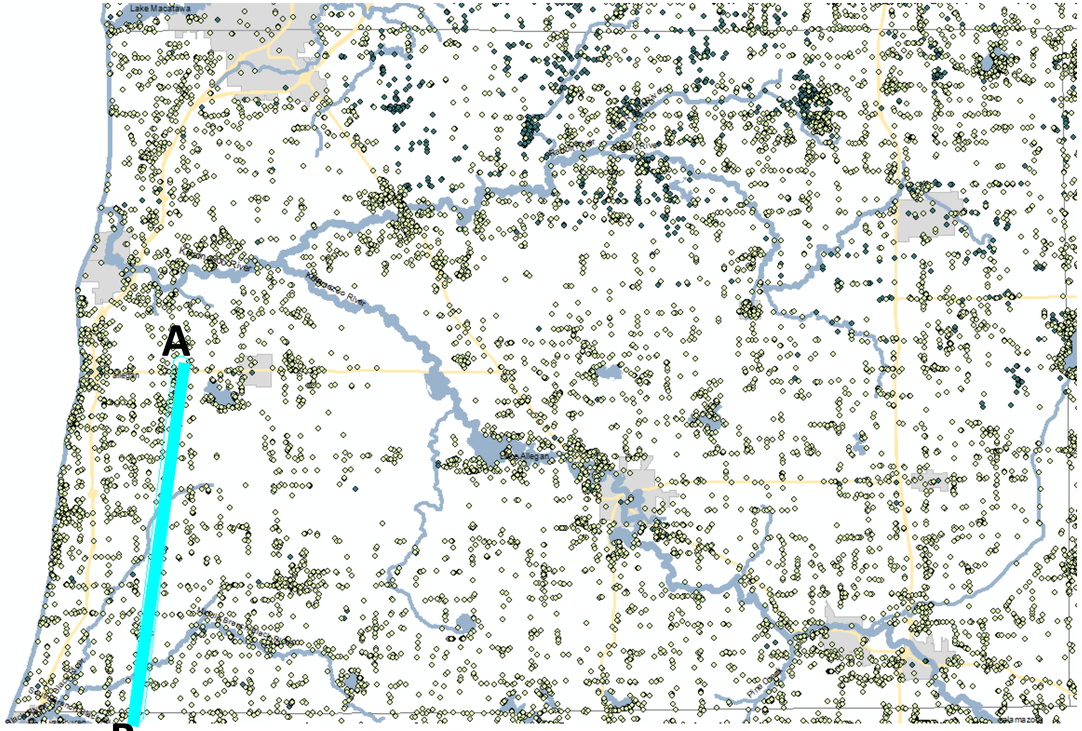
A

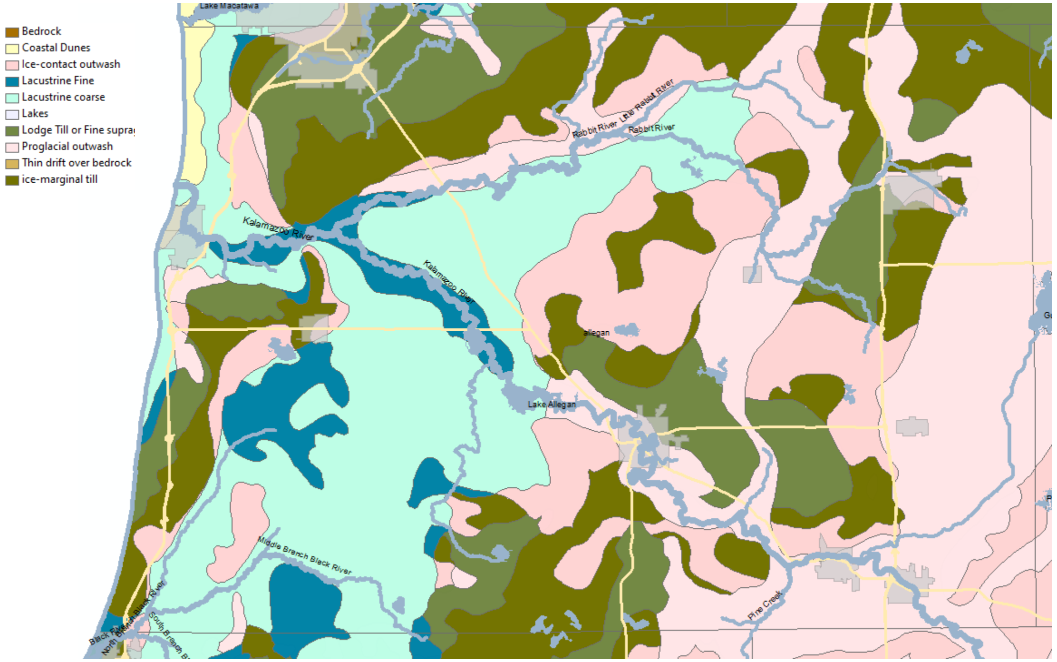
NOTE: Vertical mixing of aquifer and confining materials

B



NOTE: Confining material underlain by aquifer materials





Aquifer Cross-sections with Well Lithologies

West-east cross-section, north-northwestern portion of Allegan County

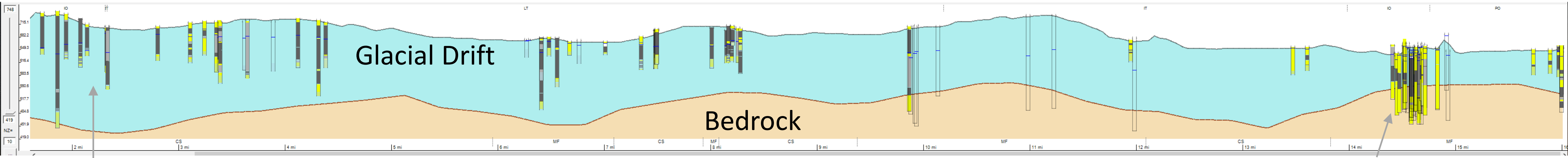
Aquifer Material

Marginal Aquifer / Partially Confining Material

Confining Material

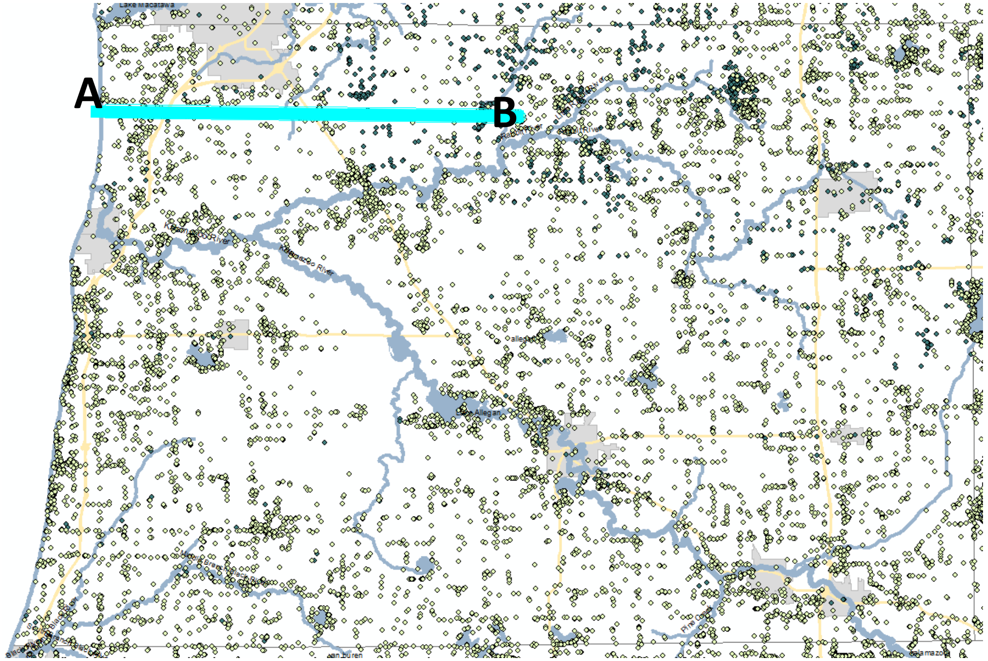
A

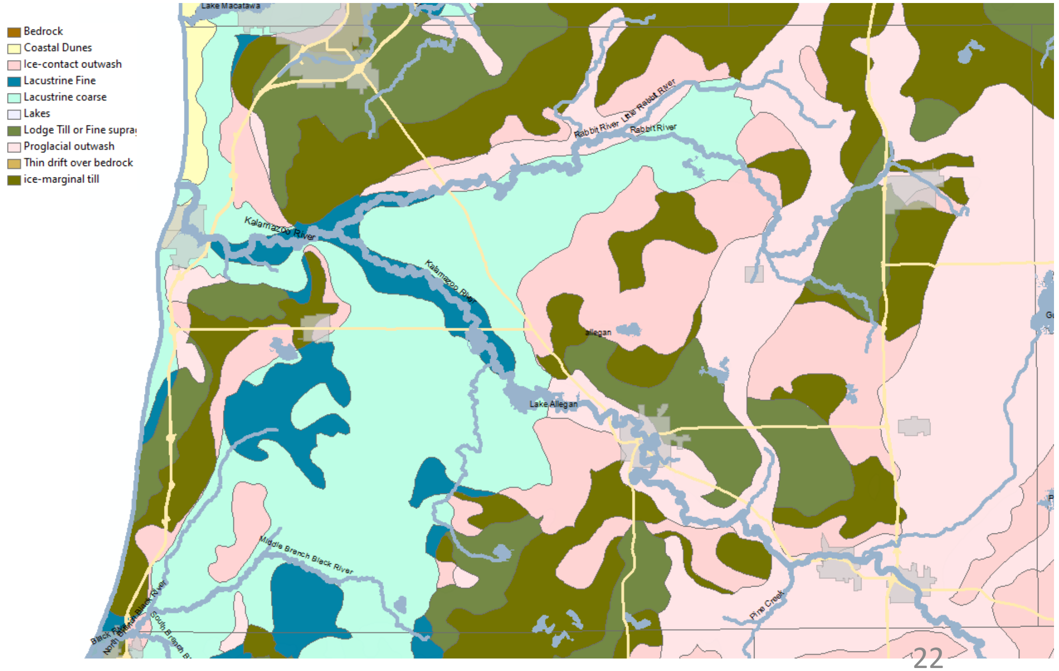
B



NOTE: Thick deposits of confining material

NOTE: AQ materials underlain by confining materials, underlain by bedrock aquifer





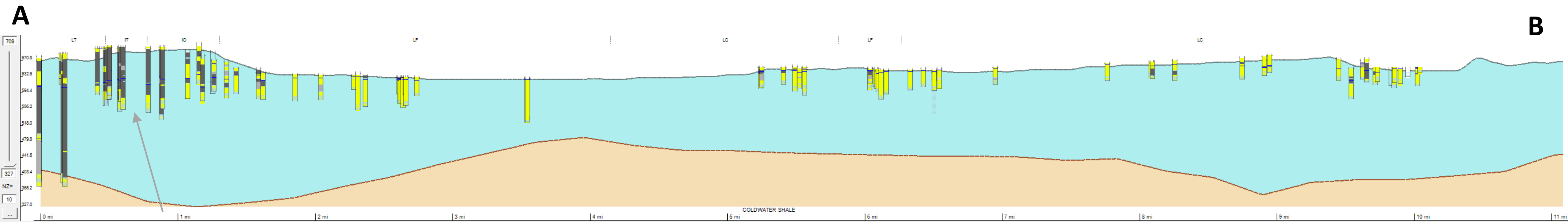
Aquifer Cross-sections with Well Lithologies

West-east cross-section, western portion of Allegan County

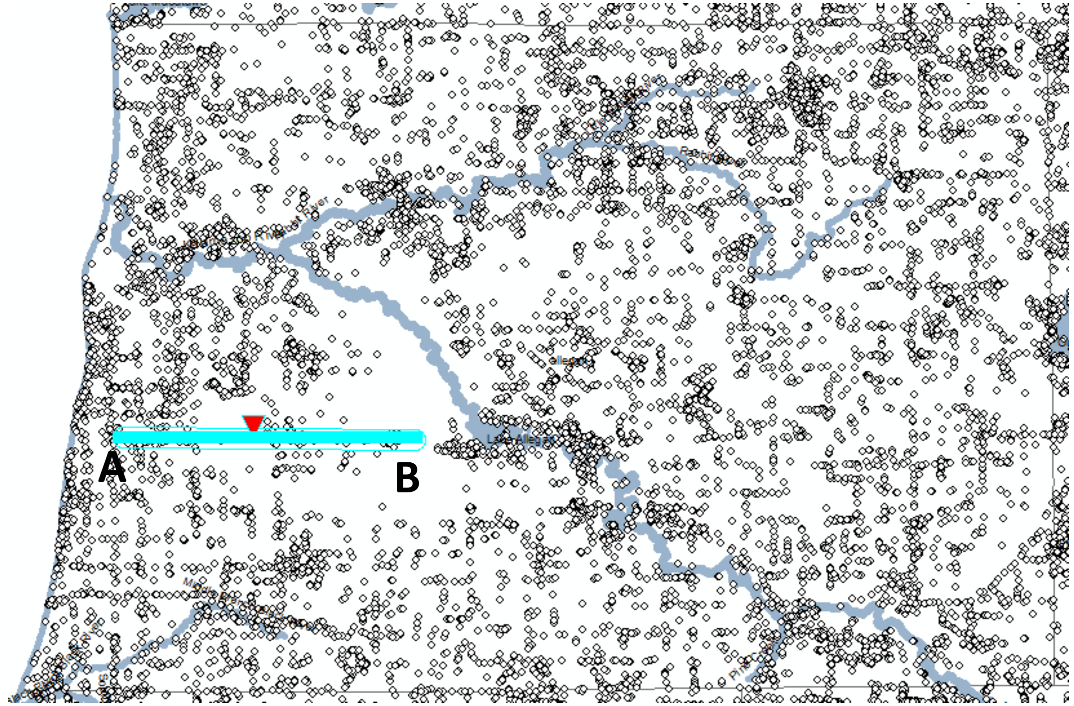
Aquifer Material

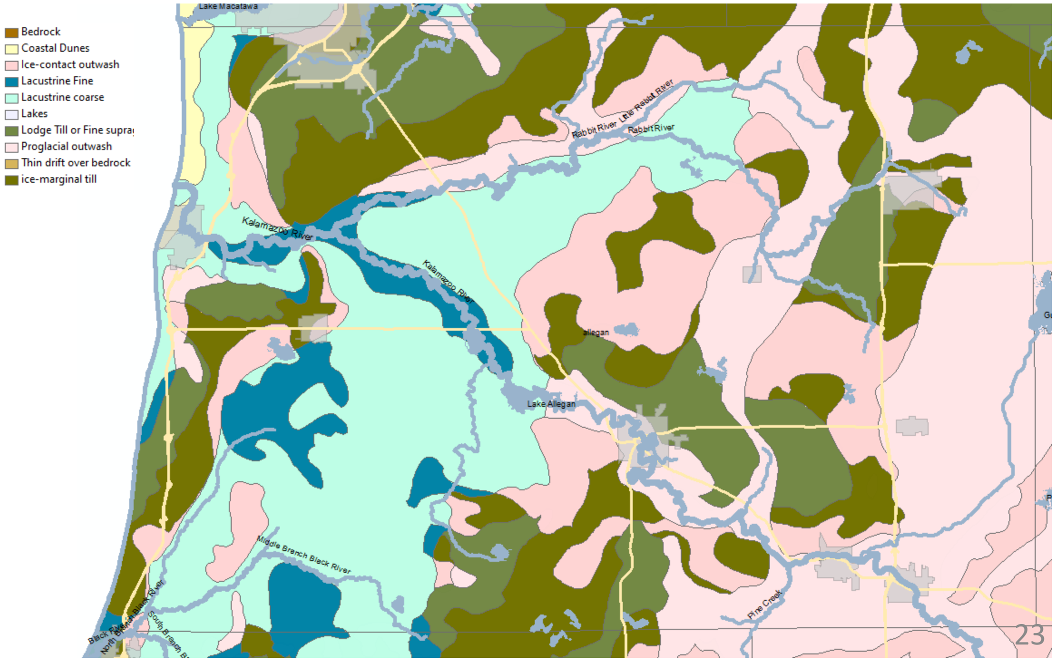
Marginal Aquifer / Partially Confining Material

Confining Material



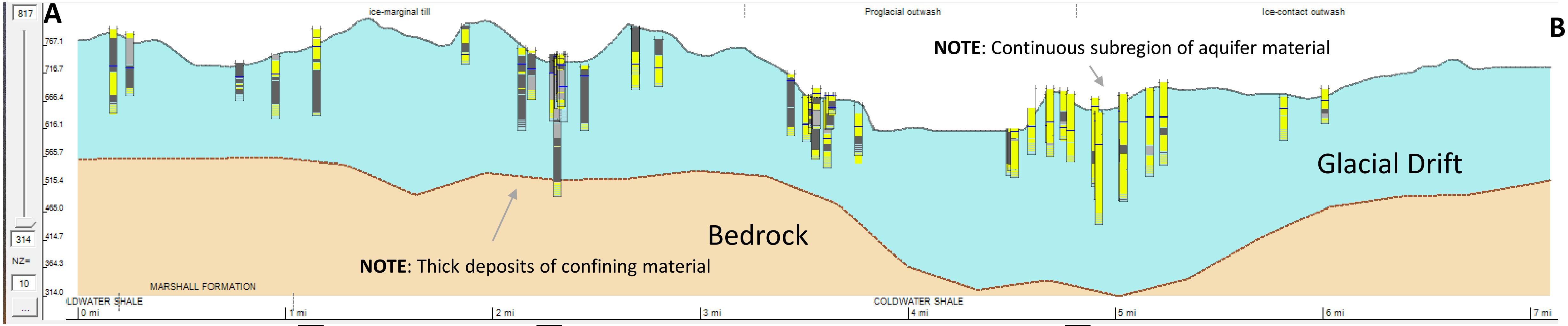
NOTE: Confining material underlain by aquifer materials



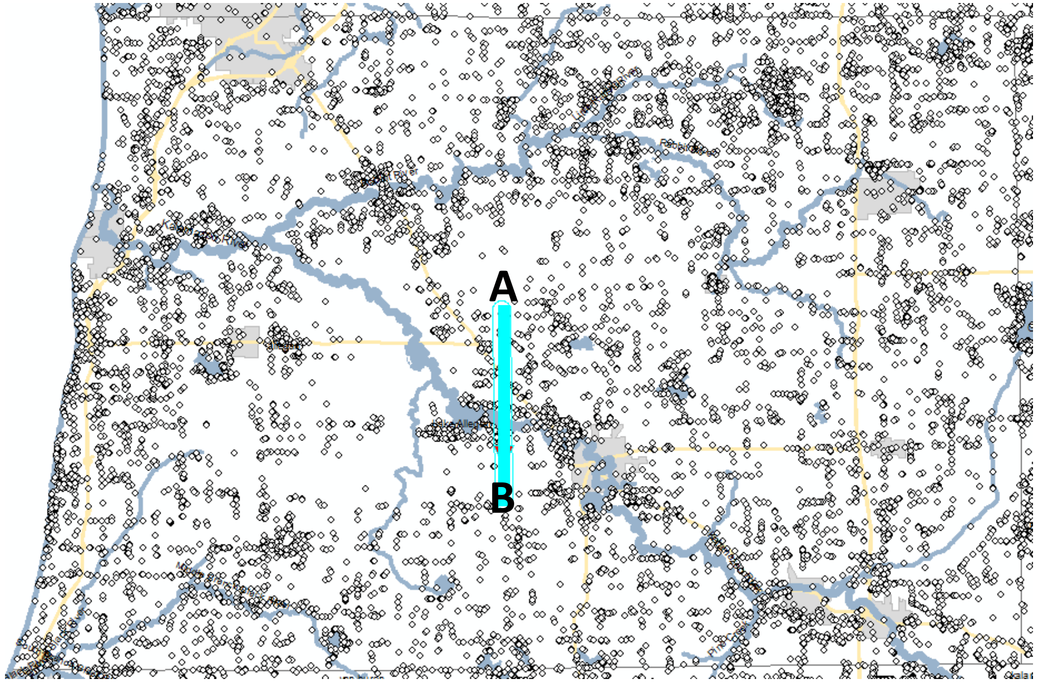


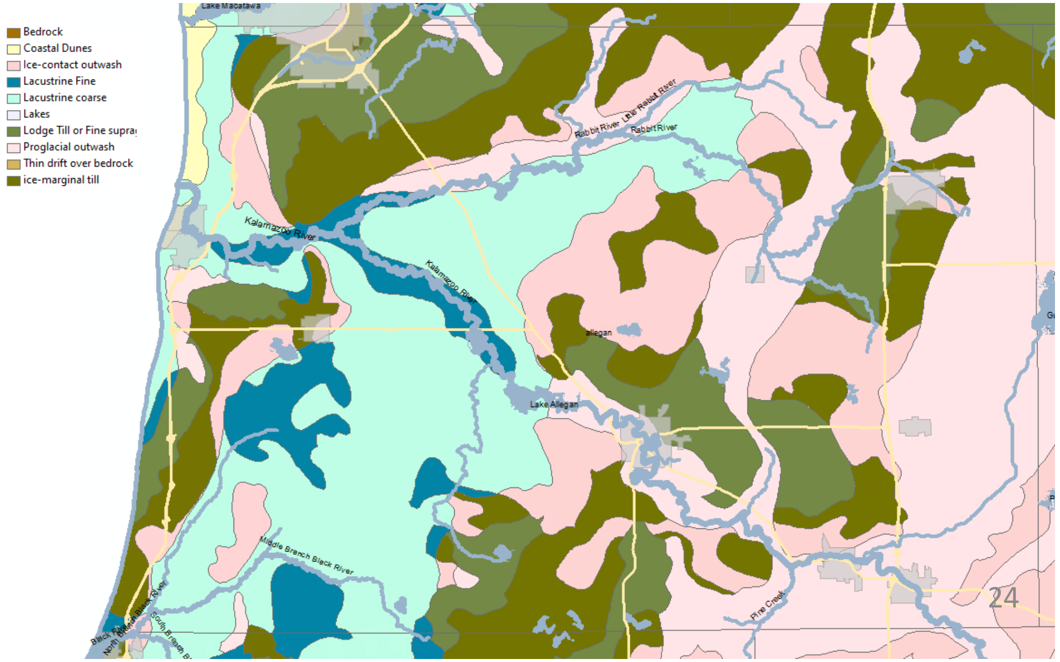
Aquifer Cross-sections with Well Lithologies

North-south cross-section, central portion of Allegan County



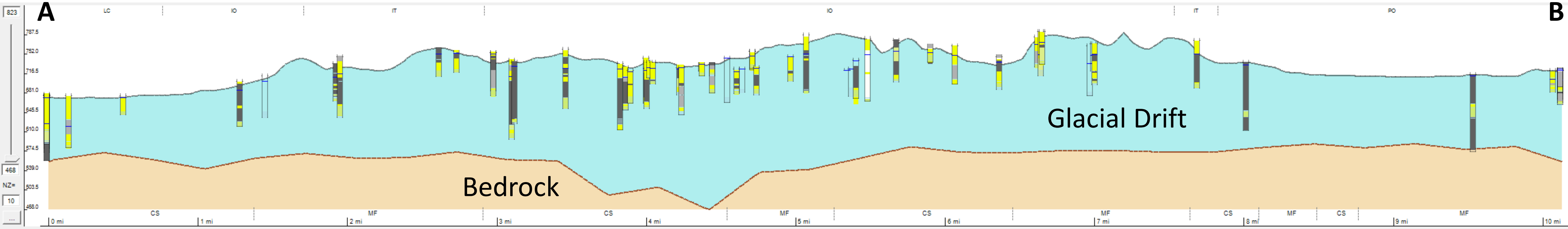
Aquifer Material   Marginal Aquifer / Partially Confining Material   Confining Material



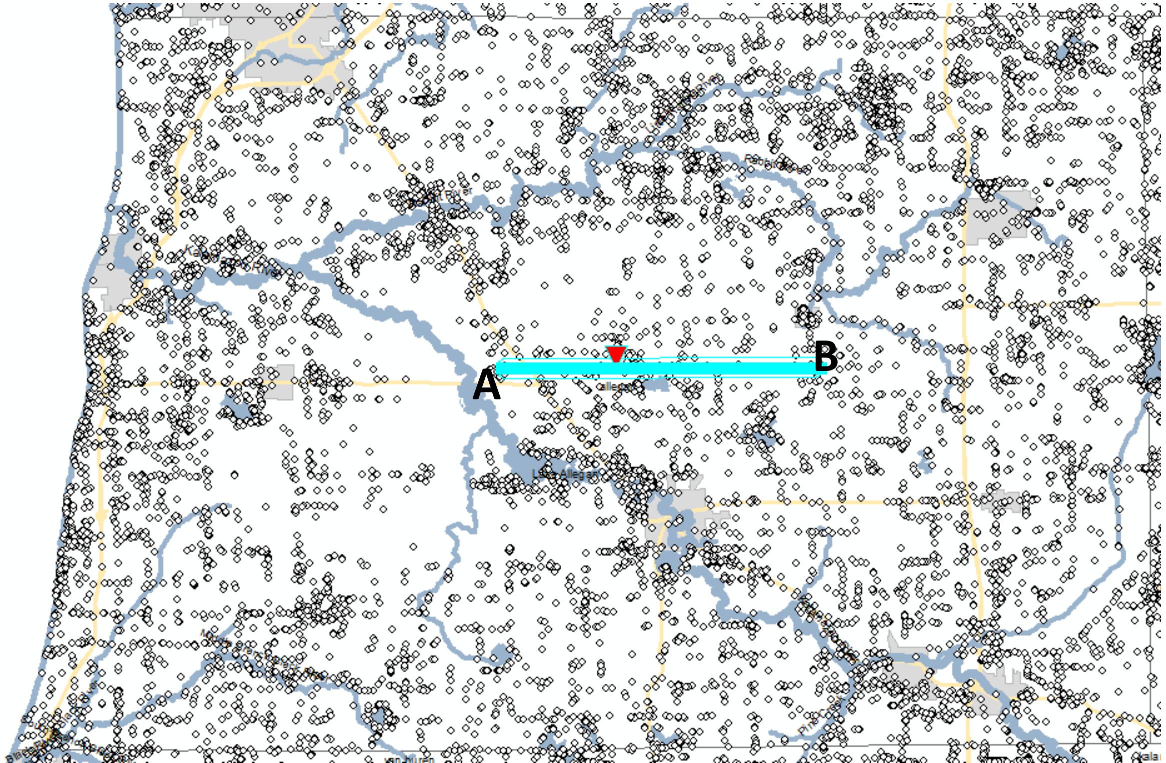


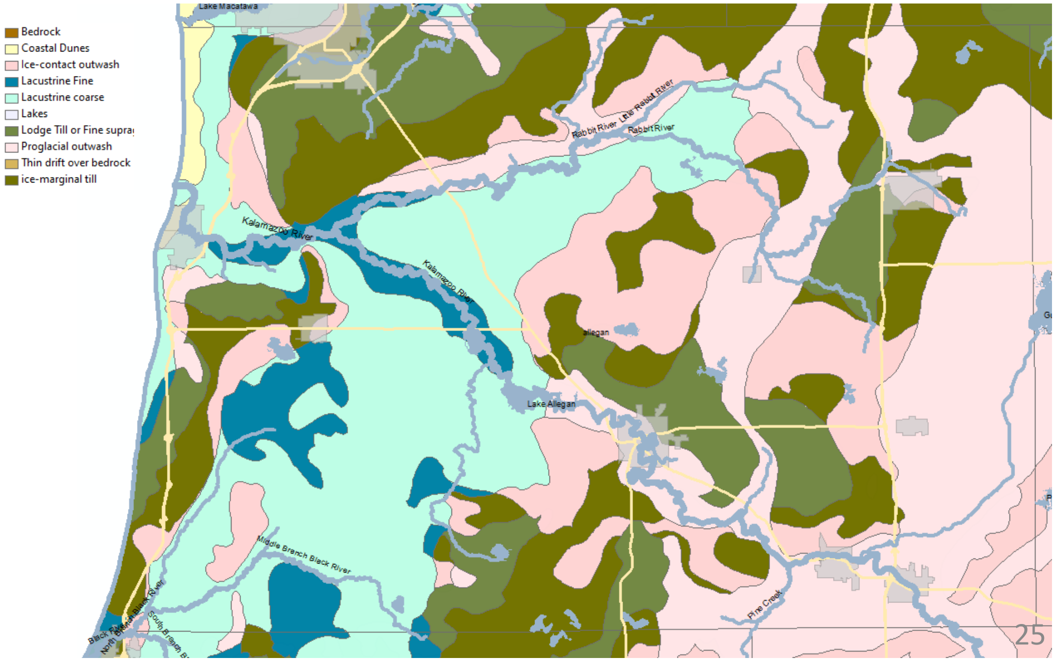
Aquifer Cross-sections with Well Lithologies

West-east cross-section, central portion of Allegan County



Aquifer Material   Marginal Aquifer / Partially Confining Material   Confining Material





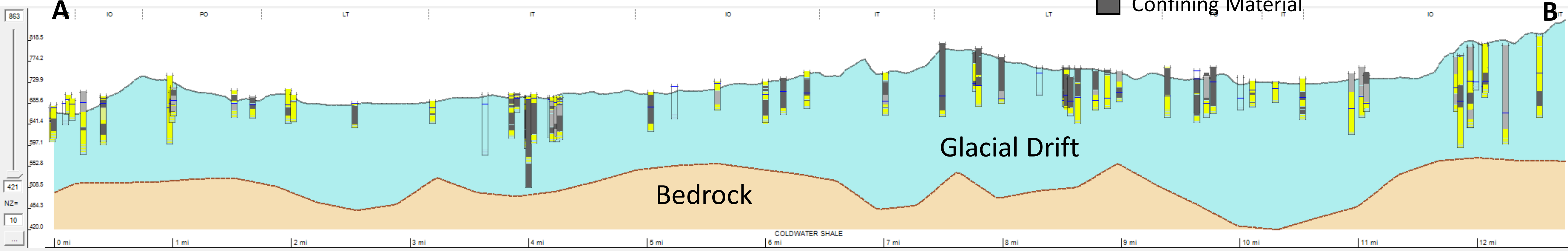
Aquifer Cross-sections with Well Lithologies

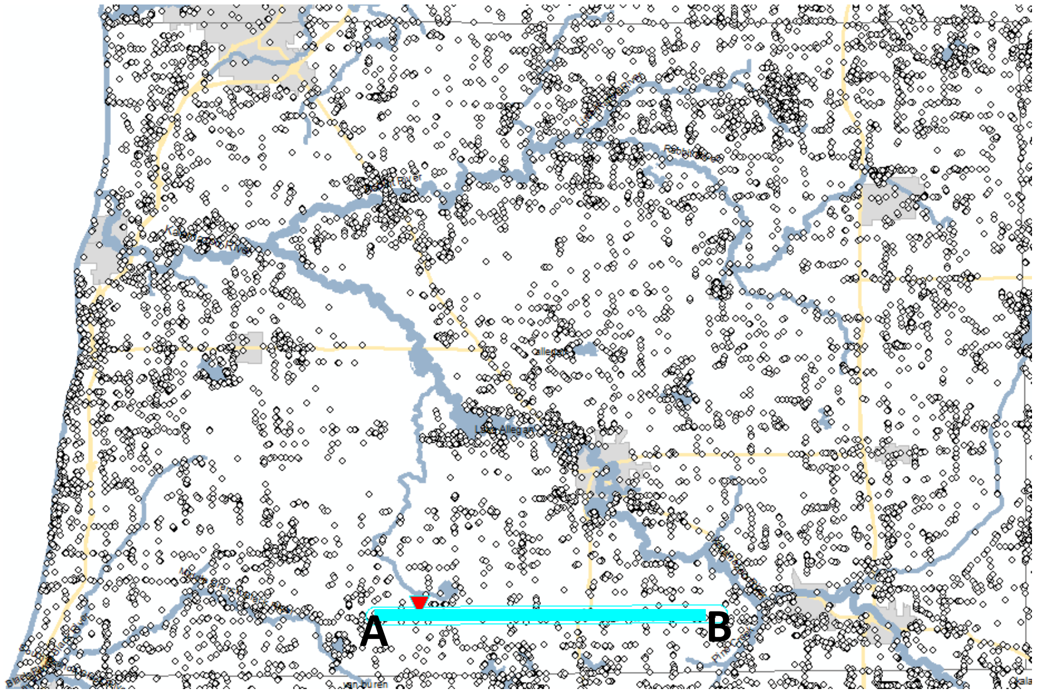
West-east cross-section, south-central portion of Allegan County

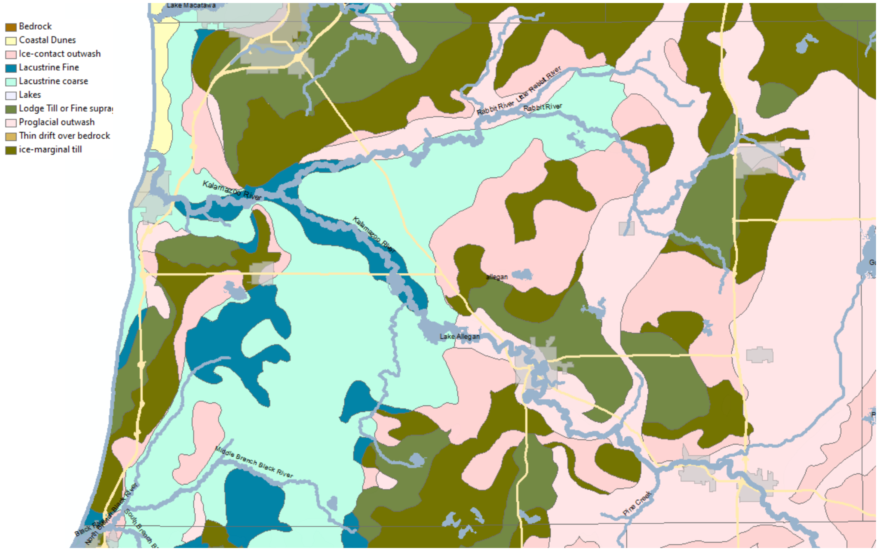
Aquifer Material

Marginal Aquifer / Partially Confining Material

Confining Material

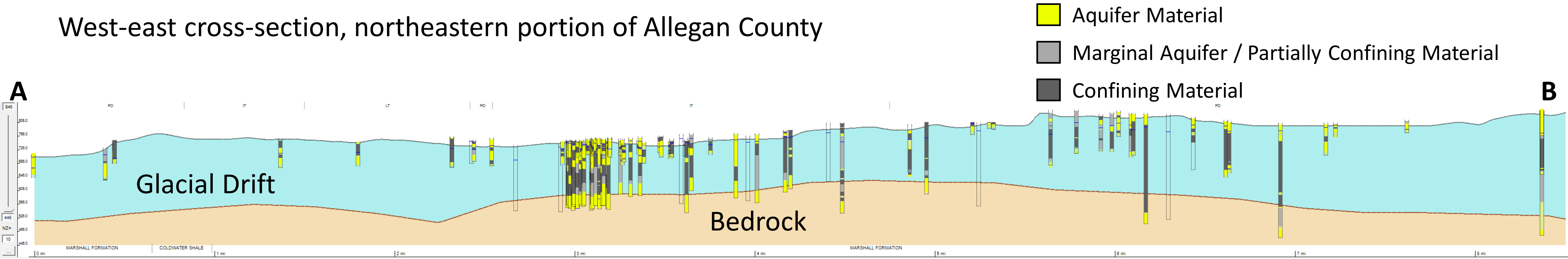


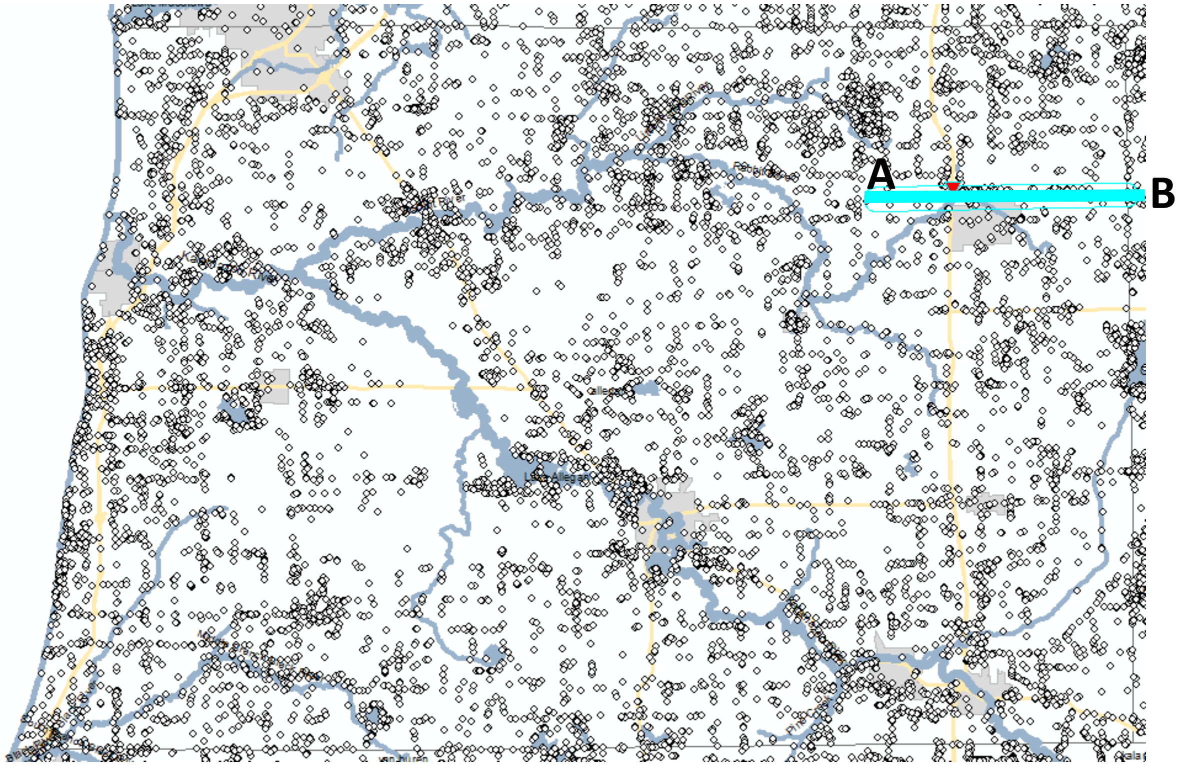


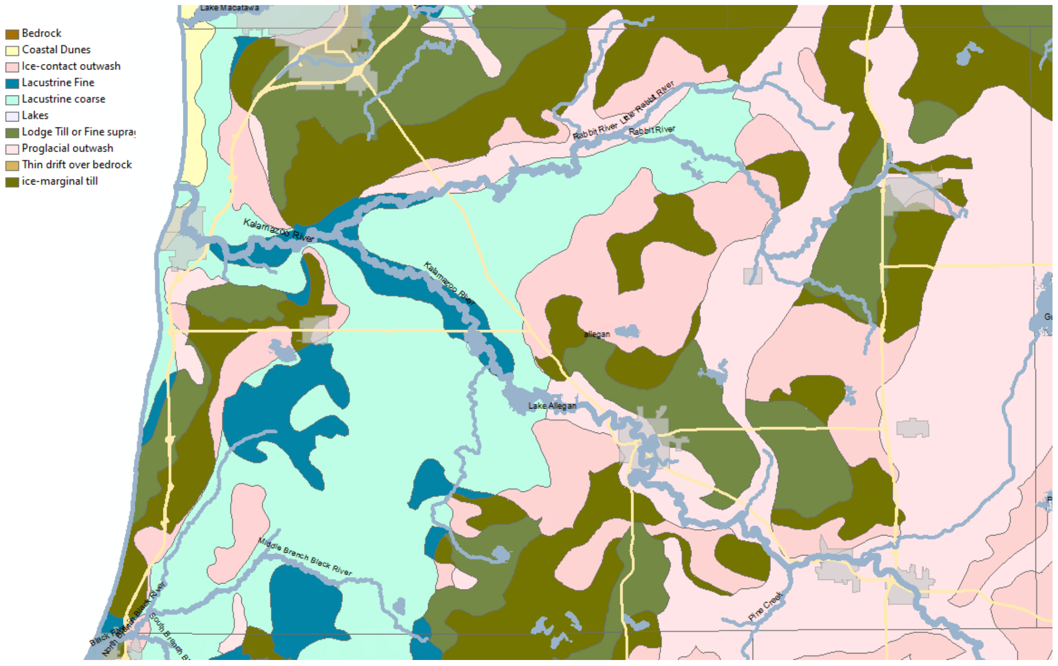


Aquifer Cross-sections with Well Lithologies

West-east cross-section, northeastern portion of Allegan County







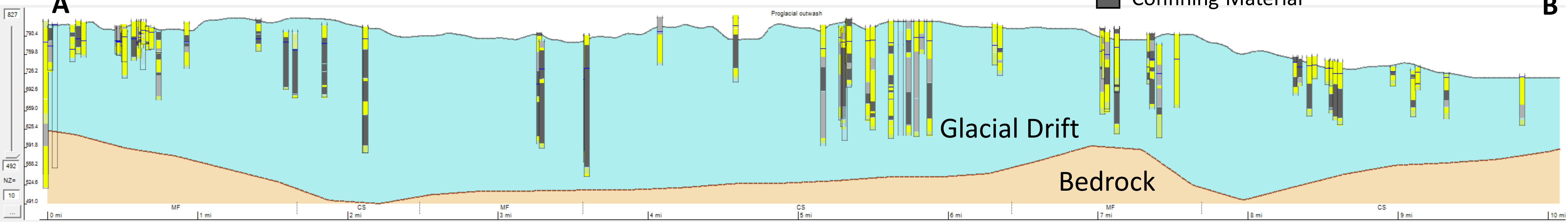
Aquifer Cross-sections with Well Lithologies

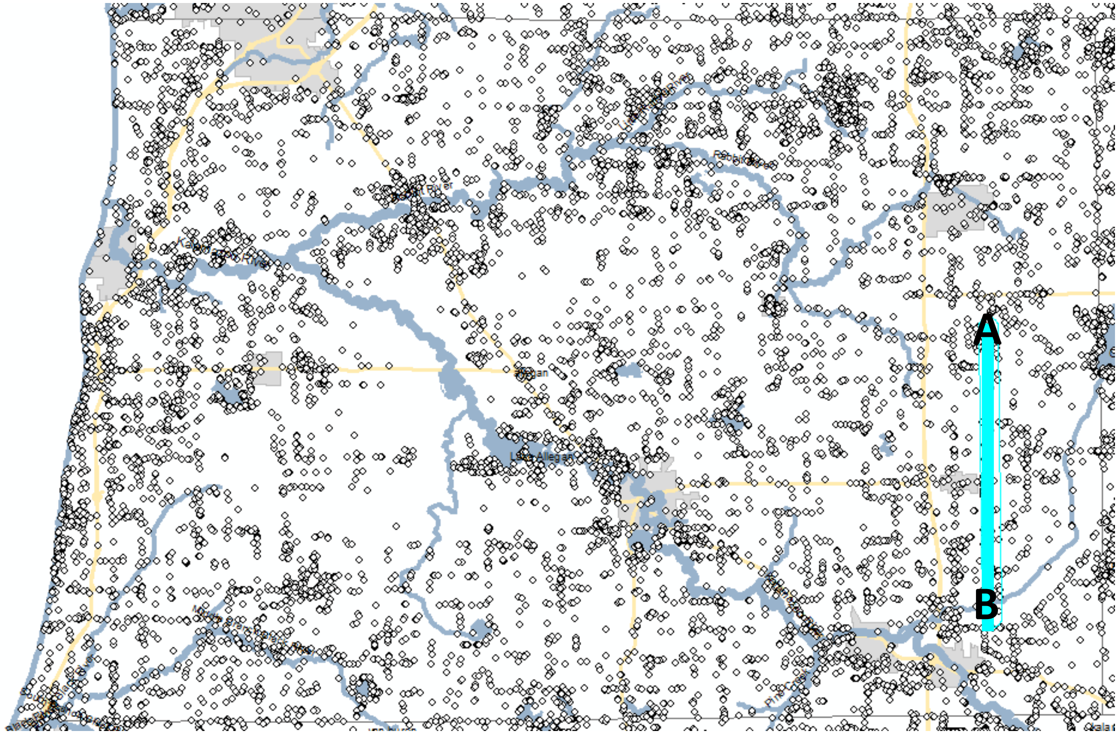
North-south cross-section, eastern-southeastern portion of Allegan County

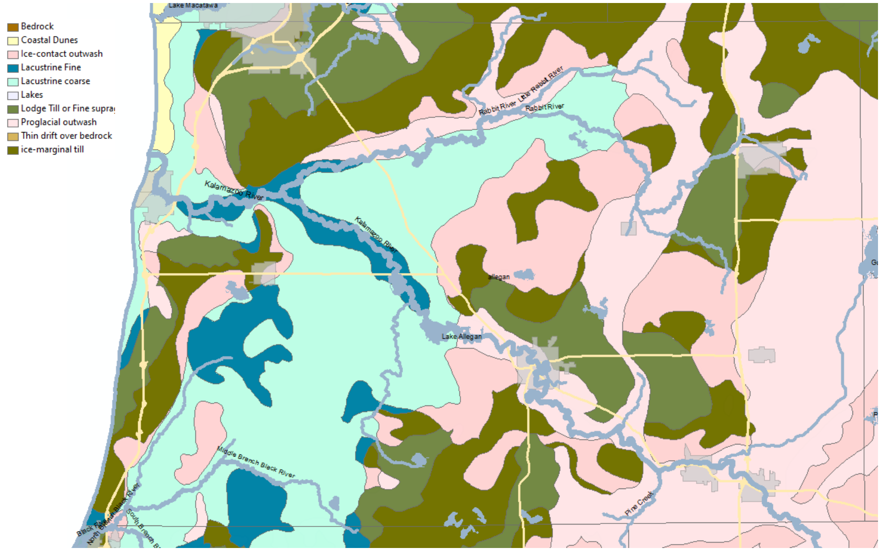
Aquifer Material

Marginal Aquifer / Partially Confining Material

Confining Material







3D Model of Glacial Aquifer Heterogeneity

We developed a regional glacial aquifer heterogeneity model for Allegan County using the transition probability geostatistical simulation technique on more than 10,000 wells (with lithology information available) in the *Wellogic* dataset. The model was built at a resolution of 250 m horizontally and 3.5m vertically. The reclassified boreholes (subjective descriptions -> material types: aquifer material [AQ], marginal aquifer material [MAQ], partially confining material [PCM], and confining material [CM]) were analyzed to create a transition probability matrix of vertical spatial correlations between the material types as a function of lag spacing (distance between measurement points). Graphical depictions of the spatial correlations vs. 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 was used to create a 3D realization of the glacial aquifer material distribution that extends from the 10m digital elevation model (DEM) top boundary to the top of the bedrock surface interpolated from lithologic records in *Wellogic* (500m resolution). This was done by assuming a ratio of horizontal extent of a material to its vertical extent— the "lens" ratio (or anisotropy ratio) — and applying the geostatistical models derived from Z-direction Markov chain analysis. We experimented with several different sets of lens ratios, attempting to find the set that best reproduced the large-scale glacial geology. The final anisotropy ratios for AQ, MAQ, PCM, and CM were chosen as 10, 10, 10, and 9.8, respectively, which are similar to the values chosen by Sampath et al. (2016) and Liao et al. 2019 when implementing the Transition Probability approach for a geologically similar regions in Lower Michigan. Similarly, we tested several different compression ratios needed to "compress" the data in the horizontal direction during simulation because of the disparate length scales in the horizontal and vertical directions. The model showed relatively little sensitivity to a reasonable set of compression ratios (greater than one but less than 20). The final compression ratio used was 5.

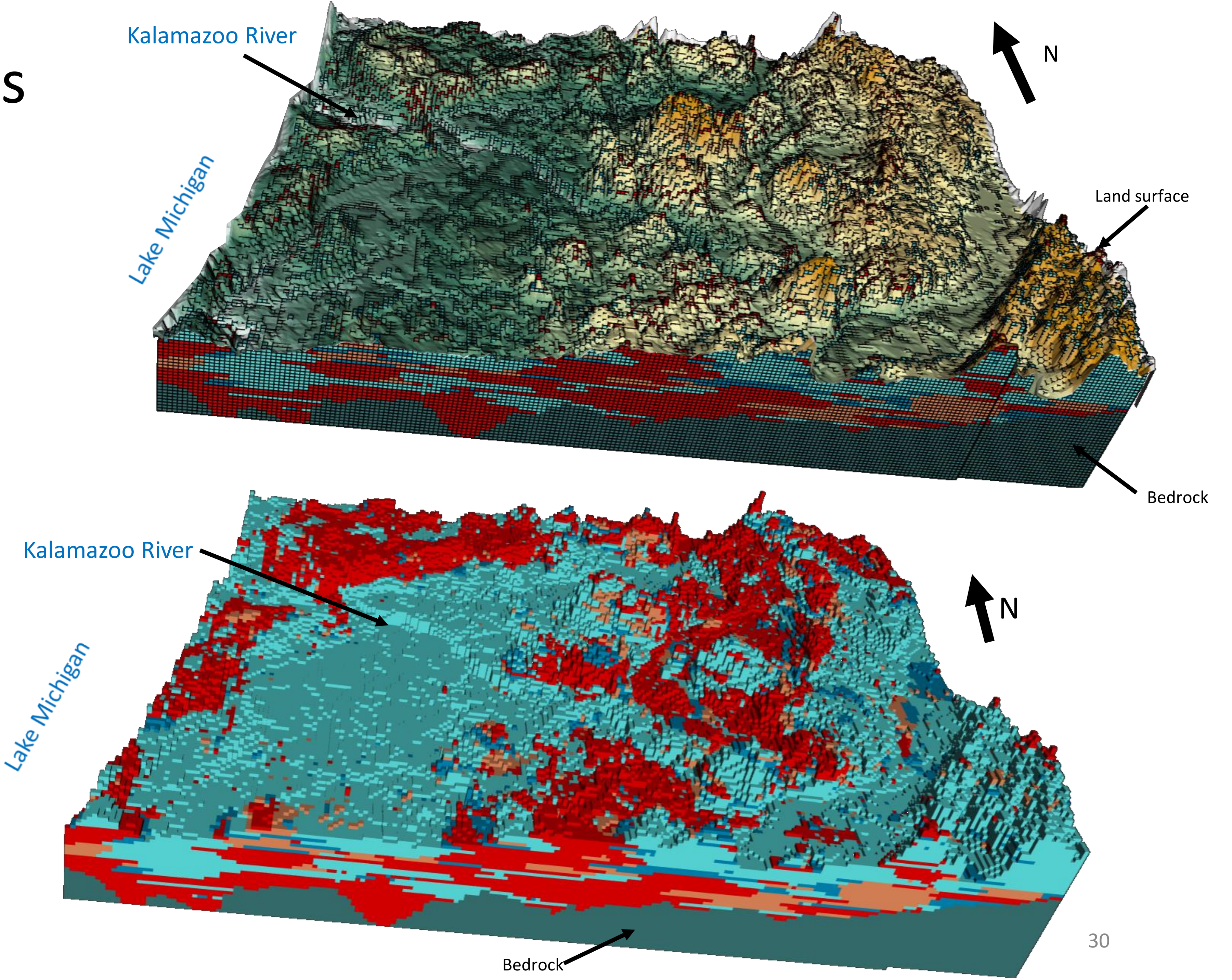
In many places in the County, water wells are within a few hundred meters of one another. Wherever multiple wells occurred in one model cell (250 x 250 m) they were virtualized or aggregated into a single well with effective lithologies interpolated to each 3.5-meter of depth. This aggregation method was necessary to enable the geostatistical simulation for the entire County.

In the resulting 3D model, each cell was assigned as one of the four material types for each model realization. Two hundred and fifty realizations were executed to produce an ensemble mean model by assigning the most frequently occurring material at each grid cell. This 3D model represents only the coarse-scale variability of glacial deposits across Allegan County. The horizontal and vertical distribution of the major lithologies (aquifer, marginal aquifer, partially confining or confining materials) within the actual glacial deposits can be significantly more heterogeneous.

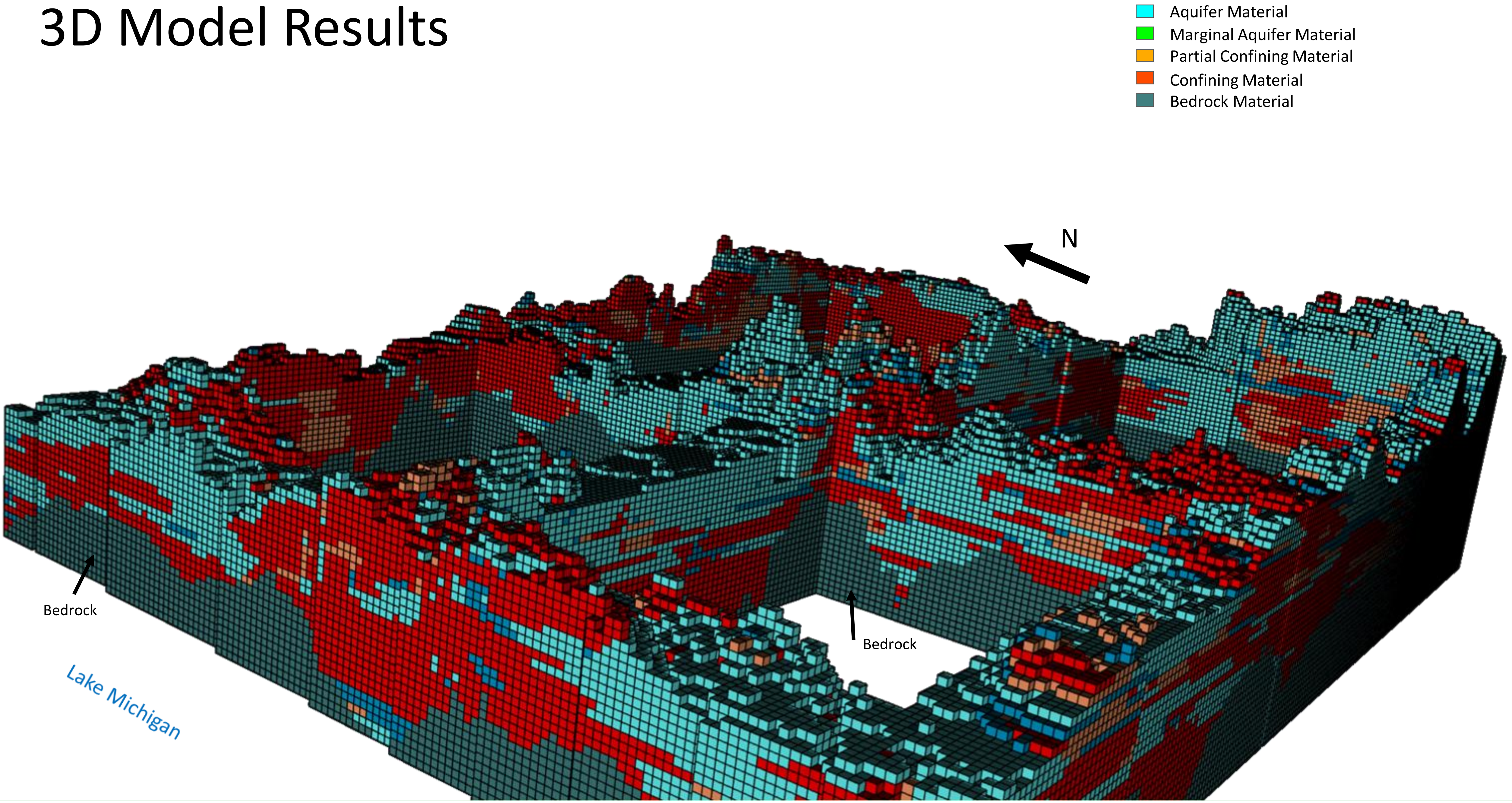
Next, we present a series of cross-sections of the countywide glacial aquifer heterogeneity model. (NOTE: It is challenging to present the highly complex 3D geology in a written report. A Decision Support-System will allow the county to interactively / dynamically identify and probe the geological model and any location or depth.)

3D Model Results

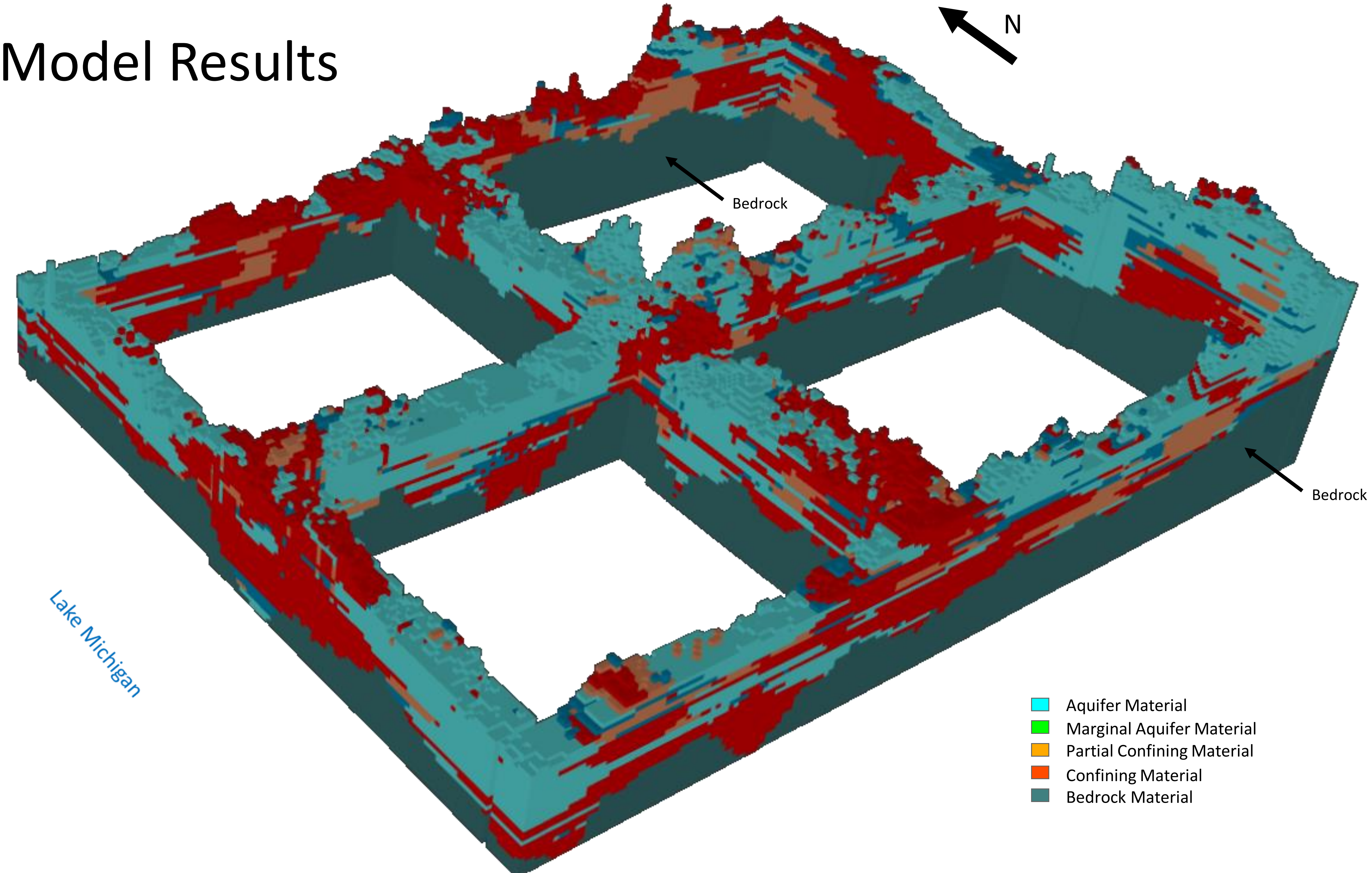
- Aquifer Material
- Marginal Aquifer Material
- Partial Confining Material
- Confining Material
- Bedrock Material

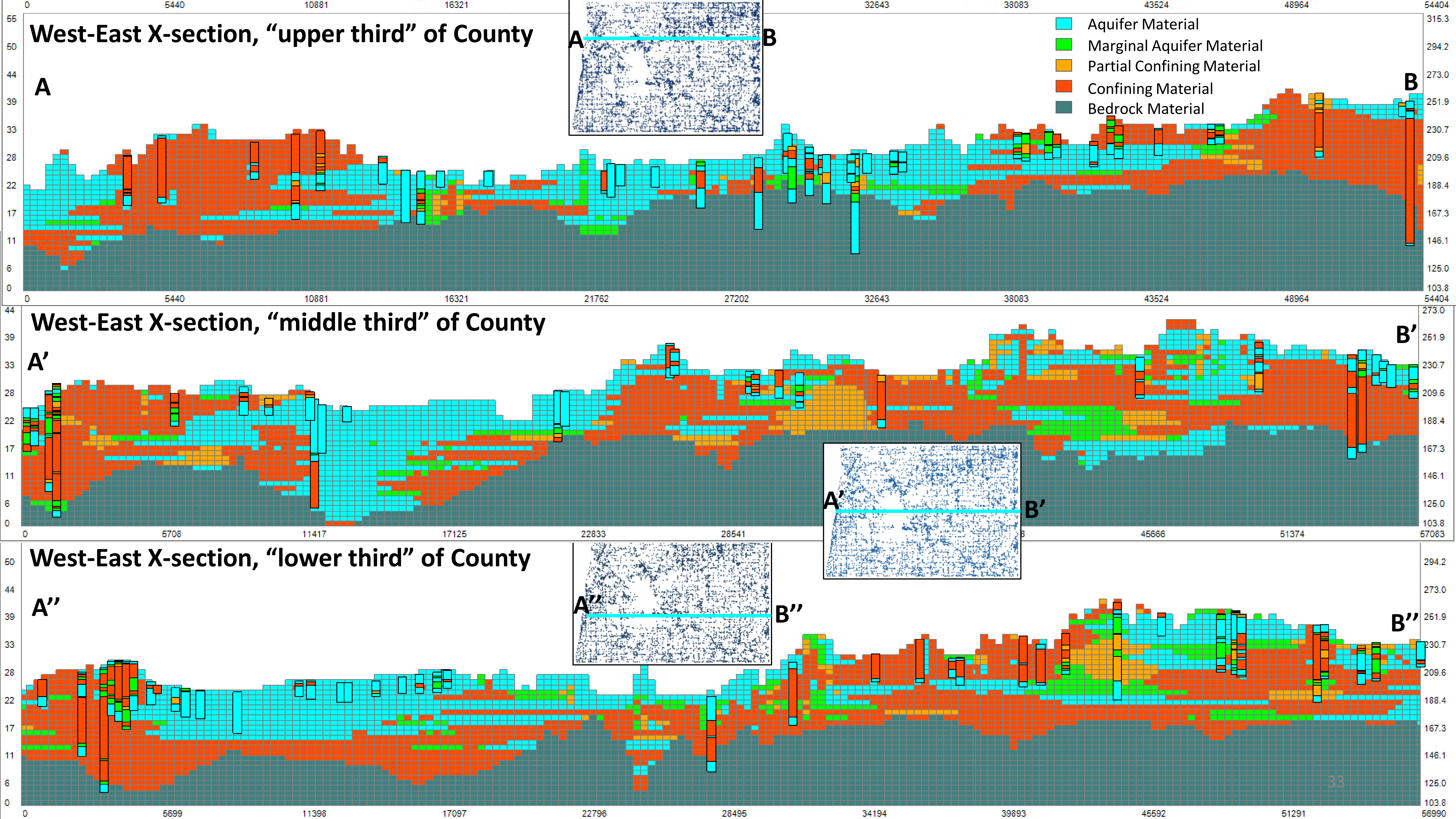


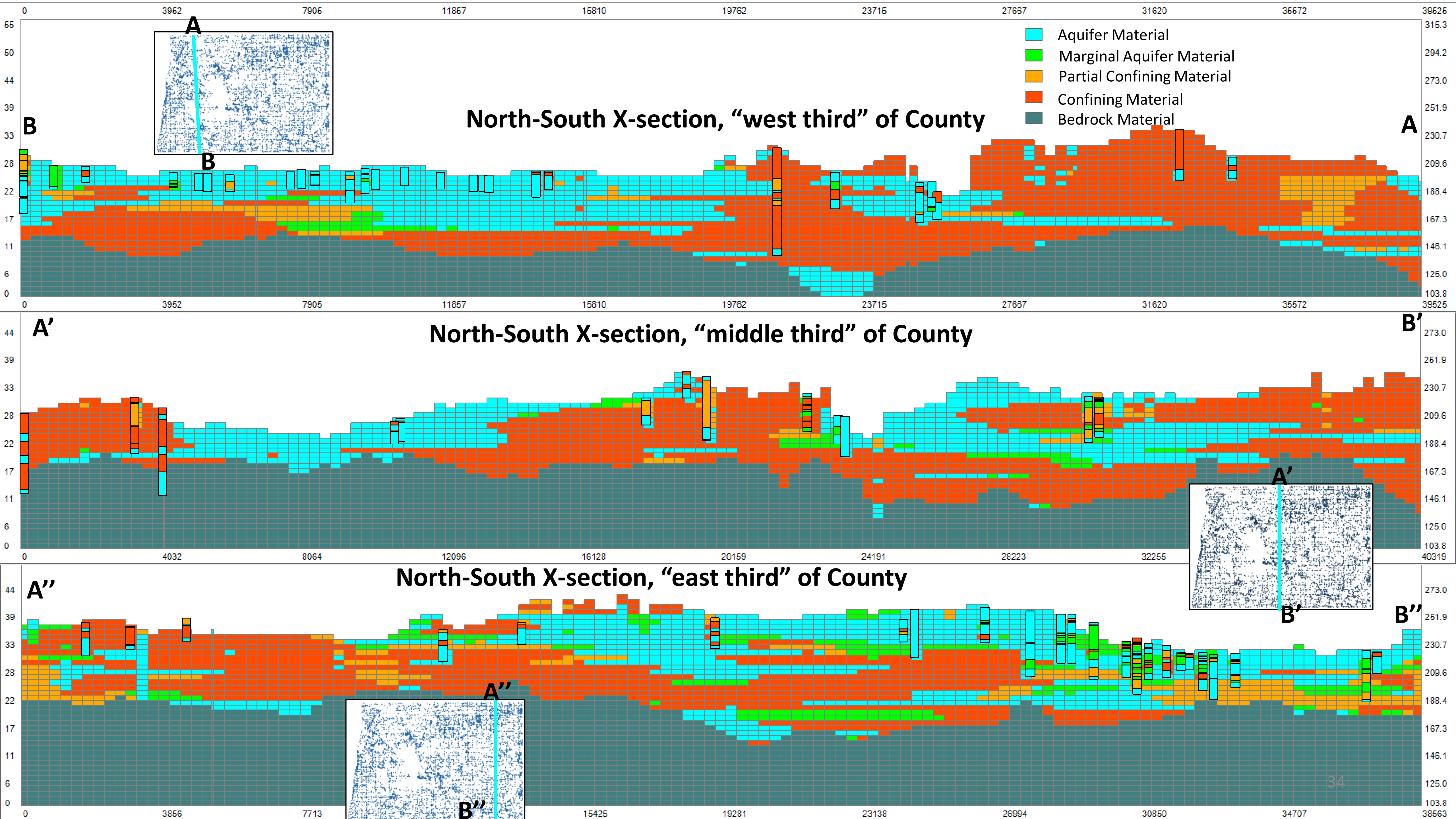
3D Model Results



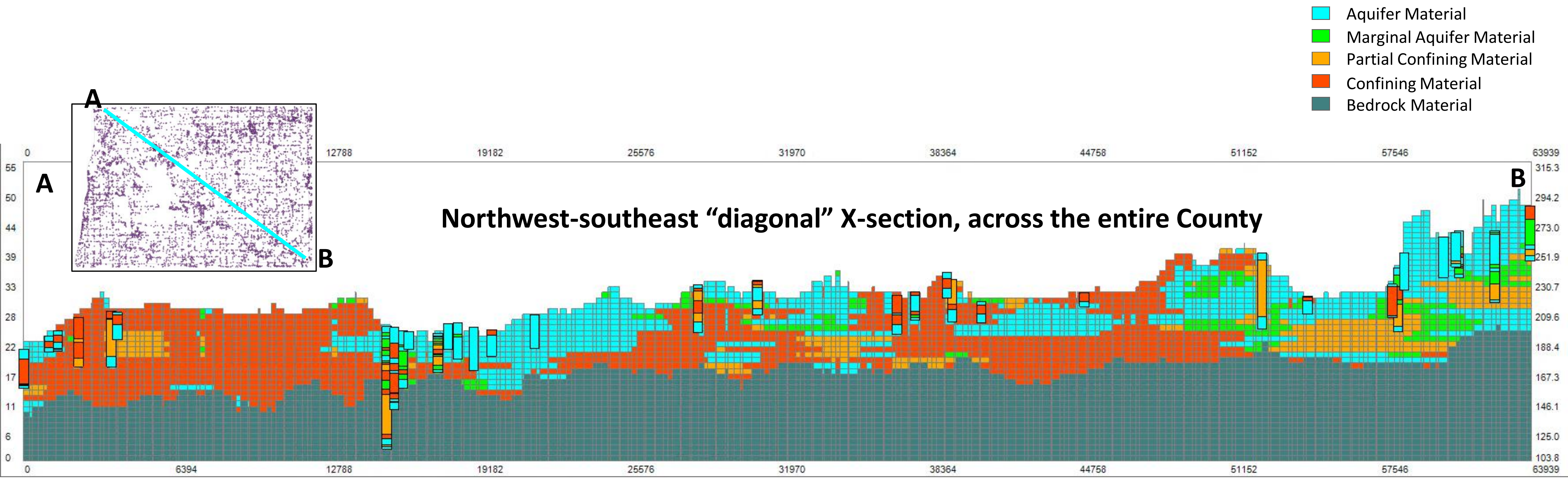
3D Model Results



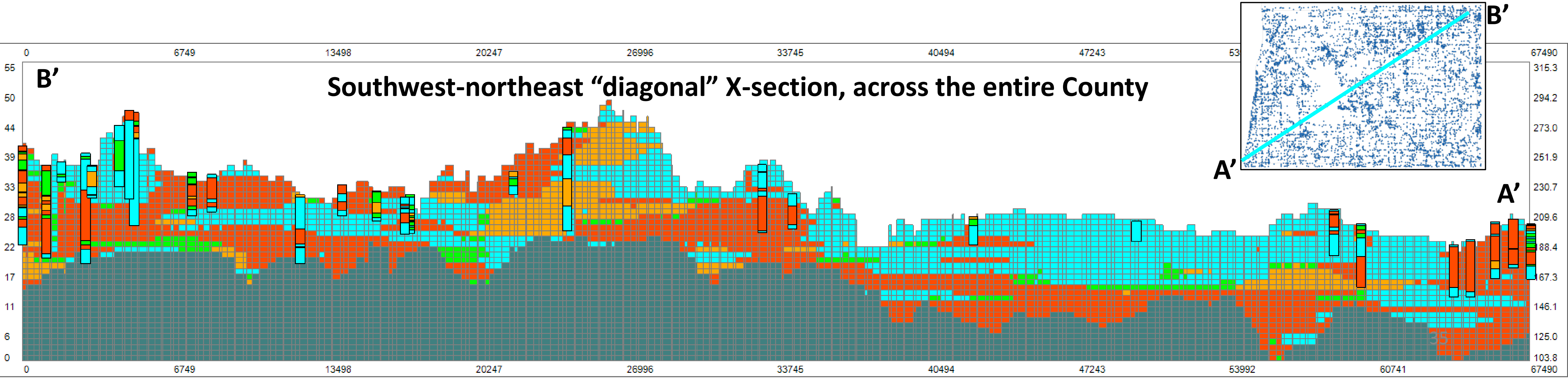

West-East X-section, "upper third" of County
A
B
Aquifer Material
Marginal Aquifer Material
Partial Confining Material
Confining Material
Bedrock Material
0 5440 10881 16321 21762 27202 32643 38083 43524 48964 54404
55 50 44 39 33 28 22 17 11 6 0
315.3 294.2 273.0 251.9 230.7 209.6 188.4 167.3 146.1 125.0 103.8
West-East X-section, "middle third" of County
A'
B'
0 5708 11417 17125 22833 28541 45666 51374 57083
44 39 33 28 22 17 11 6 0
273.0 251.9 230.7 209.6 188.4 167.3 146.1 125.0 103.8
West-East X-section, "lower third" of County
A''
B''
0 5699 11398 17097 22796 28495 34194 39893 45592 51291 56990
50 44 39 33 28 22 17 11 6 0
294.2 273.0 251.9 230.7 209.6 188.4 167.3 146.1 125.0 103.8



North-South X-section, "west third" of County
B
A
A
B
Aquifer Material
Marginal Aquifer Material
Partial Confining Material
Confining Material
Bedrock Material
0 3952 7905 11857 15810 19762 23715 27667 31620 35572 39525
55 50 44 39 33 28 22 17 11 6 0
315.3 294.2 273.0 251.9 230.7 209.6 188.4 167.3 146.1 125.0 103.8
North-South X-section, "middle third" of County
A'
B'
A'
B'
0 4032 8064 12096 16128 20159 24191 28223 32255 40319
44 39 33 28 22 17 11 6 0
273.0 251.9 230.7 209.6 188.4 167.3 146.1 125.0 103.8
North-South X-section, "east third" of County
A''
B''
A''
B''
0 3856 7713 15425 19281 23138 26994 30850 34707 38563
44 39 33 28 22 17 11 6 0
273.0 251.9 230.7 209.6 188.4 167.3 146.1 125.0 103.8

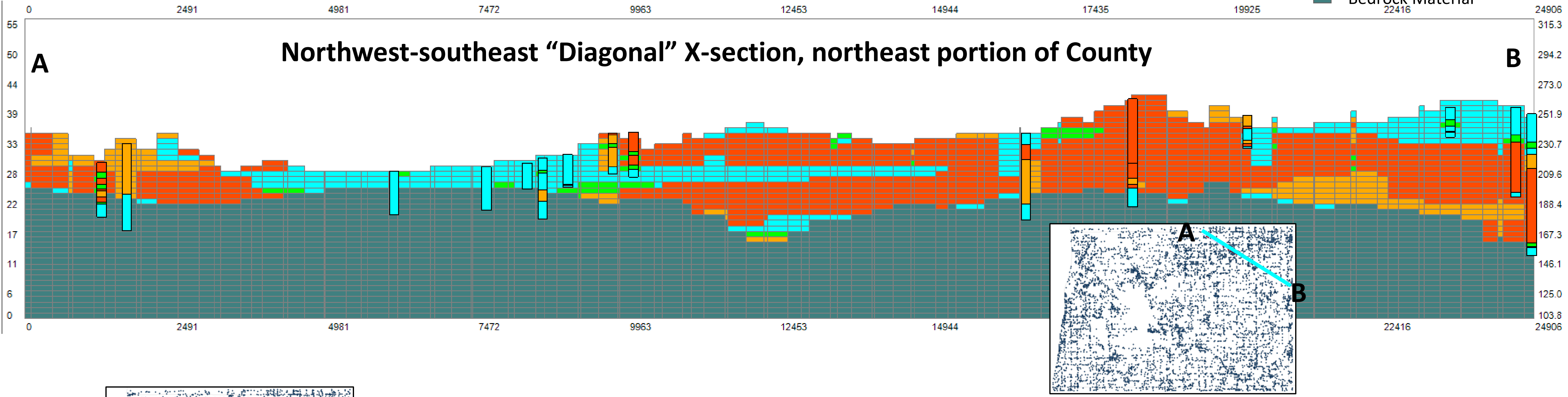


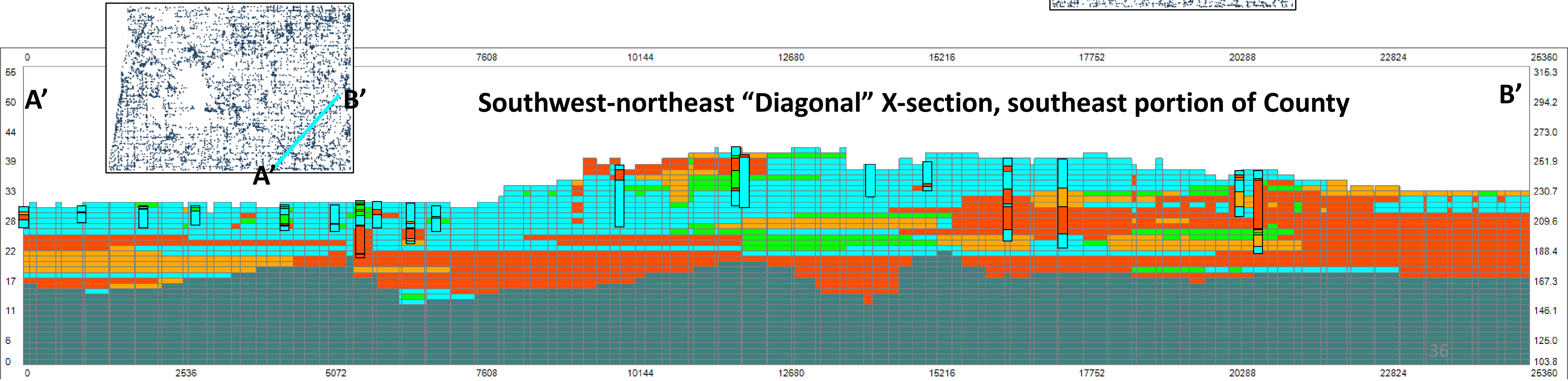
Aquifer Material
Marginal Aquifer Material
Partial Confining Material
Confining Material
Bedrock Material
A
B
Northwest-southeast “diagonal” X-section, across the entire County
0
6394
12788
19182
25576
31970
38364
44758
51152
57546
63939
55
50
44
39
33
28
22
17
11
6
0
315.3
294.2
273.0
251.9
230.7
209.6
188.4
167.3
146.1
125.0
103.8

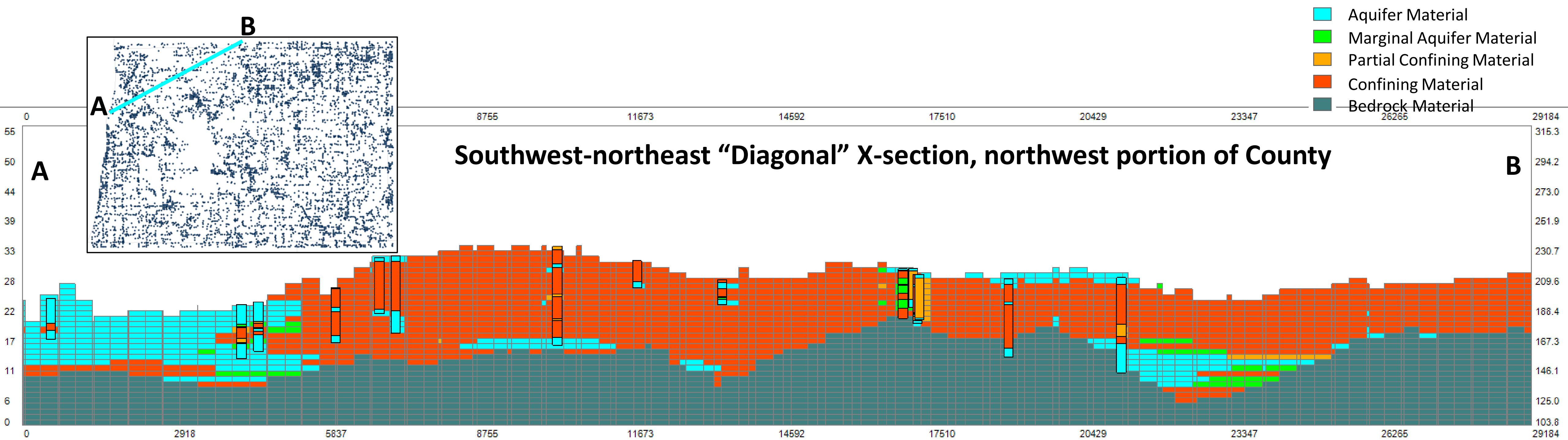


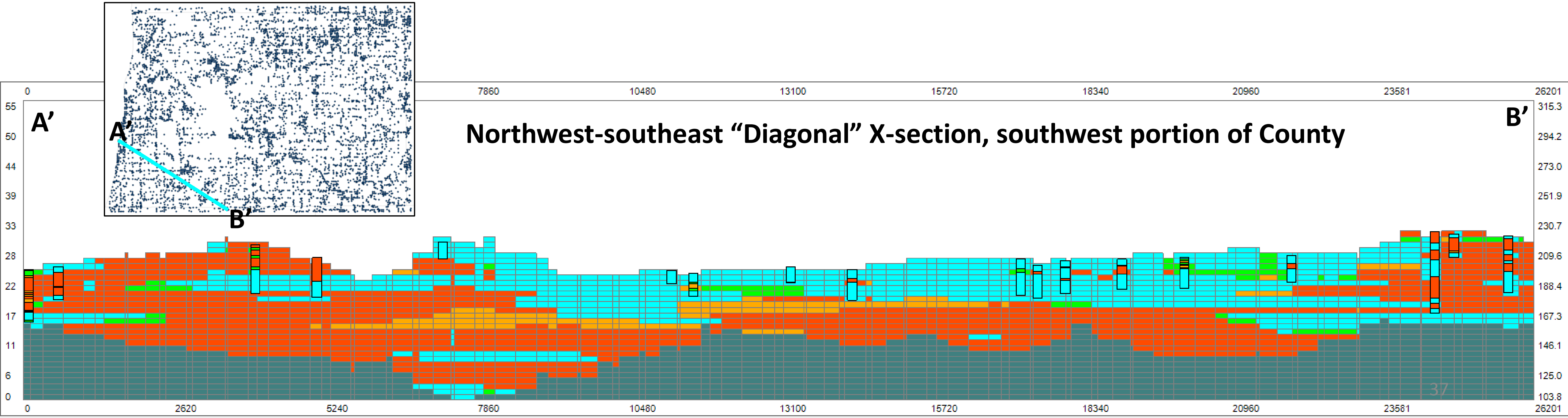
B’
A’
Southwest-northeast “diagonal” X-section, across the entire County
0
6749
13498
20247
26996
33745
40494
47243
53992
60741
67490
55
50
44
39
33
28
22
17
11
6
0
315.3
294.2
273.0
251.9
230.7
209.6
188.4
167.3
146.1
125.0
103.8

Aquifer Material
Marginal Aquifer Material
Partial Confining Material
Confining Material
Bedrock Material






Aquifer Material
Marginal Aquifer Material
Partial Confining Material
Confining Material
Bedrock Material
A
B
Southwest-northeast "Diagonal" X-section, northwest portion of County
A
B
0
2918
5837
8755
11673
14592
17510
20429
23347
26265
29184
55
50
44
39
33
28
22
17
11
6
0
315.3
294.2
273.0
251.9
230.7
209.6
188.4
167.3
146.1
125.0
103.8


A'
B'
Northwest-southeast "Diagonal" X-section, southwest portion of County
A'
B'
0
2620
5240
7860
10480
13100
15720
18340
20960
23581
26201
55
50
44
39
33
28
22
17
11
6
0
315.3
294.2
273.0
251.9
230.7
209.6
188.4
167.3
146.1
125.0
103.8

Key Messages from Geologic Modeling

The 3D model reveals that the glacial geology in Allegan County is complex and heterogeneous – both aquifer and non-aquifer (confining) material exhibits strong spatial persistence, but there are no “perfect layers”. In particular, the model shows:

1. In the northwest, south-central, central and northeast portions of the county, there are relatively extensive/continuous shallow fine-grain tills (CM and PCM) underlain by coarser-grained materials (AQ and MAQ), or aquifer “pockets”;
2. in the northeast, many wells pierce through the less permeable clays/silts (CM) to withdraw water from the Marshall Sandstone aquifer (AQ / MAQ) because layers of confining material are extensive and found throughout much of the depth of the glacial aquifer;
3. in the east, southeast, northeast, and in some central areas of the county, glacial outwash materials with significant vertical variability and lateral variability are present, with more permeable materials (AQ, MAQ) typically found near the surface – the ability to find significant yields of groundwater may vary significantly within short distances (or different depths); and
4. in the low-land areas, extensive, continuous lacustrine deposits are found, with both coarse (AQ / MAQ) and fine-grained materials (CM / PCM) present; in these areas is it common to have continuous shallow sand deposits (AQ /MAQ) underlain by clays/silts (CM / PCM), with some interbedding/fingering predicted by the TP model.

Importantly, the spatial patterns predicted by the 3D model are generally consistent with the patterns observed in the categorized borehole lithologies. Additionally, individual boreholes generally match well with the surrounding cells of the 3D model.

Note that the hydraulic properties of subsurface can often vary several orders of magnitude. The means that the hydraulic properties between the different categories (AQ, MAQ, PCM, CM) can be large (an order of magnitude or more). This also means there can can be notable variability of hydraulic properties *within* a particular category, especially between locations with similar materials but different geomorphologies (physical structure related to depositional history). In other words, AQ is not expected to be “the same everywhere”, and so on. For example, while sands are generally considered AQ material, lacustrine sands tends to have smaller grain sizes relative to glacial outwash sands or dune sands, resulting in different hydraulic properties between the similar types of material.

Allegan County Groundwater Study

Task 2 – Water Quantity Analysis

Hydrosimulatics INC.

Task 2 – Executive Summary

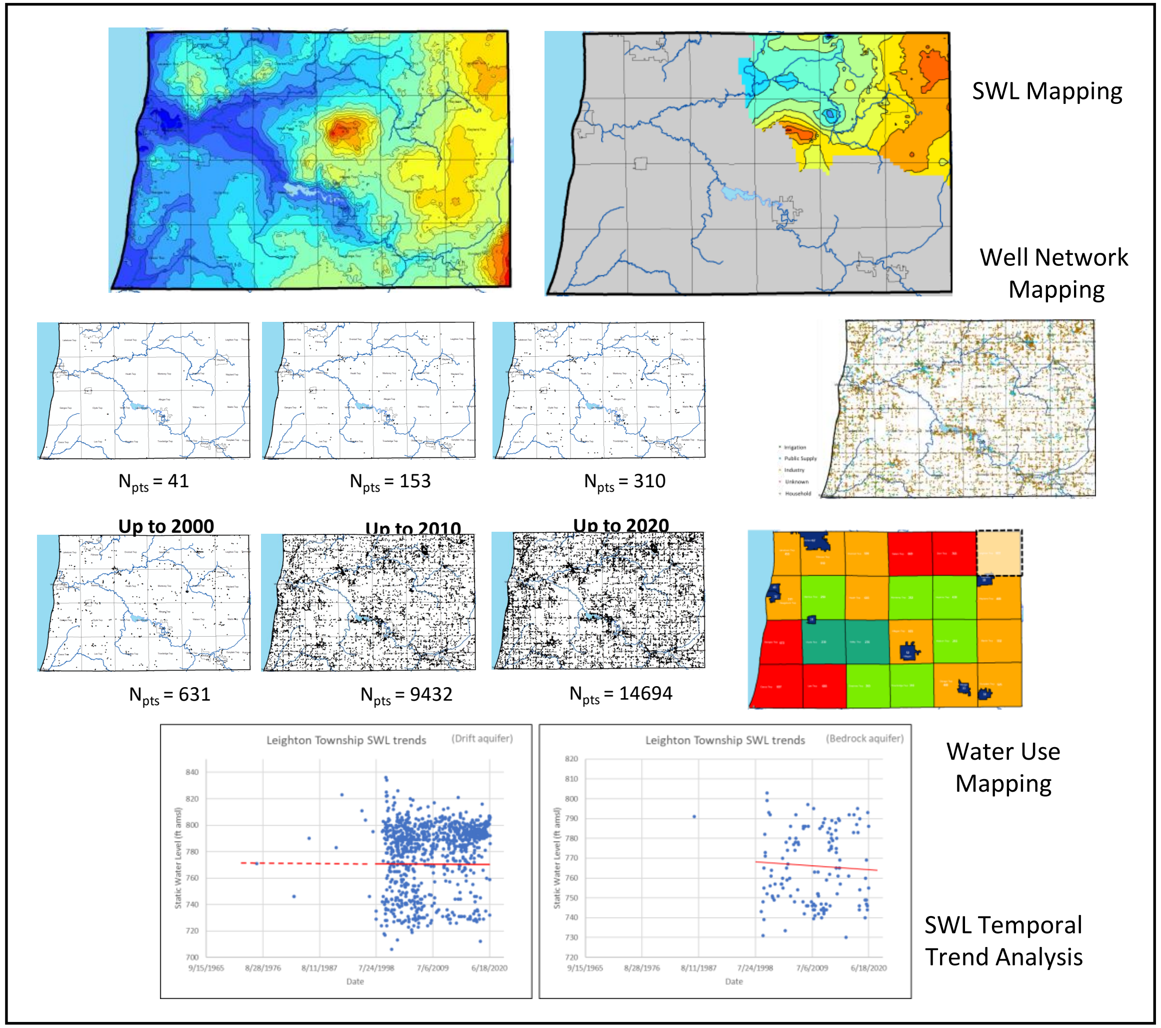
In Task 2, we characterized the groundwater quantity dynamics in Allegan County (flow patterns, availability, use, etc.). We downloaded, processed, sorted, and filtered thousands of water well records from the Wellogic database and made use of embedded physical groundwater data (Static Water Levels) and well construction information (date of installation, well type, etc.) to map water quantity dynamics across the county. We also mapped and made use of estimates of hydraulic properties of the glacial aquifer and bedrock aquifer (conductivity and transmissivity, respectively) to generate a screening-level estimate of aquifer yield.

Analysis of long-term Static Water Level (SWL) patterns in the glacial aquifer shows the groundwater predominantly moves from the major recharge areas in the central portion of the county (Monterey Twp.) and in the eastern townships (Leighton, Wayland, Martin, and Gunplain) towards major discharge areas found along the lower reaches of the Kalamazoo, Rabbit and Black Rivers. Along the Lake Michigan coastline, some locally recharged groundwater discharges directly to Lake Michigan.

The depth-to-water table is generally large in the central townships (e.g., Monterey, Allegan, Otsego and Trowbridge) and along the Lake Michigan Coastline (Ganges, Laketown, and Saugatuck Twps). As expected, the depth-to-water table is lowest at/along the streams and rivers, and is noticeably low across a broad area in the southwest corner of the county.

The bedrock aquifer appears to be recharged locally by vertical infiltration from the glacial aquifer. As a result, the bedrock aquifer flow patterns mimics those seen in the glacial aquifer (although they are more subdued): recharge “mounds” in Monterey, Leighton, Wayland, and Martin Twps.; and discharge areas corresponding with the Rabbit River and its tributaries.

“Snapshots” of the countywide well network were mapped for different years from 1970-2020. The results show a consistent increase in the number of wells in most parts of the county, especially after the year 2000 (note: this is, at least in part, related to the fact that new wells started going directly into Wellogic starting around 2000). Currently, the townships with the most wells are: Dorr, Salem, Leighton, Allegan, Ganges, and Otsego. A large majority of the wells are private-use domestic wells pumping at low rates relative to irrigation, public supply, and industrial / commercial wells.

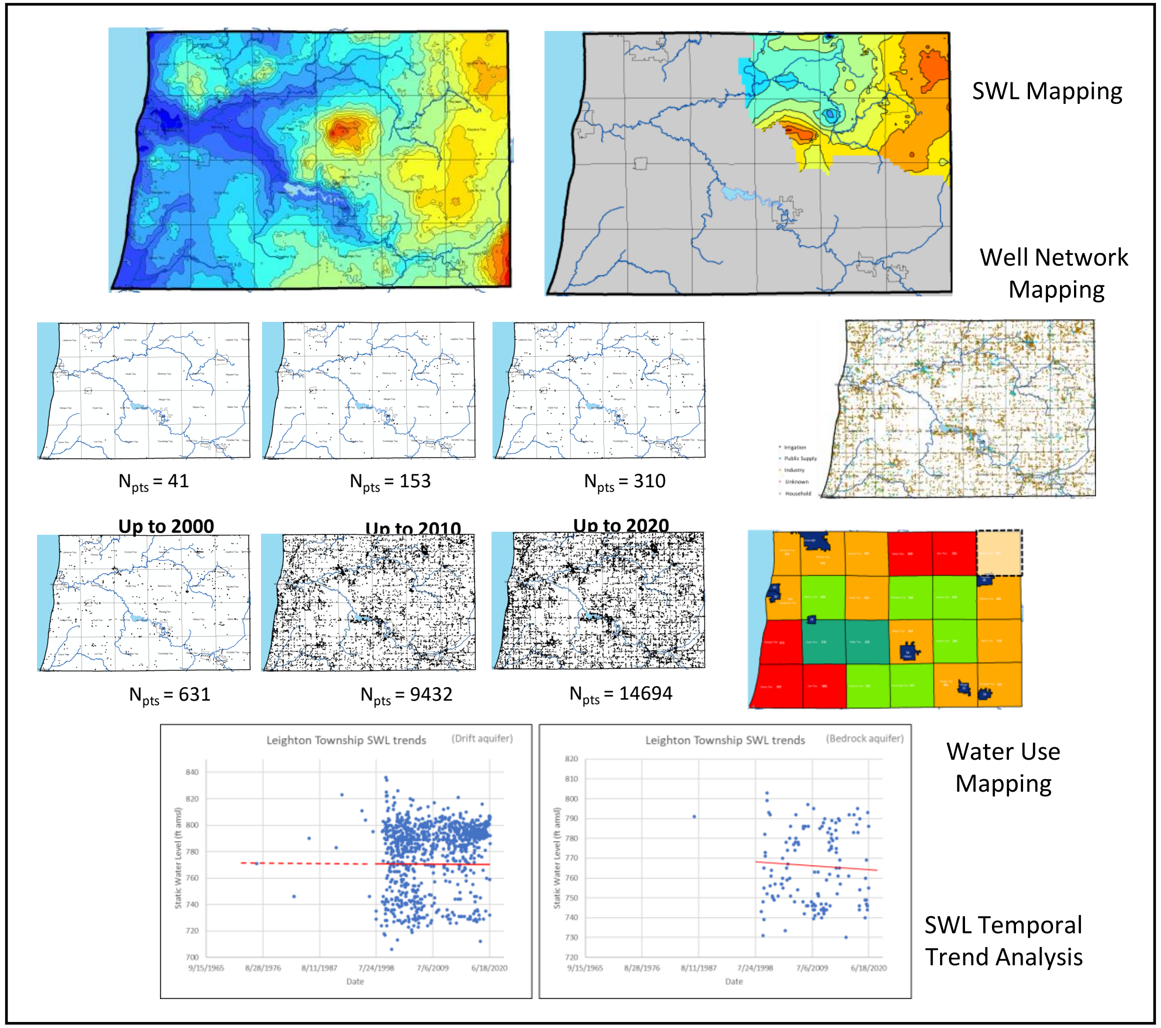


Task 2 – Executive Summary (Cont’d)

A screening-level countywide water use map was generated based on the spatial network of Wellogic water well records and a few simplifying assumptions about pumping rates for wells of different types (irrigation, public supply, industrial/commercial, and household). Present day water use is highest in Ganges, Casco, Lee, Salem and Dorr Twps. Clyde and Valley Townships use the least amount of groundwater.

Static Water Levels from Wellogic records were analyzed in areas of highest groundwater use to determine if groundwater levels are significantly decreasing in response to pumping. This was done on a township-by-township basis and for some sub-township areas (i.e., 2-3 sections aggregated together) when enough data were available. In all areas / sub-areas, there was not enough data prior to 2000 for meaningful analysis for the 1970-2000 period, but data coverage was sufficient for 2000-2020. The analyses suggest that some areas of the county may be undergoing systematic decline of 5-10 ft because of increased pumping in the past few decades, for example: parts of Dorr Twp., northern Saugatuck / southern Lake town Twps., and parts of Allegan Twp. Overall, the large amount of noise in the SWL data and the large SWL spatial variability makes it difficult to identify temporal trends with a high degree of confidence. Nonetheless, the analyses help to prioritize resources for site-specific data collection.

Finally, a “baseline’ or first-order estimate of aquifer yield was made using the Jacob-Cooper approximation to the Theis well solution and detailed information of the aquifer transmissivity across the county. Aquifer yield was defined as the maximum pumping rate that can be applied to prevent drawdown (lowering) of the water table greater than half of the saturated thickness of the aquifer. The results show that aquifer yield is generally low or very low in the western and northwest / northcentral portions of the county, and is much higher in the eastern, southeastern, south-central and south-central portions, although there is significant variability within a particular township or sub-township area

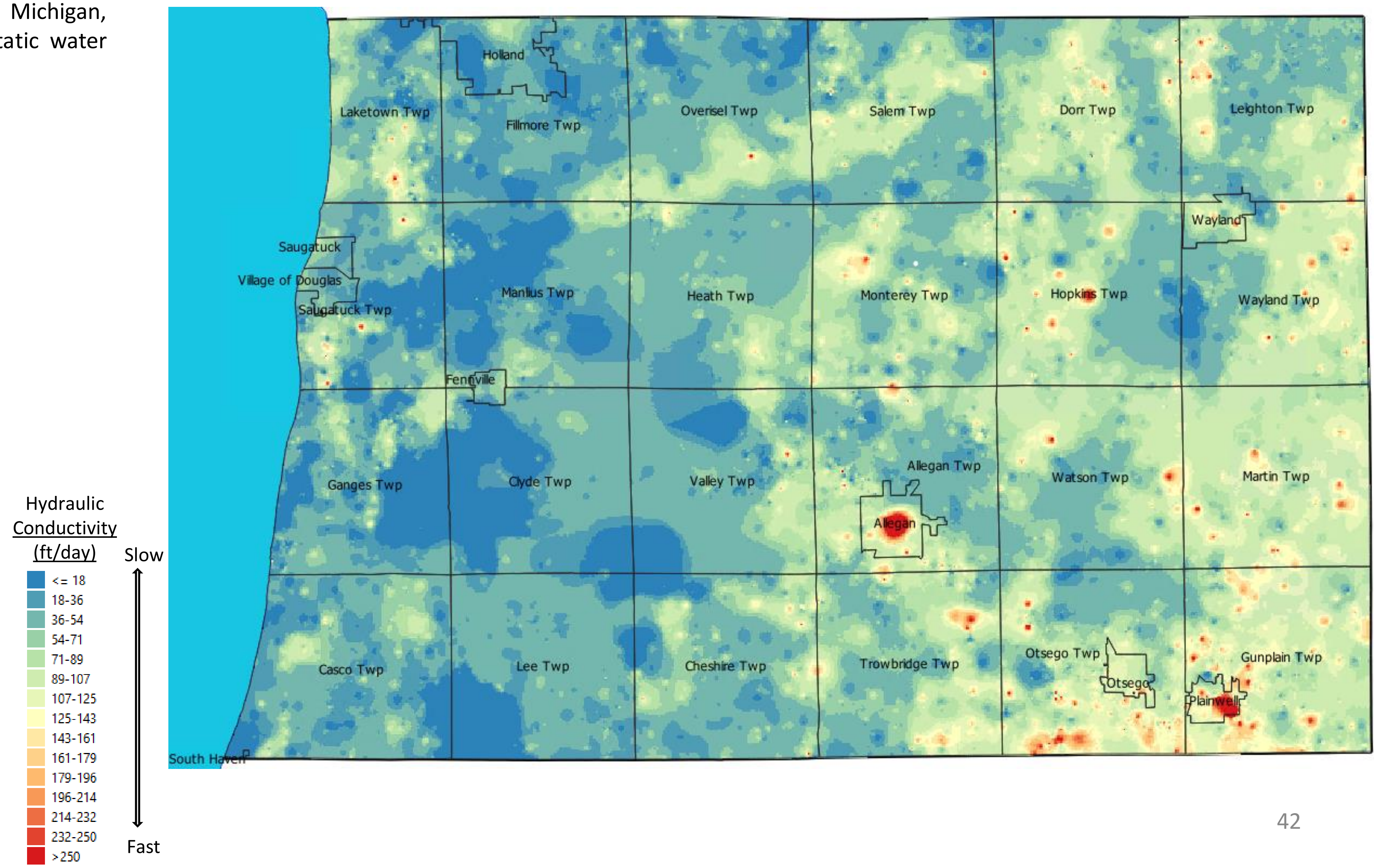


Hydraulic Conductivity of Glacial Aquifer

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

Note:

- Zones of higher conductivity are found in the north (Overisel and Salem Twps., parts of Hopkins Twp.), northeast (Dorr and Leighton Twps.), east (Wayland and Martin Twps.), and southeast (Ostego and Gunplain Twps., and parts of Trowbridge Twp.), primarily consisting of coarse-grained glacial outwash materials with significant vertical variability and lateral variability.
- Zones of lower conductivity occur in the low-lying portions of west-central and and southwest Allegan County where fine- and coarse-grained lacustrine deposits dominate. The observed borehole lithologies and the 3D geologic model generally predict shallow AQ deposits underlain by PCM / CM materials (e.g. clay). Note that the conductivity of AQ materials in these areas (e.g. lacustrine sands) is lower than the conductivity of AQ materials found in the western portion of the county (glacial outwash sands and gravels).



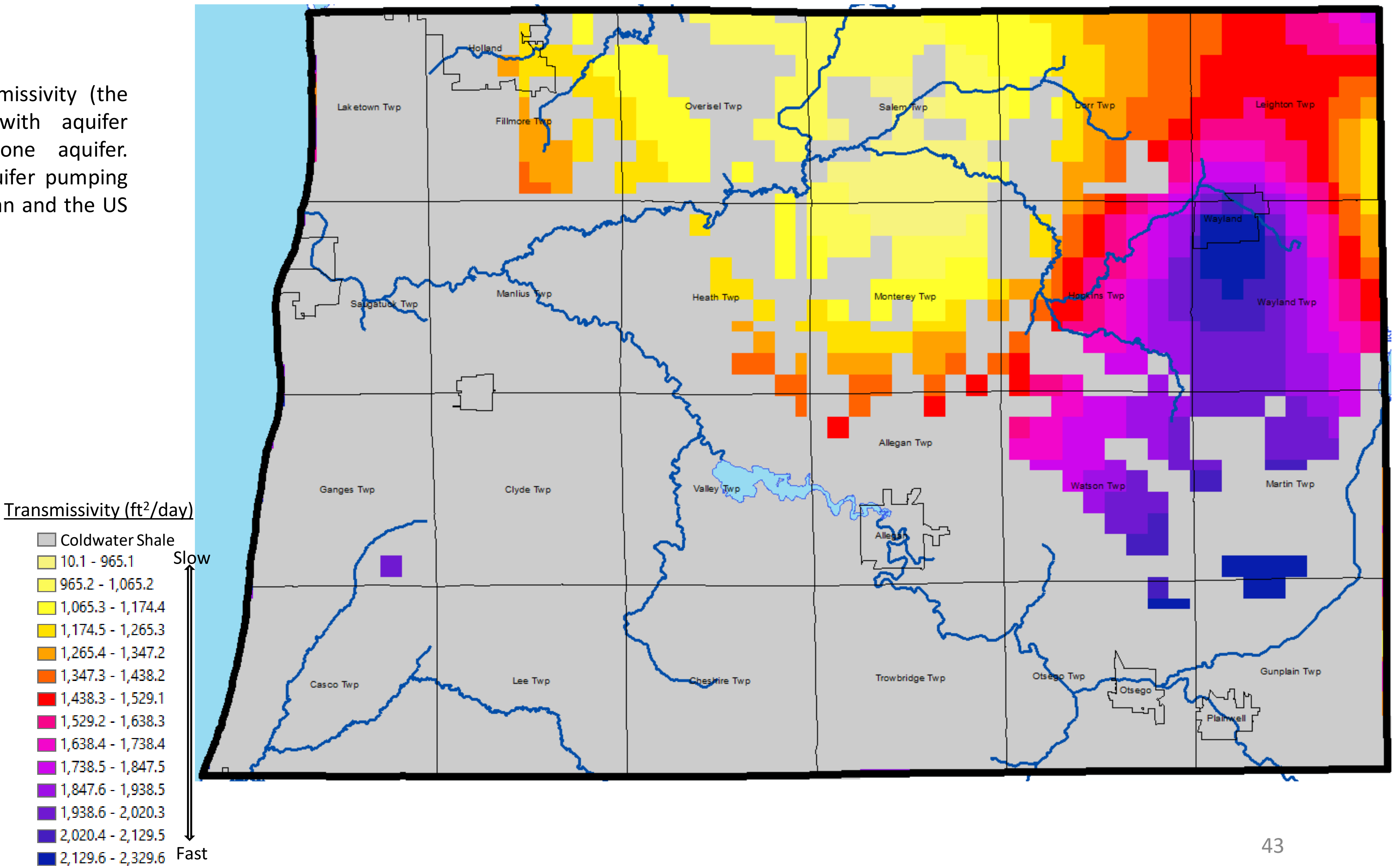
Transmissivity of Bedrock Aquifer

Countywide Map

This slide shows a 2D map of transmissivity (the product of hydraulic conductivity with aquifer thickness) of the Marshall Sandstone aquifer. Transmissivity was estimated from aquifer pumping tests conducted by the State of Michigan and the US Geological Survey.

Note:

- Bedrock transmissivity is generally higher in the east-northeastern portions of the county (Wayland, Leighton, and Hopkins Twps.), and in parts of Watson and Martin Twps. where the aquifer pinches out against the Coldwater Shale, with a large “pocket” of high transmissivity predicted for northwest Wayland Twp.
- Transmissivity decreases along a southeast-northwest gradient, with relatively low values found in Salem, Monterey an Overisel Townships.

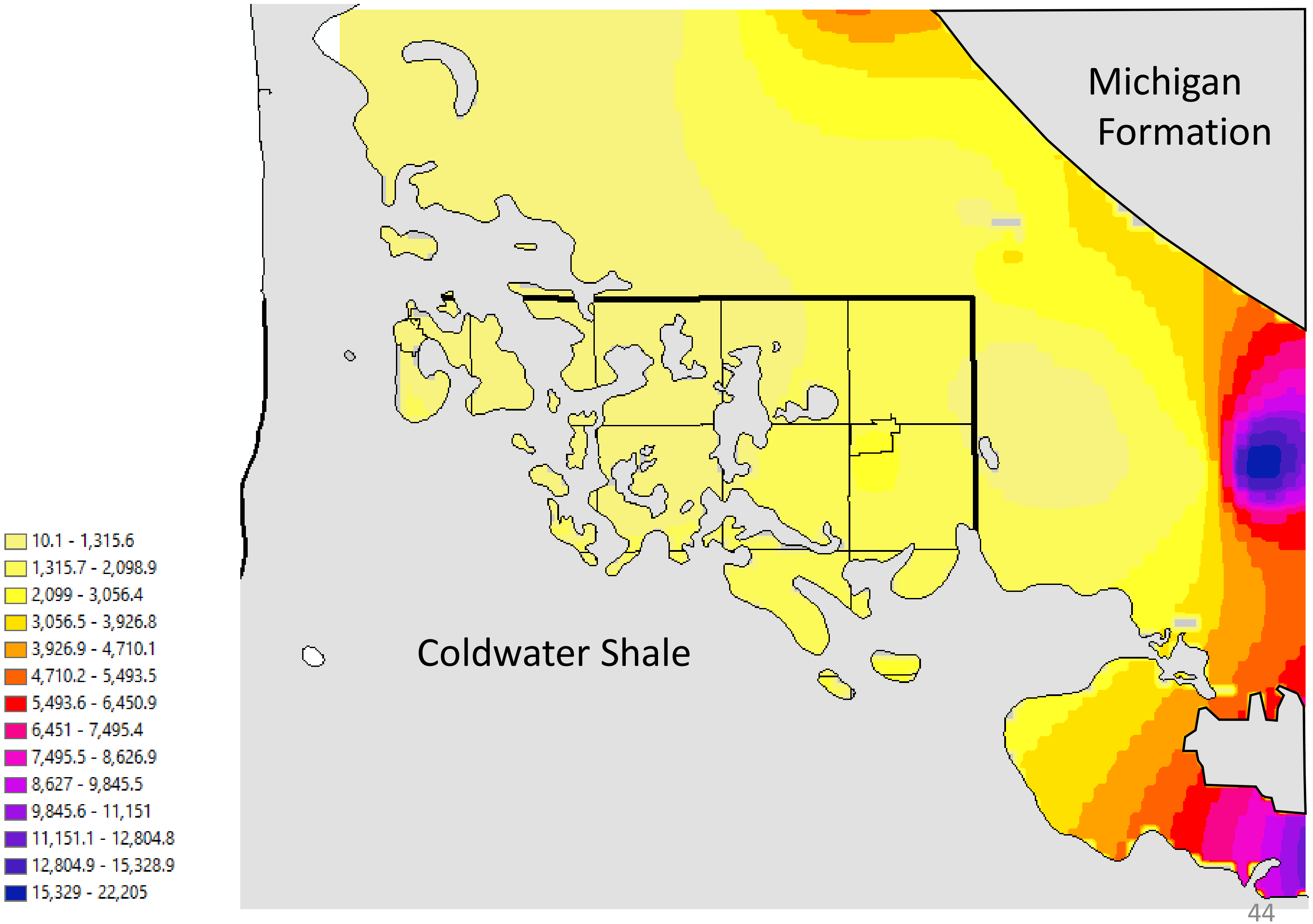


Transmissivity of Bedrock Aquifer

Regional Map

For additional perspective, this slide shows a 2D map of Marshall Sandstone aquifer for the larger regional area, including part of Ottawa County to the north, the southwestern corner of Kent County, and Barry County to the east.

At this scale, the bedrock aquifer in Allegan county represents an area of low or very low transmissivity that extends north-northwest into Ottawa County. Transmissivity increases significantly towards the southeast; the highest transmissivities in the State are found in part of Kalamazoo and Calhoun counties.



Estimated Recharge

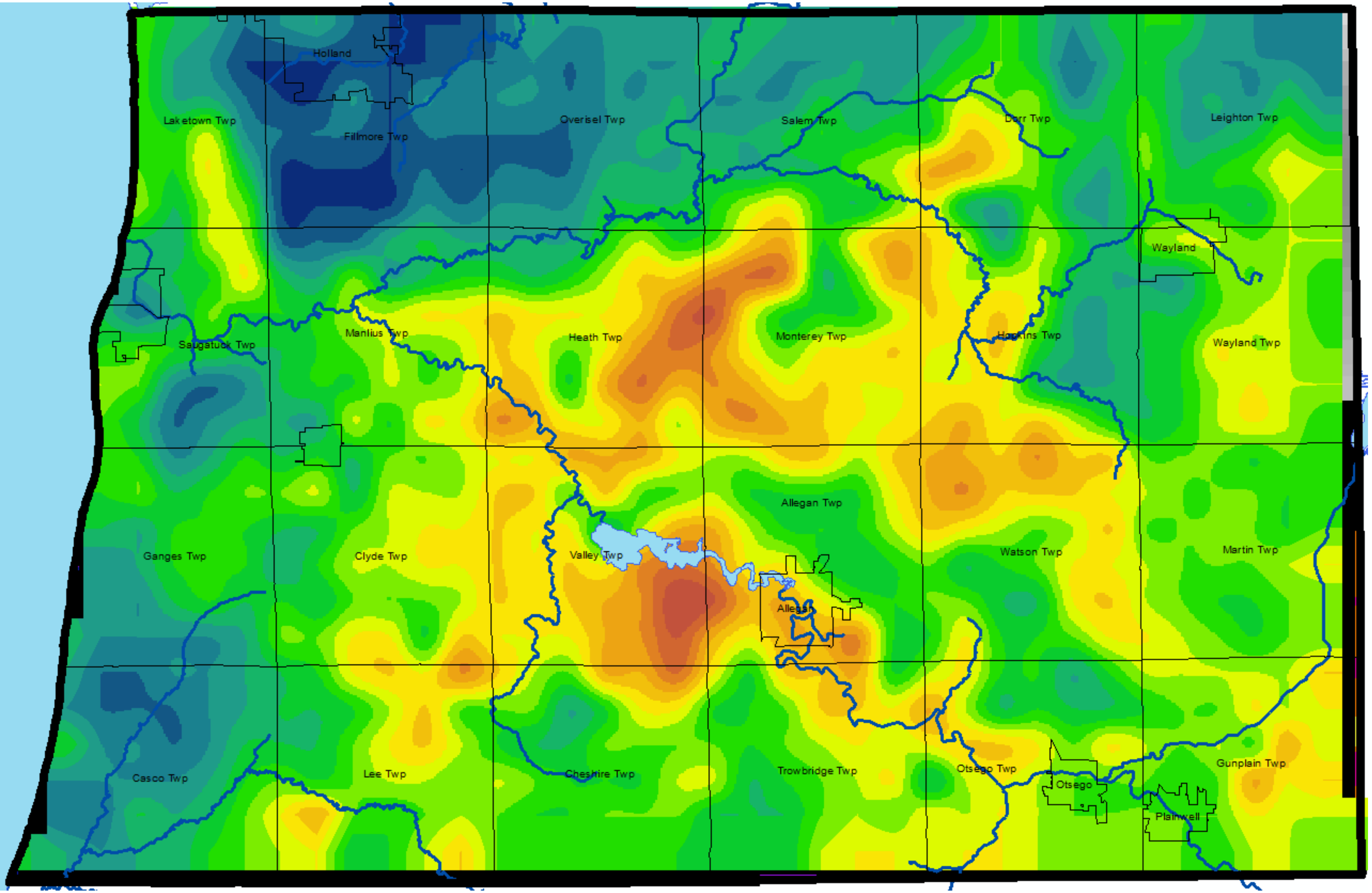
This slide shows a recharge map (net infiltration of precipitation to the water table) generated following empirical methods presented in Holtschlag (1997) involving observed stream flow hydrographs and information related to land use, soil conditions, and watershed characteristics (State of Michigan, 2006).

Note:

- Recharge is generally largest in the central portions of the county, north and south-southeast of Lake Allegan, and along the upper and middle reaches of the Kalamazoo River dominated by glacial outwash deposits.
- Recharge is generally lowest in the upland areas of Fillmore and Overisel Townships and in the portions of Casco and Ganges Townships (and Saugatuck Twp., to lesser degree) where low permeability clays and silts are found at/near the surface.

Recharge (in./yr.)

- 7
- 7.1 - 8
- 8.1 - 9
- 9.1 - 10
- 10.1 - 11
- 11.1 - 12
- 12.1 - 13
- 13.1 - 14
- 14.1 - 15
- 15.1 - 15.
- 16 - 17
- 17.1 - 18
- 18.1 - 19
- 19.1 - 20
- 20.1 - 21



Static Water Level Mapping

Static Water Levels (SWLs) from water well records contained in Wellogic were analyzed to develop countywide maps of the water table and potentiometric surface of the glacial and bedrock aquifers, respectively.

Our approach to using water well records followed a three-step filtering procedure (see Curtis et al., 2018 for complete details):

1. Remove “black/white” errors. This step removes data values that are clearly wrong using a simple GIS-based query analysis.
2. Remove statistical outliers. This step performs a moving window statistical data analysis and identifies and removes data values that deviate significantly from local trends based on a predefined criterion (e.g., outside three standard deviations).
3. Remove “gray” errors. This step attempts to remove “randomly” distributed data noises representing errors caused by inaccurate well location, seasonal variability, measurement uncertainty, and “driller variability”. We achieve this using an advanced “moving window, non-stationary multiscale kriging technique”. This filtering technique, using a location-dependent variogram, enables removing noise in complex datasets in the presence of strongly non-stationary spatial trends.

A low-filter smoothing filter was applied to the spatial interpolation of the processed SWL data.

The results are shown on the following slides.

Water Table in the Glacial Aquifer

Countywide Map

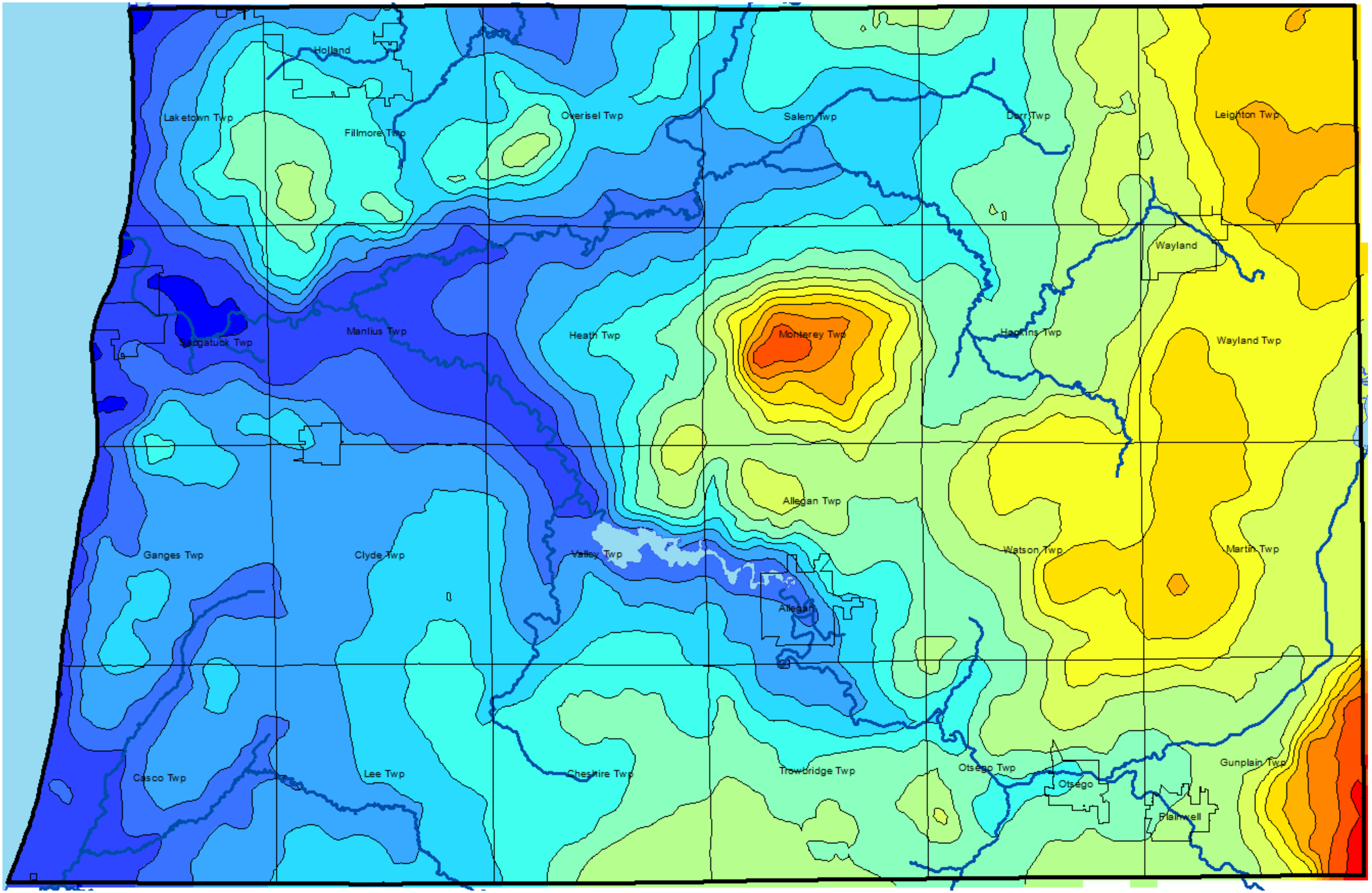
Long-term Mean Water Table

This slide shows a map of the long-term (1966-2020) average water levels in the glacial aquifer (water table).

The red areas are the high-elevation water table regions and the blue areas are where the water table is at low elevations. The maximum water level difference is about 310 ft.

Note that the “footprint” of the Kalamazoo, Rabbit, and Black Rivers and their tributaries is clearly seen in the “valleys” of the water table surface. The water table depression in topographic lowlands where surface water bodies are found is typical in regional discharge areas where groundwater is converging to streams, rivers, wetlands, etc.

The following slides present more detailed water table distributions for each of the four “quadrants” of the county.



Water Level (m)

170.1 - 176.8
176.9 - 183.5
183.6 - 190.2
190.3 - 196.9
197 - 203.7
203.8 - 210.4
210.5 - 217.1
217.2 - 223.8
223.9 - 230.5
230.6 - 237.3
237.4 - 244
244.1 - 250.7
250.8 - 257.4
257.5 - 264.1
264.2 - 270.9

Water Table in the Glacial Aquifer - Subregions

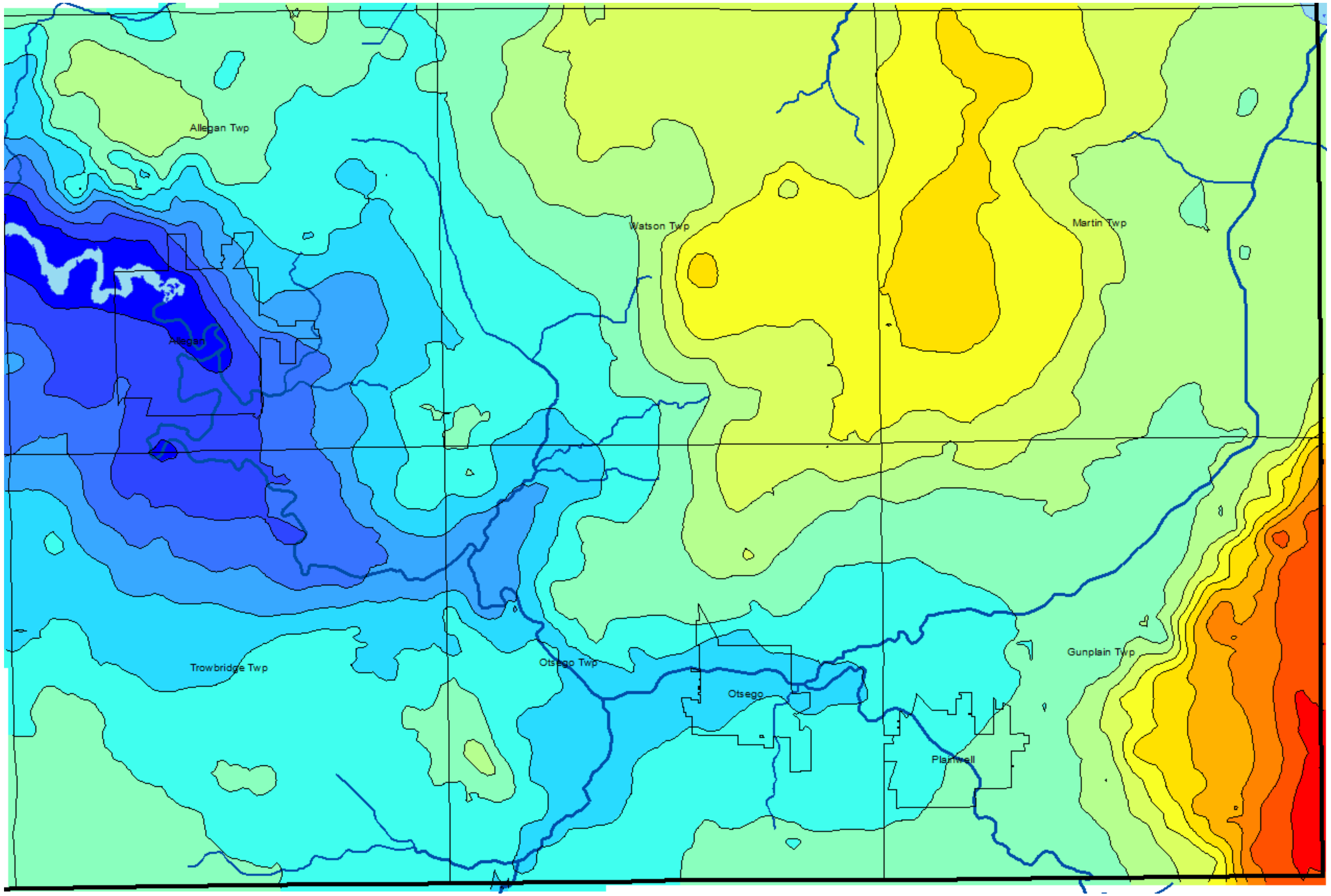
Southeast Quadrant Map

Long-term Mean Water Table

This slide shows a map of the long-term (1966-2020) average water levels in the glacial aquifer for the *southeast* “quadrant” of the county: Allegan, Watson, Martin, Trowbridge, Ostego, and Gunplain Townships.

The maximum water level difference is about 87m (285 ft).

The map shows groundwater converging to the Kalamazoo River from both sides (predominantly the north and south directions) with large head gradients (faster velocities) in the eastern half of Gunplain Township.



Water Level (m)
- 183.9 - 189.6
- 189.7 - 195.4
- 195.5 - 201.2
- 201.3 - 207
- 207.1 - 212.8
- 212.9 - 218.6
- 218.7 - 224.4
- 224.5 - 230.1
- 230.2 - 235.9
- 236 - 241.7
- 241.8 - 247.5
- 247.6 - 253.3
- 253.4 - 259.1
- 259.2 - 264.9
- 265 - 270.6

Water Table in the Glacial Aquifer - Subregions

Southwest Quadrant Map

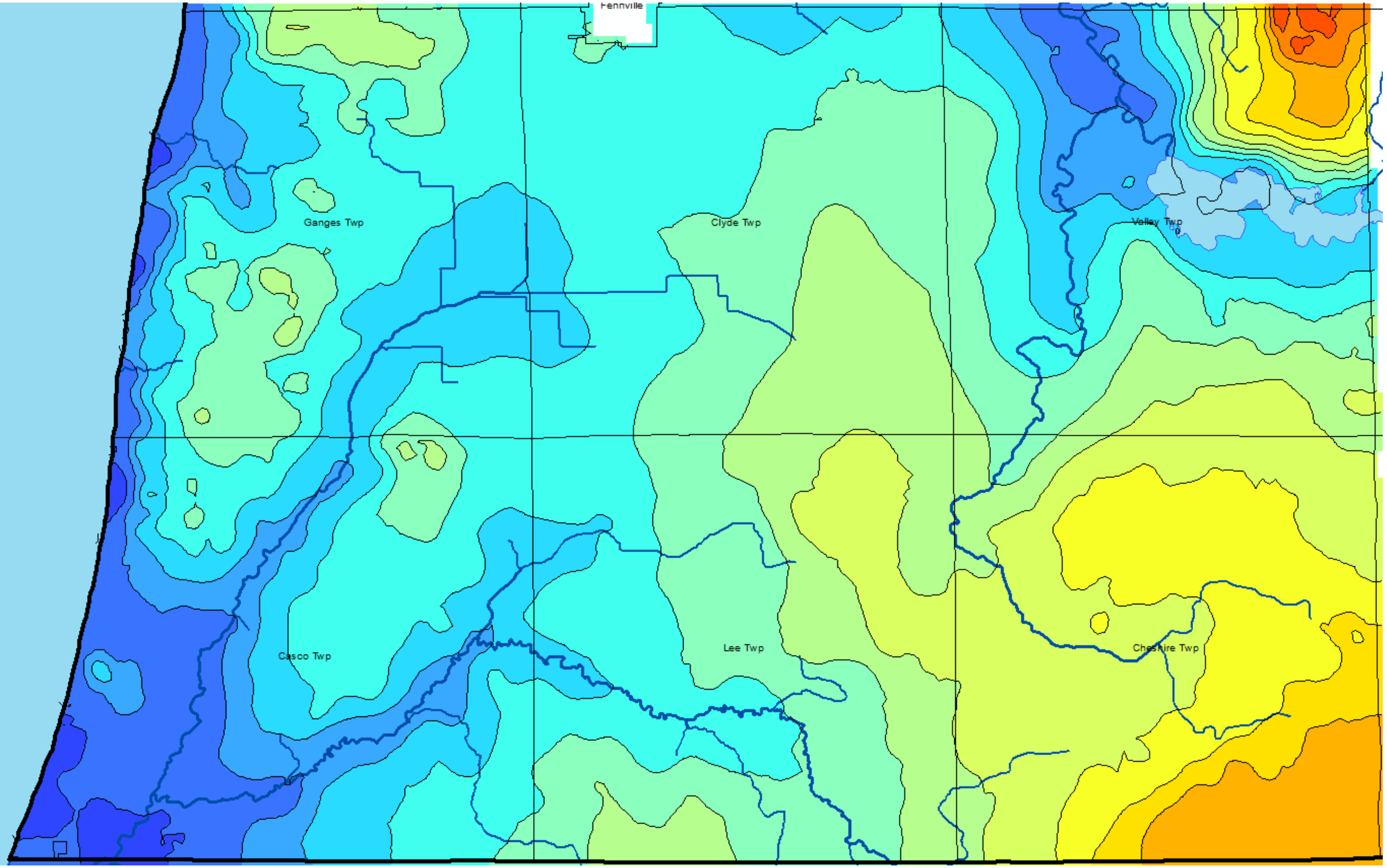
Long-term Mean Water Table

This slide shows a map of the long-term (1966-2020) average water levels in the glacial aquifer for the *southwest* “quadrant” of the county: Ganges, Clyde, Valley, Casco, Lee, and Cheshire Townships.

The maximum water level difference is about 76m (250 ft).

The map shows the water table is highest in the northeast corner of Valley Twp. and in Cheshire Twp. There are also local recharge mounds in parts of Ganges, Casco, and Lee Twp.

Groundwater moves toward and eventually discharges into the Kalamazoo River (in the north) or towards the Black River and its tributaries (in the south / southwest).



Water Level (m)

- 168.7 - 173.3
- 173.4 - 177.8
- 177.9 - 182.4
- 182.5 - 186.9
- 187 - 191.5
- 191.6 - 196
- 196.1 - 200.6
- 200.7 - 205.1
- 205.2 - 209.7
- 209.8 - 214.3
- 214.4 - 218.8
- 218.9 - 223.4
- 223.5 - 227.9
- 228 - 232.5
- 232.6 - 237

Water Table in the Glacial Aquifer - Subregions

Northwest Quadrant Map

Long-term Mean Water Table

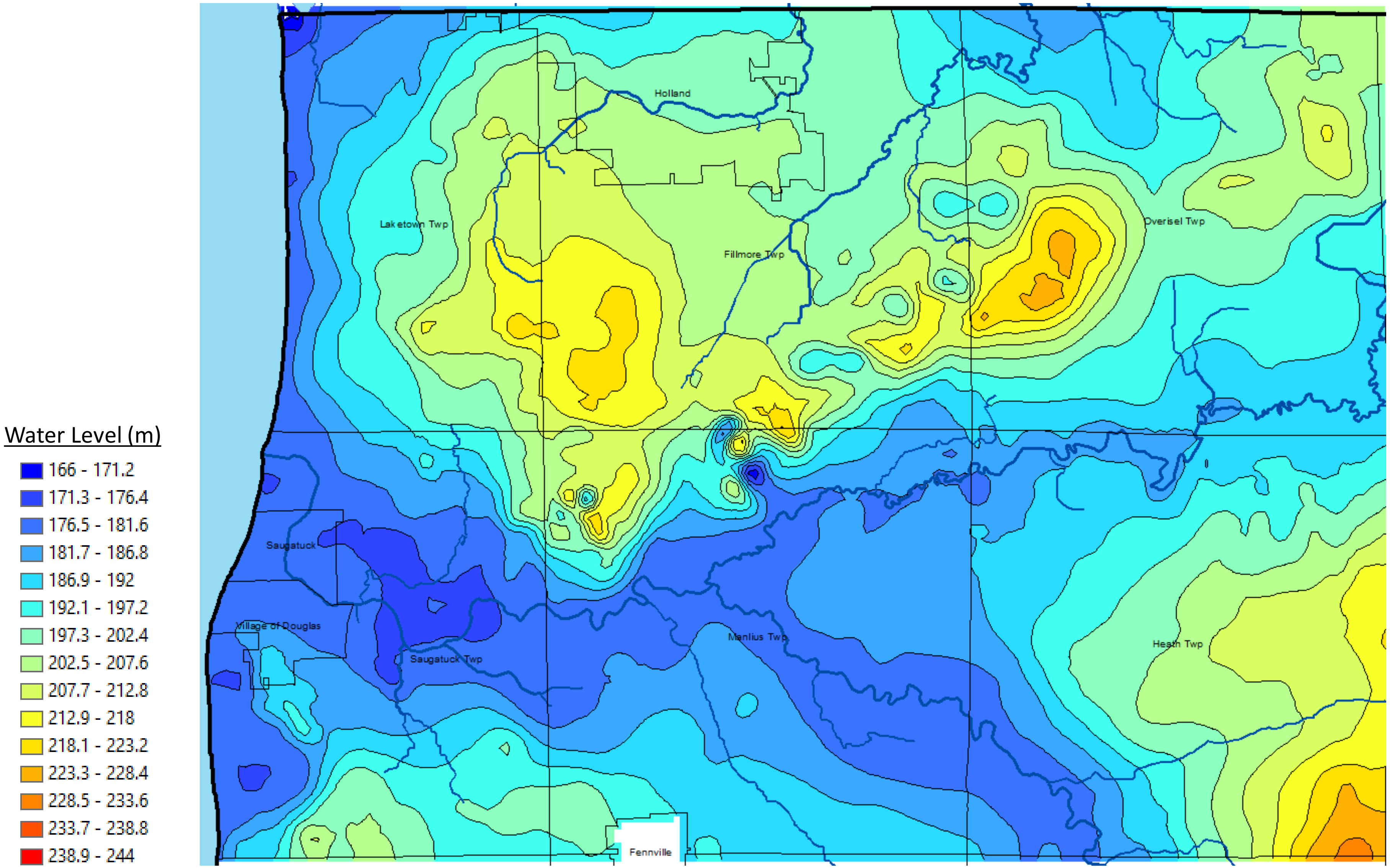
This slide shows a map of the long-term (1966-2020) average water levels in the glacial aquifer for the *northwest* “quadrant” of the county: Laketown, Fillmore (and Holland), Overisel, Saugatuck (and the Villages of Saugatuck and Douglas), Manlius, and Heath Townships.

The maximum water level difference is about 76m (250 ft).

The map shows that the water table is highest in the northern townships (Laketown, Fillmore, and Overisel Twps.) and in the southeast corner of Heath Twp.

Groundwater converges toward and discharges into the Rabbit and Kalamazoo Rivers. Near the Lake Michigan coastline, groundwater moves directly westward toward Lake Michigan.

In northwest Fillmore Twp. and northwest Overisel Twp., groundwater flows north toward branches of the Macatawa River.



Water Table in the Glacial Aquifer - Subregions

Northeast Quadrant Map

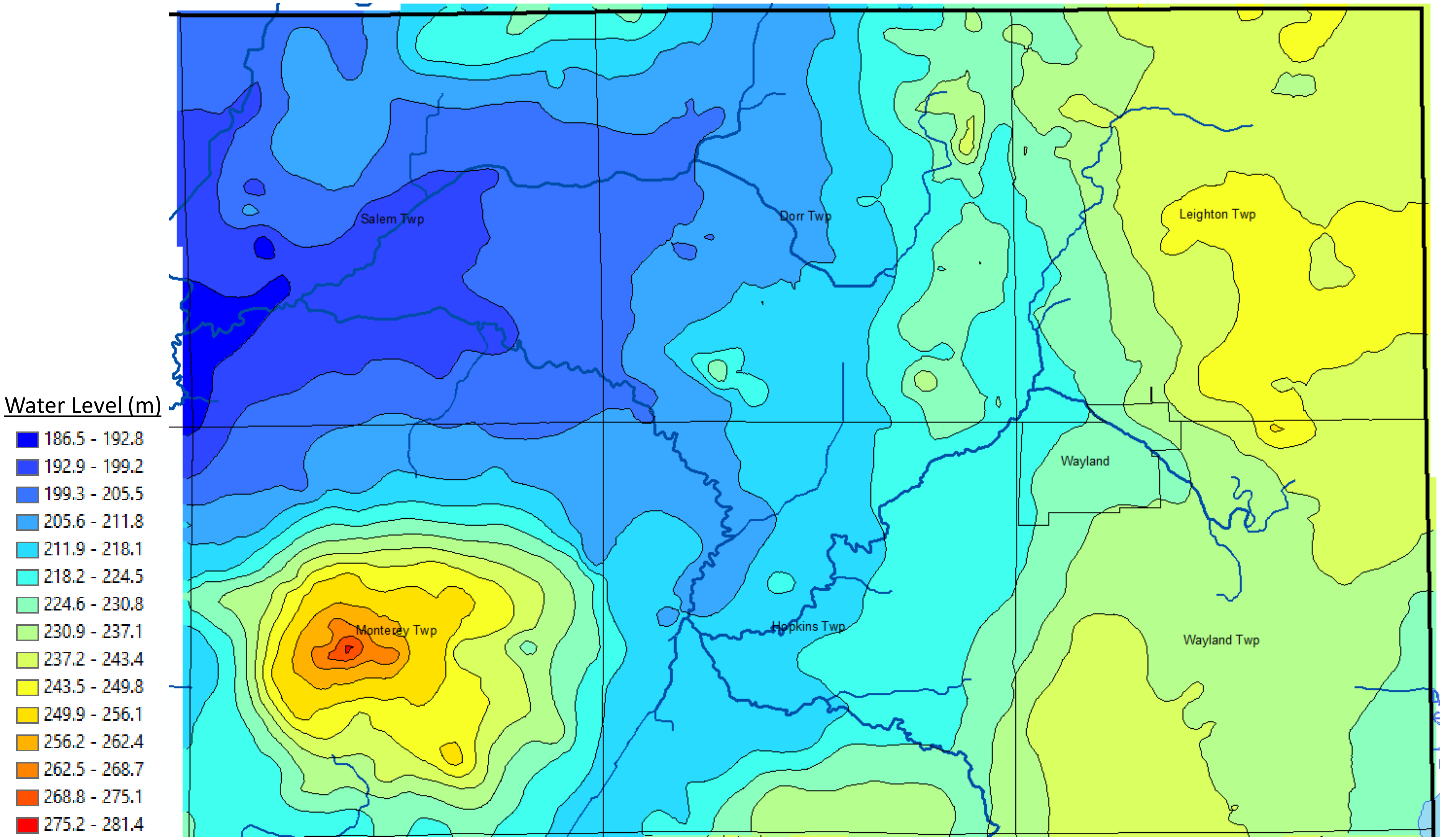
Long-term Mean Water Table

This slide shows a map of the long-term (1966-2020) average water levels in the glacial aquifer for the *northeast* "quadrant" of the county: Salem, Dorr, Leighton, Monterey, Hopkins, and Wayland Townships.

The maximum water level difference is 94m (310 ft).

The map shows groundwater mounding (recharging) in Monterey Twp. and Leighton Twp. (and Wayland Twp., to a lesser degree) and moving to the north or northwest to eventually discharge into the Rabbit River (or it's tributaries) in Salem, Door and Hopkins Townships.

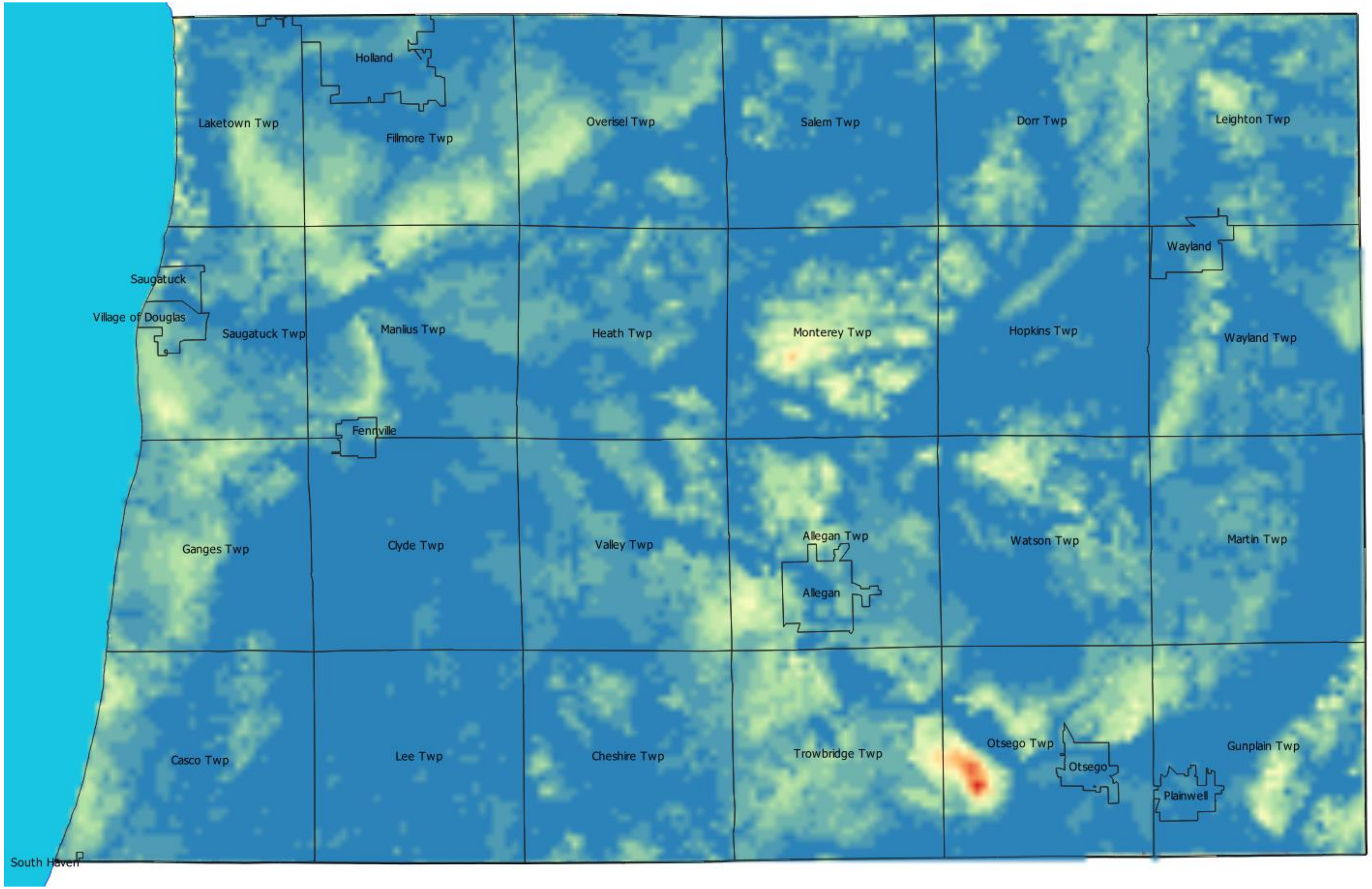
There are also less pronounced recharge mounds situated between streams in Leighton Twp. and parts of Wayland Twp.



Depth to Water Table

This slide shows a map of the depth-to-water table measured from the land surface. It is computed by subtracting the water table elevation from the land elevation.

The depth to water table is expected to be large (>50ft) along the Lake Michigan coastline and in highland areas in central, south-central, and eastern portions of the county. The depth to water table is small along streams and rivers and in the low-lying flat areas of western / southwestern Allegan County.



Depth to Water (ft)

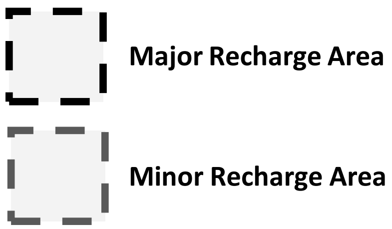
- 0-18
- 18-37
- 37-55
- 55-73
- 73-91
- 91-110
- 110-182
- 128-146
- 146-165
- 165-183
- 183-201
- 201-219
- 219-238
- 238-256
- 256-274
- 274-293

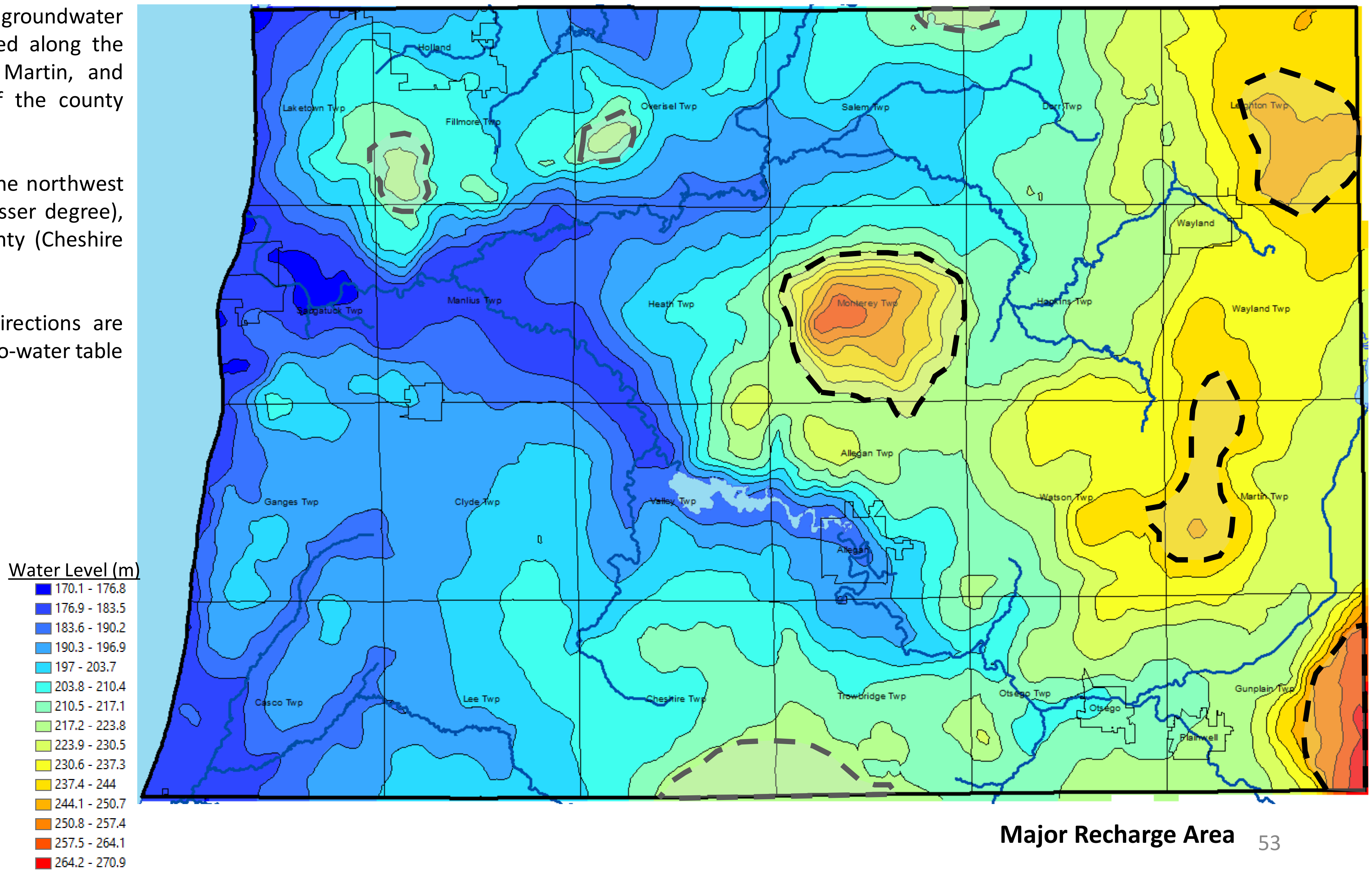
Distribution of Recharge Areas

At a countywide-scale, the major groundwater "mounds", or recharge areas, are situated along the eastern townships (Leighton, Wayland, Martin, and Gunplain) and in the central portion of the county (primarily Monterey Twp.).

There are minor local recharge areas in the northwest (Fillmore Twp., and Overisel Twp. to a lesser degree), NS the south-central portion of the county (Cheshire and Trowbridge Townships).

In these recharge areas, groundwater directions are predominantly downward and the depth-to-water table may be large.



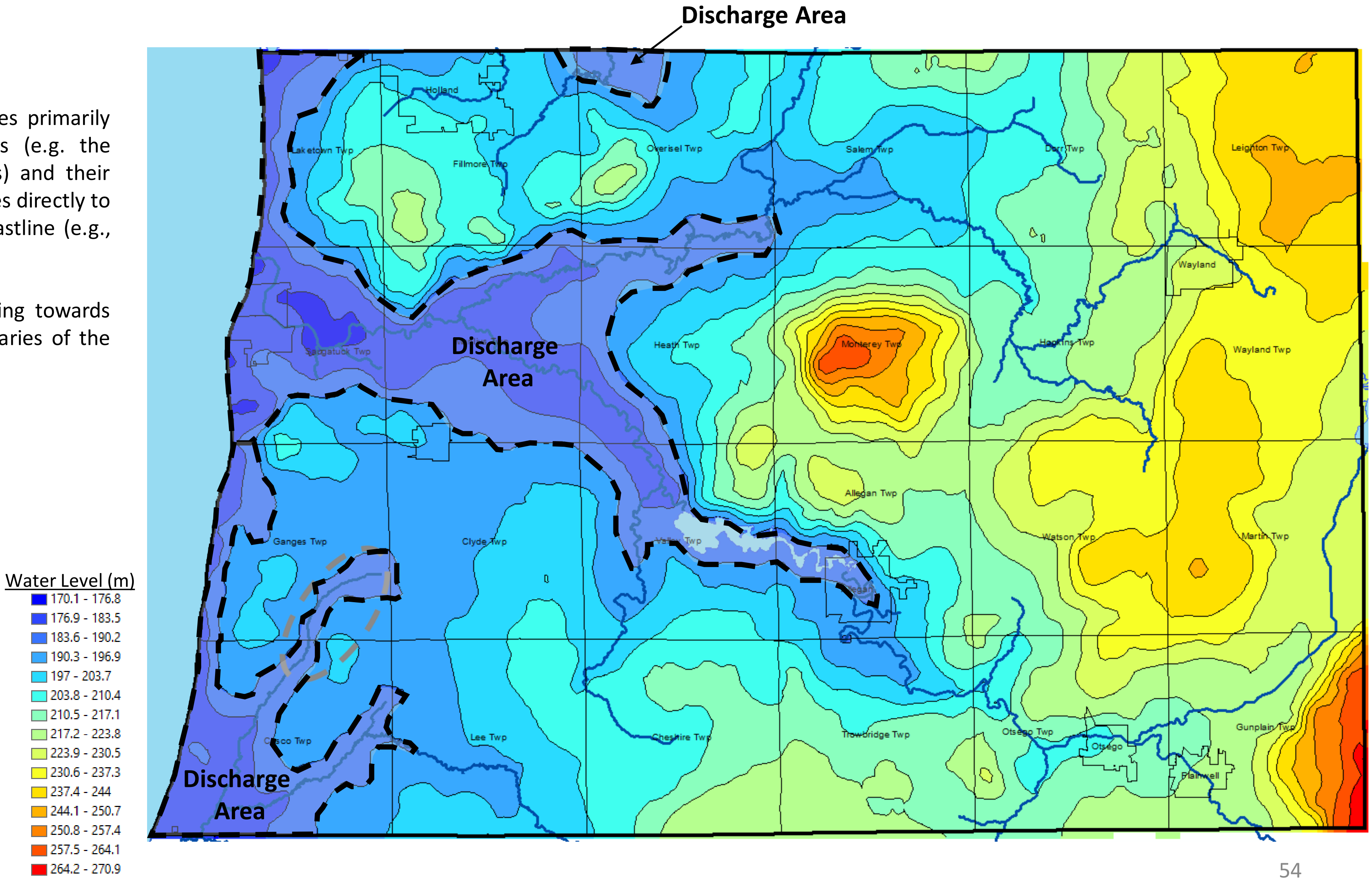


Major Recharge Area

Distribution of Discharge Areas

In the county, groundwater discharges primarily to the major surface water bodies (e.g. the Rabbit, Kalamazoo, and Black Rivers) and their corridors. Groundwater also discharges directly to Lake Michigan along parts of the coastline (e.g., Laketown Twp., Ganges Twp.)

Groundwater is also clearly converging towards and discharging into upstream tributaries of the Rabbit, Kalamazoo, and Black River.



Countywide Aquifer Yield Estimates

Screening-Level Aquifer Yield Mapping

A "baseline' or first-order estimate of aquifer yield was made for the glacial aquifer at 300m by 300m (984ft by 984ft) resolution for the entire county. In this analysis, yield is defined as the pumping rate that would be required to lower the hydraulic head at the well to fifty percent of the available drawdown after 100 days of pumping.

To estimate aquifer yield, first an estimate of transmissivity (T) was made based on the local hydraulic properties of the aquifer (hydraulic conductivity and saturated thickness, i.e., the distance from the bottom of the well screen to the static water level). Then, aquifer yield (Q_{max}) is computed using the Jacob-Cooper approximation to the Theis well solution (Cooper and Jacob 1946; Jacob 1950):

$$Q_{max} = \mathrm{T}\frac{4\pi}{2.3} s_{\mathrm{Theis}} \left[\log\left(\frac{2.25Tt}{r^2 S}\right)\right]^{-1}$$

where S is the specific yield, r is the radial distance to the center of the well at which drawdown is measured, t is pumping duration, and s_{Theis} is the drawdown in the well. In our analysis, we assumed S=0.0016 (typical of a leaky-confined aquifer), r=0.01m (i.e., inside the well), and t=100 days.

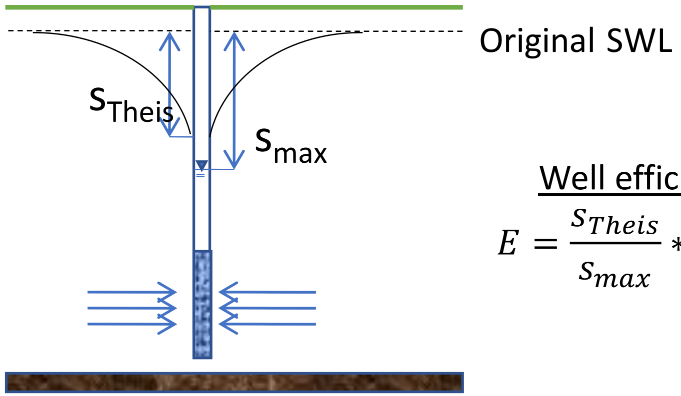
We also assumed a well-efficiency of 70% so that $s_{Theis} = 0.7*s_{max}$ (see figure below).

Aquifer yield was not mapped for the bedrock aquifer because much of the county is underlain by the low productivity Coldwater Shale unit, and the estimate of saturated thickness of the Marshall aquifer (where it is subcropping) is relatively uncertain.

<u>Parameters used</u>:

t = 100 days
S_y = 0.0016
r = 0.01m

Well Efficiency= 70%



<u>Well efficiency</u>:

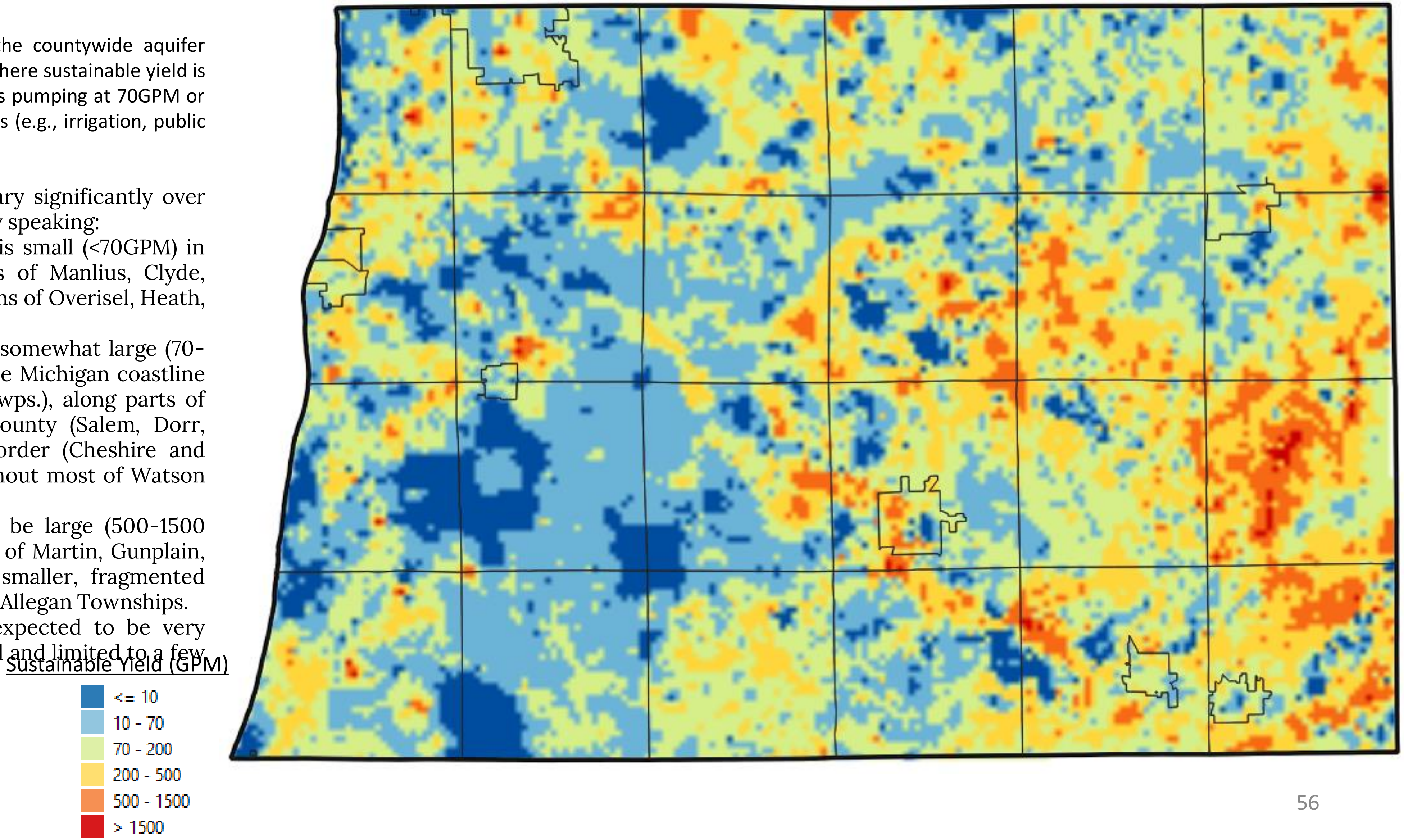
$$E = \frac{s_{Theis}}{s_{max}} * 100\%$$

Countywide Aquifer Yield Estimates

This slide presents the results from the countywide aquifer yield analysis. Areas that are blue are where sustainable yield is predicted to be less than 70 GPM; wells pumping at 70GPM or more are considered high-capacity wells (e.g., irrigation, public supply) by the state.

Note that sustainable yield can vary significantly over small distances; however, generally speaking:

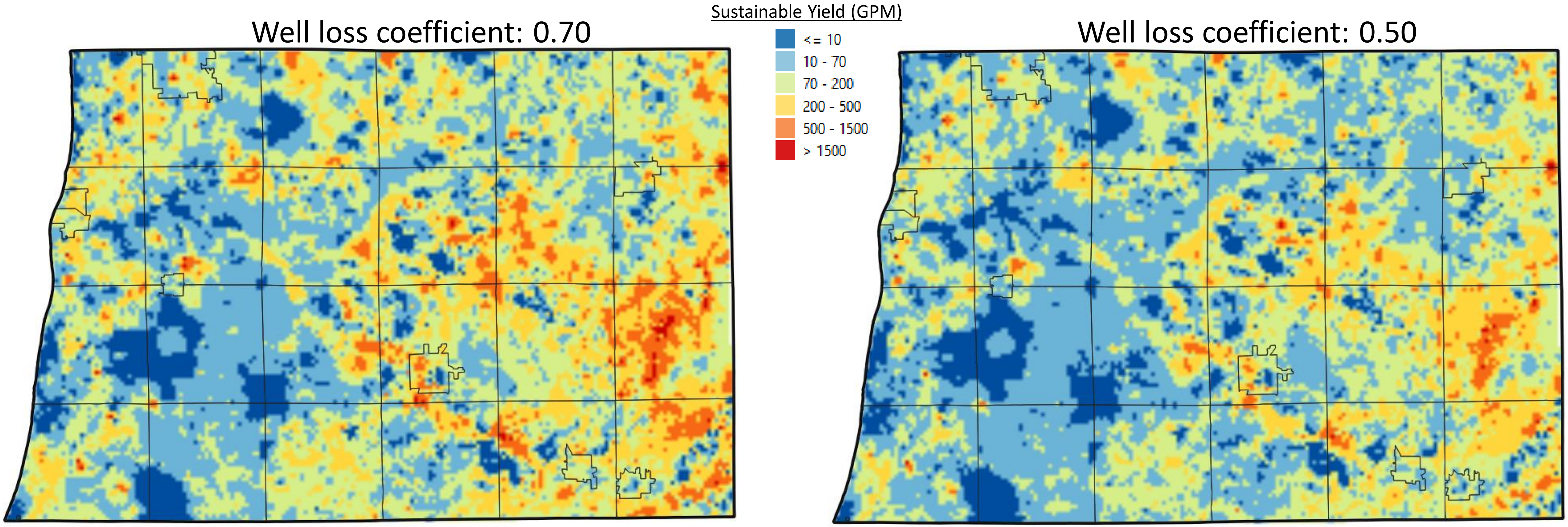
- Aquifer yield (as defined here) is small (<70GPM) in the western-central Townships of Manlius, Clyde, and Lee, and also in large portions of Overisel, Heath, Valley, and Ganges Townships.
- Aquifer yield is expected to be somewhat large (70-500GPM) along most of the Lake Michigan coastline (Laketown, Saugatuck, Casco Twps.), along parts of the northern border of the county (Salem, Dorr, Leighton) and the southern border (Cheshire and Trowbridge Twps.), and throughout most of Watson Township.
- Aquifer yields are expected to be large (500-1500 GPM) in the eastern Townships of Martin, Gunplain, Hopkins, and Otsego) and in smaller, fragmented areas of Monterey, Hopkins and Allegan Townships.
- Areas where aquifer yield is expected to be very large (>1500 GPM) are very small and limited to a few locations.



Countywide Sustainable Yield Estimates

Note that this analysis assumes 2D flow to the well, but in reality, there is significant vertical flow with associated head loss. Therefore, an additional analysis using a loss coefficient of 0.5 (0.3 for well loss, and additional 0.2 for 3D formation loss) was performed to give additional insight into the range of possible yields expected to be encountered in the field. This slide compares the countywide mapping of sustainable yield utilizing a well loss coefficient of 0.70 and 0.50.

As expected, the spatial patterns are very similar in both cases, but in the case of a well loss coefficient of 0.5, the areas of small sustainable yield (<70 GPM) increased (at the expense of moderate yield areas) while the areas of large yield (500-1500GPM) decreased.



Water Levels in the Bedrock Aquifer

Countywide Map

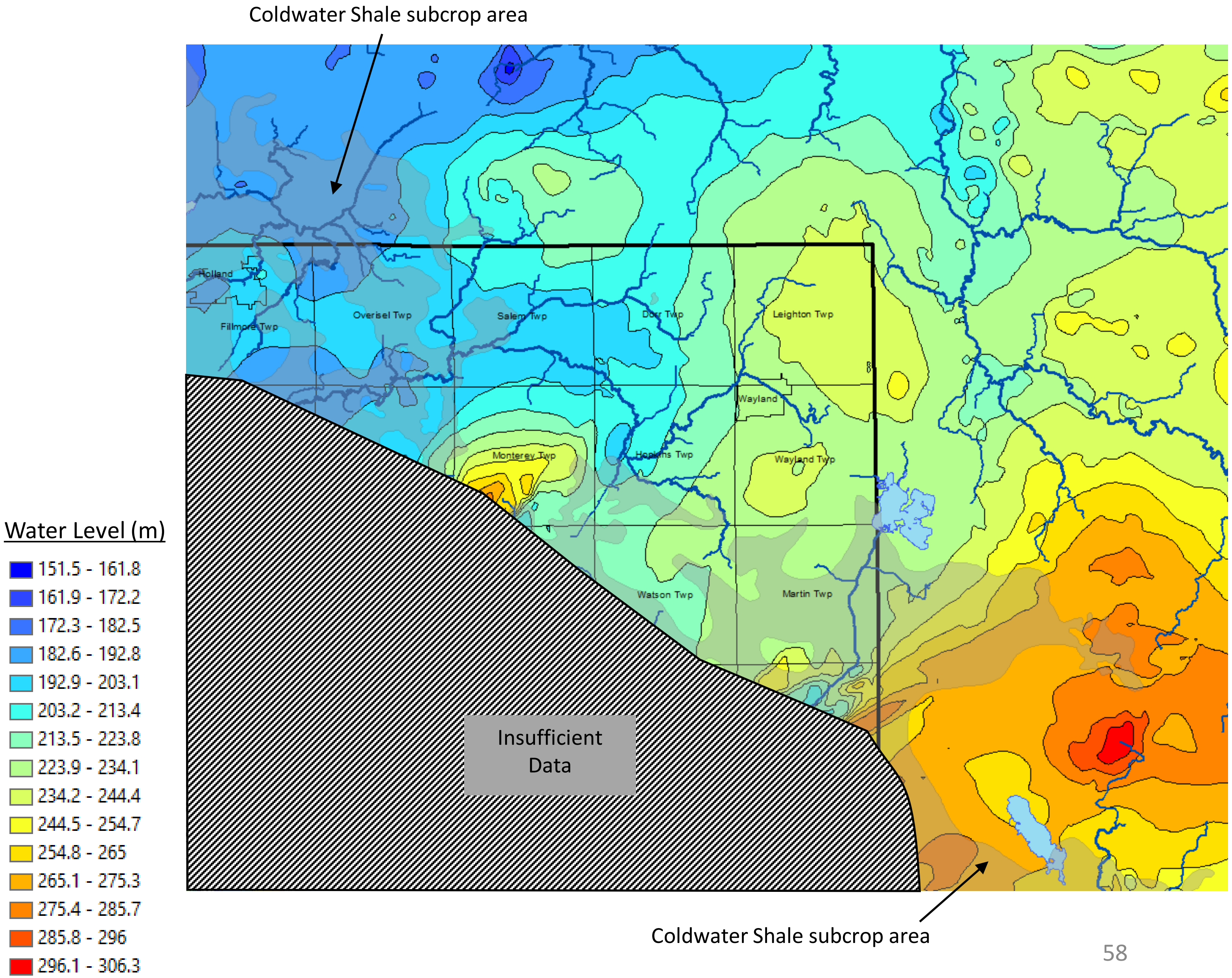
Long-term Mean Water Table

This slide shows a map of the long-term (1966-2020) average water levels in the bedrock aquifer in Allegan County and the surrounding area to the north, northeast and east. The red areas are the high-elevation water table regions and the blue areas are where the water table is at low elevations. The maximum bedrock water level difference within the county is about 94m (310 ft).

Water levels in the bedrock are highest in the northwest corner of the county (Leighton Twp.) and along the interface with the Coldwater Shale in Monterey Twp. These areas are local recharge areas for the bedrock aquifer. The latter (Monterey Twp.) benefits from relatively large recharge to the glacial aquifer in this area and the permeable outwash materials overlying the bedrock (i.e., there is good vertical connection between the aquifers).

Groundwater in the bedrock discharges toward the surface (through the glacial aquifer) to the Little Rabbit River and the Rabbit River.

Regionally, the bedrock is recharged to the east in Barry County (see the “mound” in the figure); however, the regional gradient inside Allegan County is small, meaning the bedrock flow system in the county is localized (i.e., there is relatively little flux of groundwater from the regional recharge mound). This is consistent with the low transmissivity of the bedrock noted on slide 43.



Well Network Growth Over Time

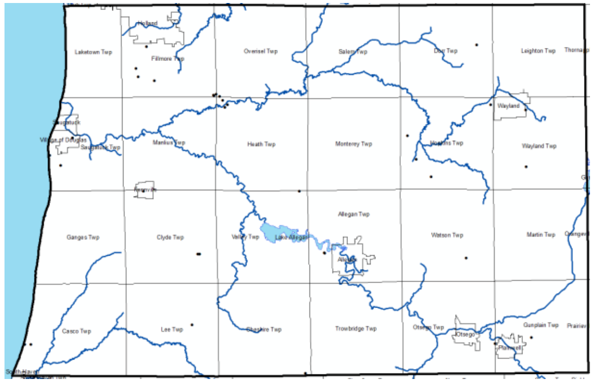
1960s - 2020

This slide shows the distribution of wells in the *Wellogic* database at different "snapshots" in time: up to 1970s (i.e., all wells built before 1970), up to 1980, up to 1990, up to 2000, up to 2010, and up to 2020.

There is a gradual increase in the number of wells from the 1970s through the 1990s. Then, a significant number of wells were added after 2000 throughout all parts of the county. This is in part because of increases in groundwater use in response to increased water demand.

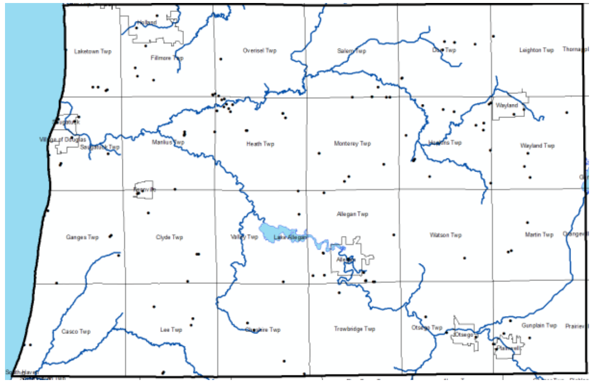
But also note that the year 2000 was about the time which new wells began to be routinely directly added to *Wellogic*. It's possible that there are a significant number of wells missing from the database prior to 2000. And while the reported values are not meant to be exact or highly certain estimates, this type of spatial mapping analysis is an effective way to estimate relative differences in well density across space (and time).

Up to 1970



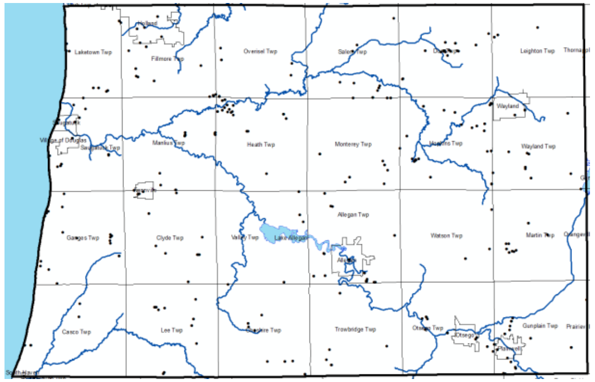
$N_{pts} = 41$

Up to 1980



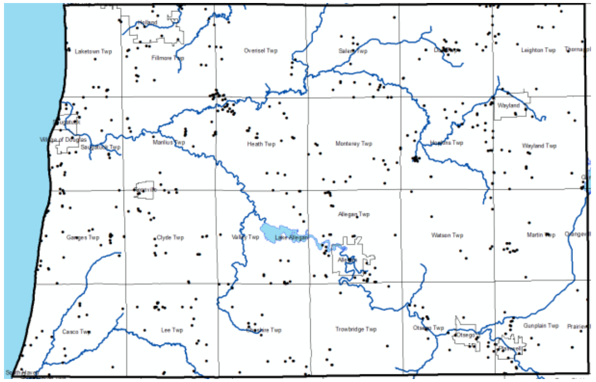
$N_{pts} = 153$

Up to 1990



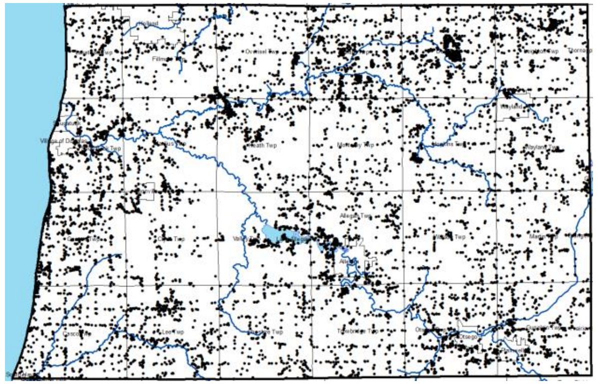
$N_{pts} = 310$

Up to 2000



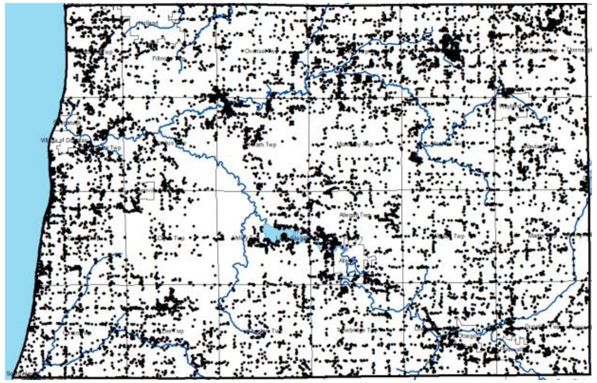
$N_{pts} = 631$

Up to 2010



$N_{pts} = 9432$

Up to 2020



$N_{pts} = 14694$

Well Network Growth Over Time

2002 - 2020

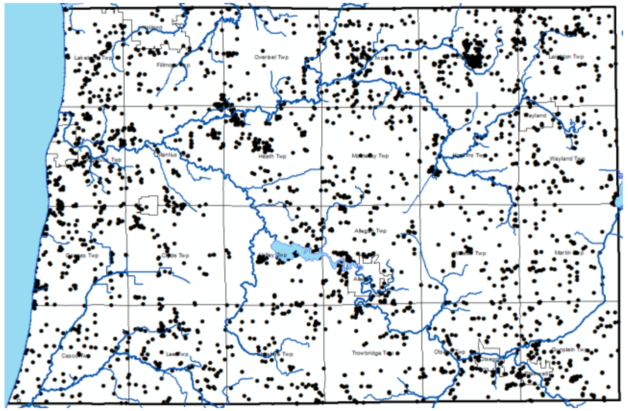
This slide focusing on the 2000-2020 time period in more detail (i.e., more temporal resolution).

While there is significant growth seen in all parts of the county, the areas seeing the largest growth are:

- in the "outer" townships along the periphery of the county; and
- along the Kalamazoo River and Lake Allegan in Heath, Allegan, and Otsego Townships.

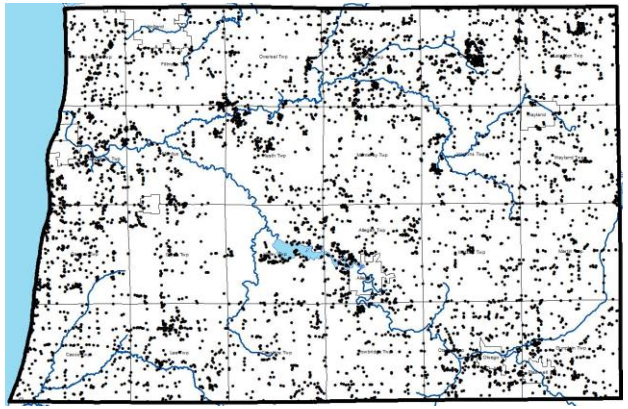
The following slides present township-by-township and section-by-section analysis of well density generated from the point data presented here.

Up to 2002



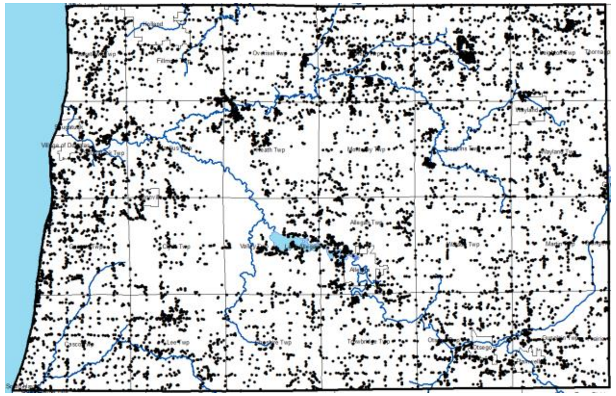
$N_{pts} = 2765$

Up to 2005



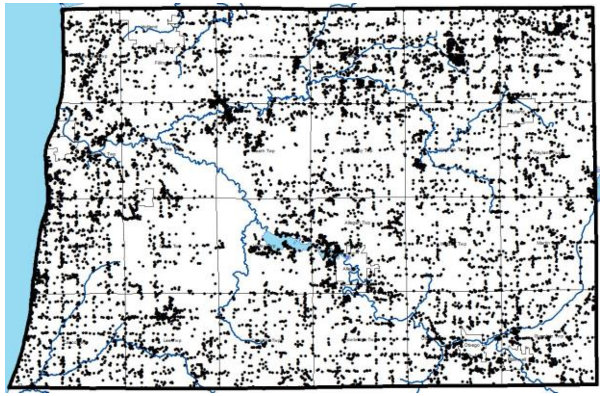
$N_{pts} = 5975$

Up to 2010



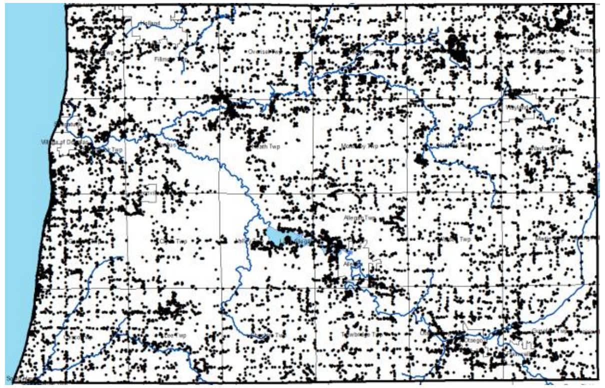
$N_{pts} = 9432$

Up to 2015



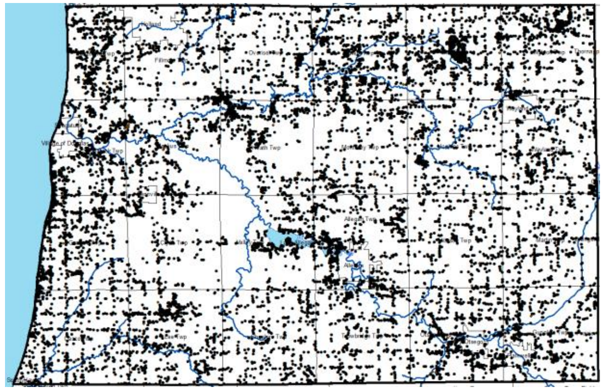
$N_{pts} = 11852$

Up to 2020



$N_{pts} = 14694$

As of Aug. 2020



$N_{pts} = 15114$

Present-day Distribution of Wells

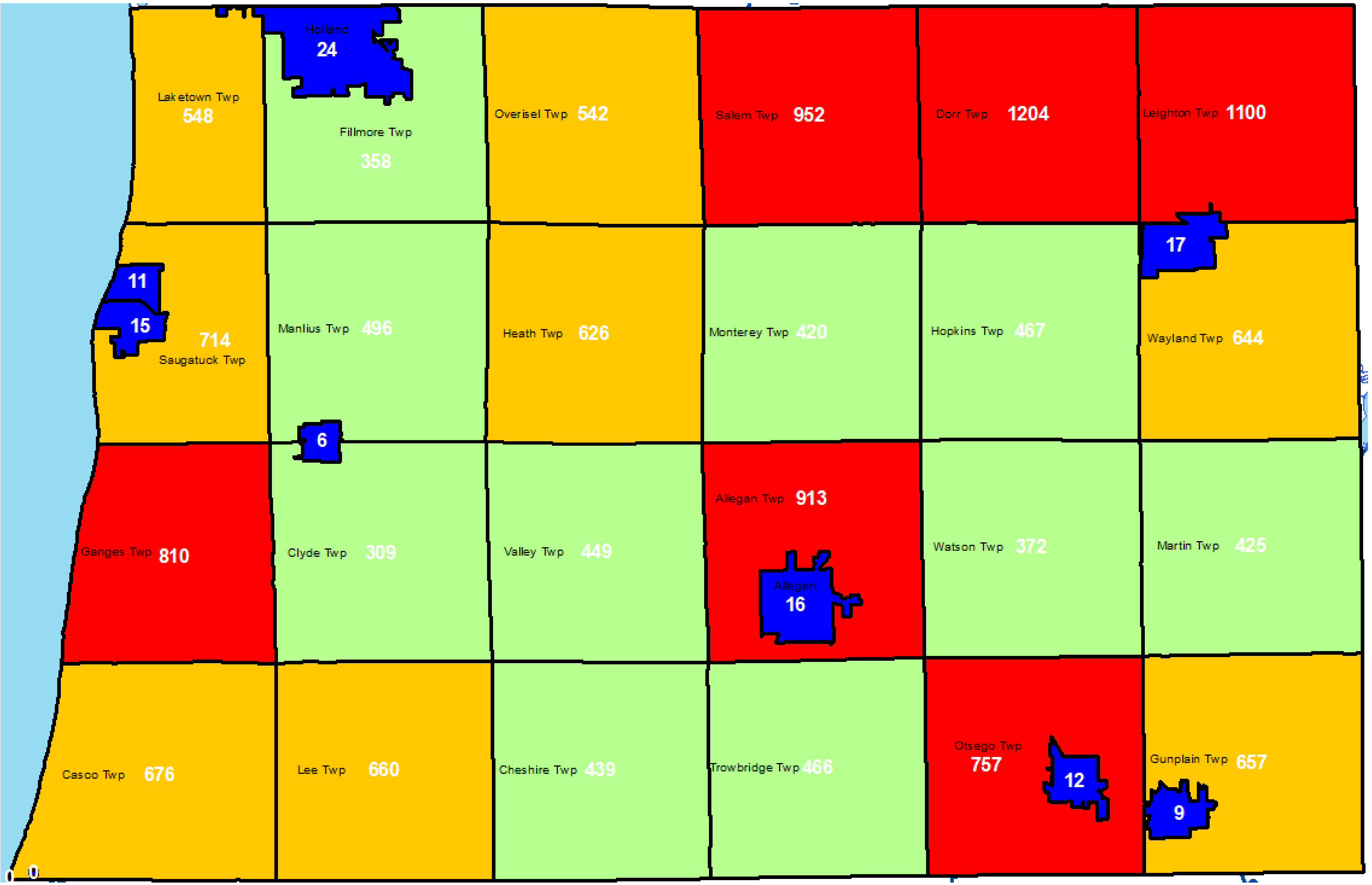
Township-by-township

This slide presents the present-day well density distribution on a township-by-township basis.

The townships with the most wells include: Dorr (1204 wells), Leighton (1100), Salem (952), Allegan (913), Ganges (810), and Otsego (757).

Clyde, Fillmore, and Watson Townships have the fewest wells (<400 wells). All cities and villages (e.g., Holland, Allegan, etc.) have fewer than 25 wells in the Wellogic database.

Again, It is known that the actual number of water wells in Michigan far exceeds the number of water well records in Wellogic - perhaps as much as 67% of the total number of wells are missing on a statewide scale. Although the percentage of missing wells in Allegan County is unknown, the number of wells reported here are underestimates. The relative number of wells (e.g., in one township versus another) is accurate based on our analysis in other parts of the state.



Number of Wells

- 0 - 100
- 101 - 250
- 251 - 500
- 501 - 750
- 751 - 1204

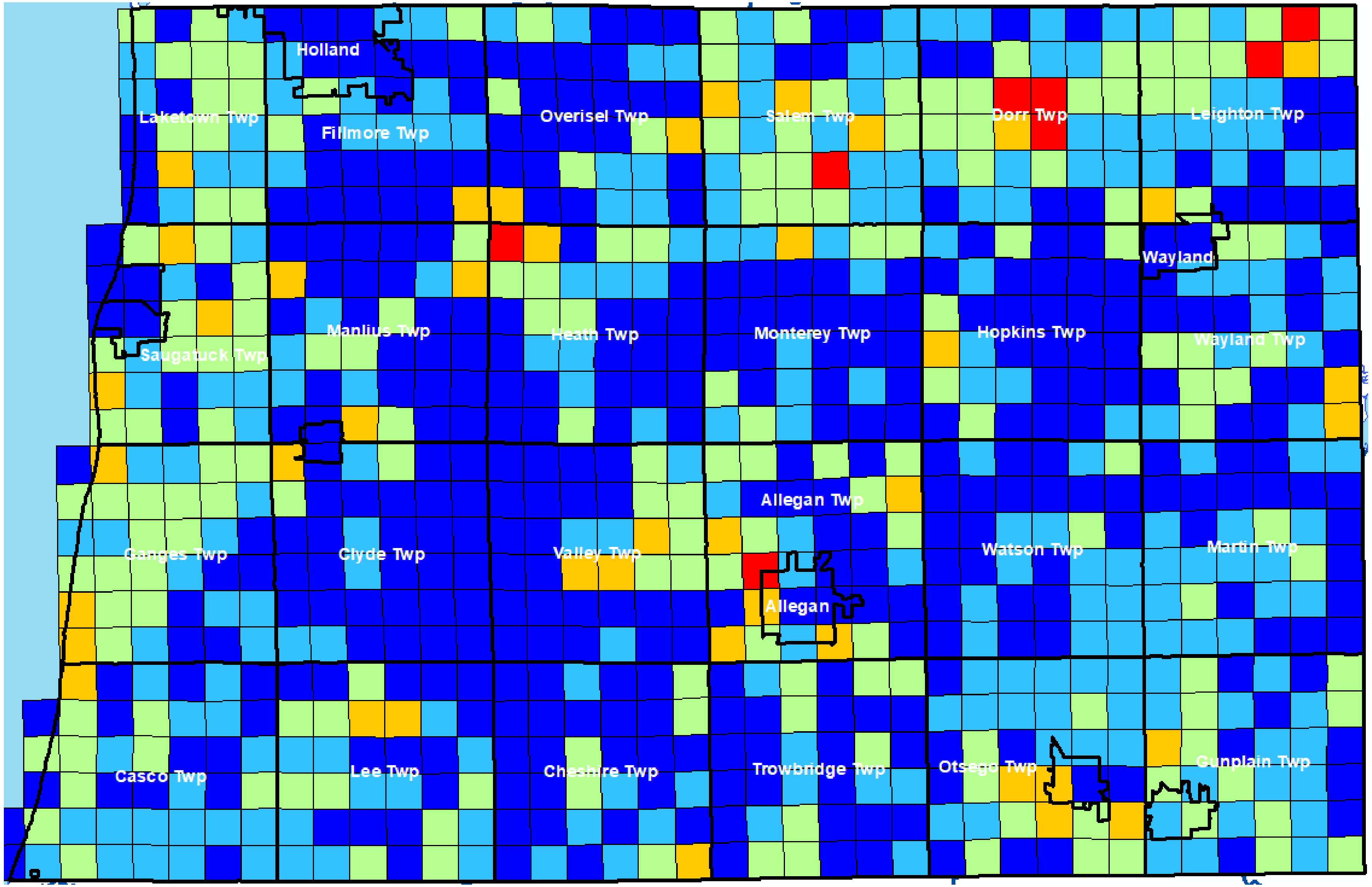
Present-day Distribution of Wells

Section-by-section

This slide shows section-by-section well density distribution for present day (Aug. 2020).

Several "hot-spots" can be seen:

- central Door Township
- north-northeast Leighton Township
- western Allegan Township / Allegan City.
- portions of Saugatuck, Ganges, Laketown, Salem, Otsego and Gunplain Townships



Number of Wells

- 0 - 10
- 11 - 20
- 21 - 50
- 51 - 100
- 101 - 268

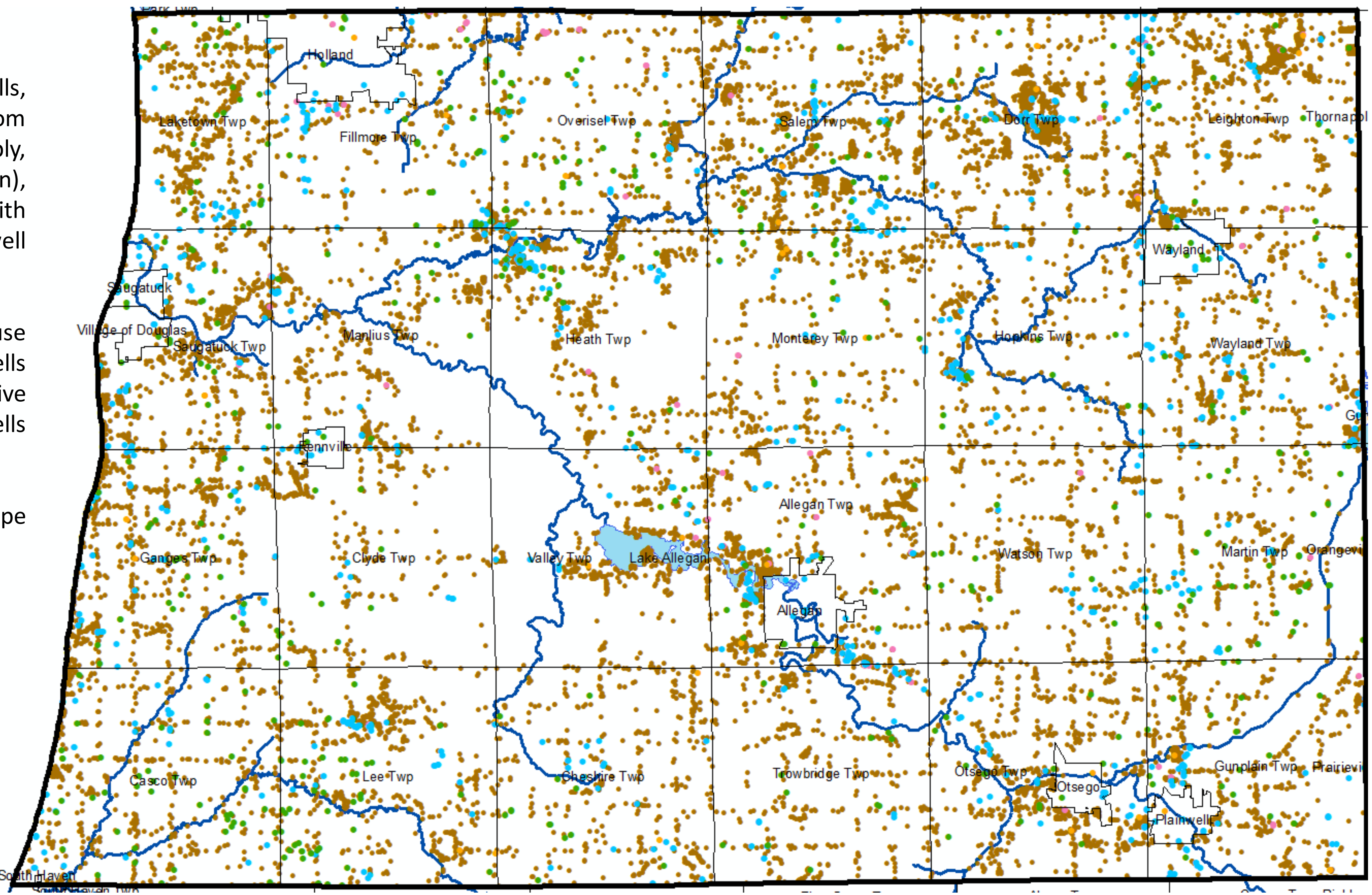
Present-day Distribution of Wells

By Water Sector

This slide shows the present-day distribution of wells, with different color circles representing wells from different water use sectors: irrigation, public supply, commercial / industry (including power generation), and private household (or domestic). Wells with records lacking sufficient information to assign a well type were classified as Unknown.

Note that a vast majority of the wells are low-use domestic wells. However, when many household wells are operating in close proximity, the cumulative impacts of pumping can mirror high-capacity wells used for irrigation, public supply, and/or industry.

The following slide shows the distribution of each type of well individually.



- Irrigation
- Public Supply
- Industry
- Unknown
- Household

Present-day Distribution of Wells

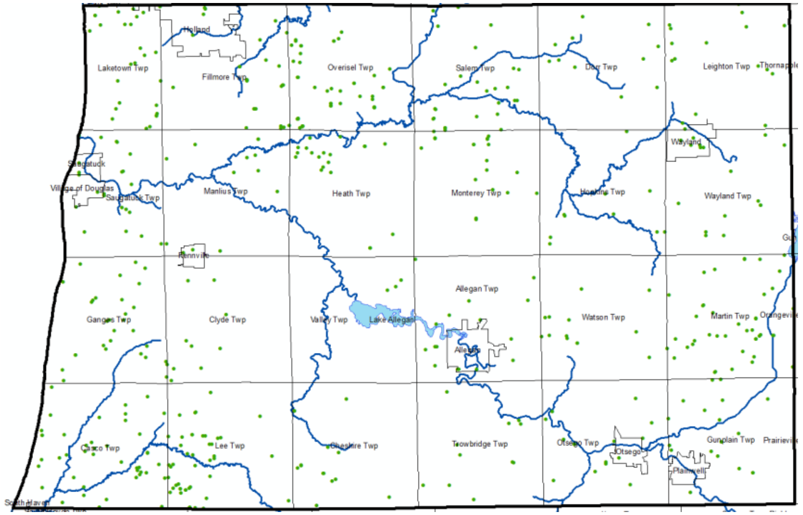
By Water Sector

Irrigation: many irrigation wells are found along a broad west-to-east swath in the northern third of the county, and in the southwestern (especially Ganges, Casco, and Lee Twps.) and southeastern (especially Martin Twp.) portions of the county. Five hundred twenty one (521) irrigation wells from Wellogic were classified as irrigation.

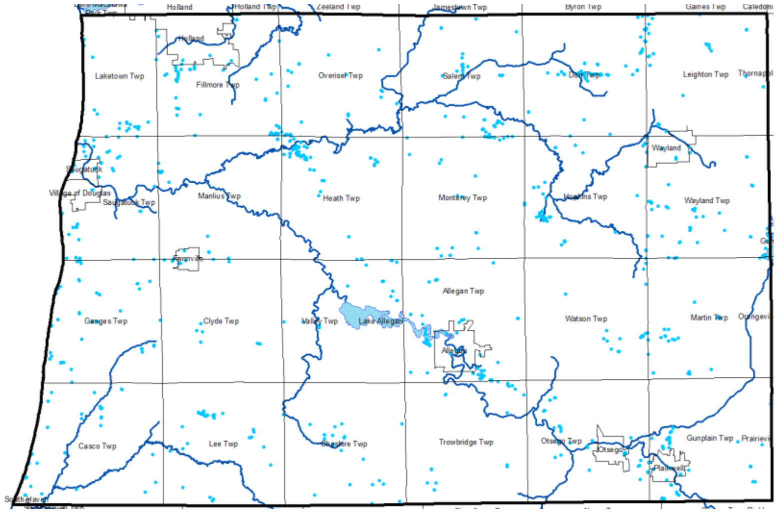
Public Supply: most public supply wells are, not surprisingly, found in/near population centers, with intermittent occurrences in between. Eight hundred ninety six (896) wells from Wellogic were classified as public supply.

Industry: There are significantly fewer wells that were classified as industry / commercial (42). Most are in / near population centers.

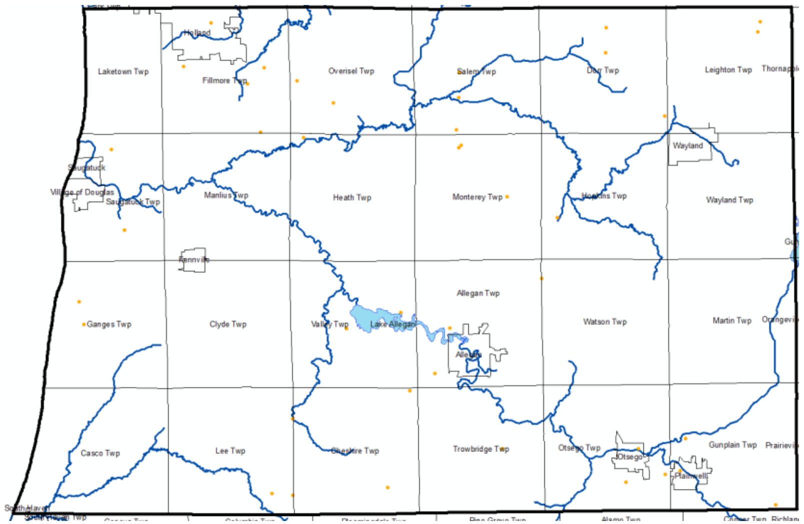
Household: By far, most wells from *Wellogic* were classified as household (13,050). They occur throughout the county, with high-densities in/near population centers but also rural areas. Some townships have notably fewer household wells (e.g., Fillmore, Clyde, and Monterey Townships).



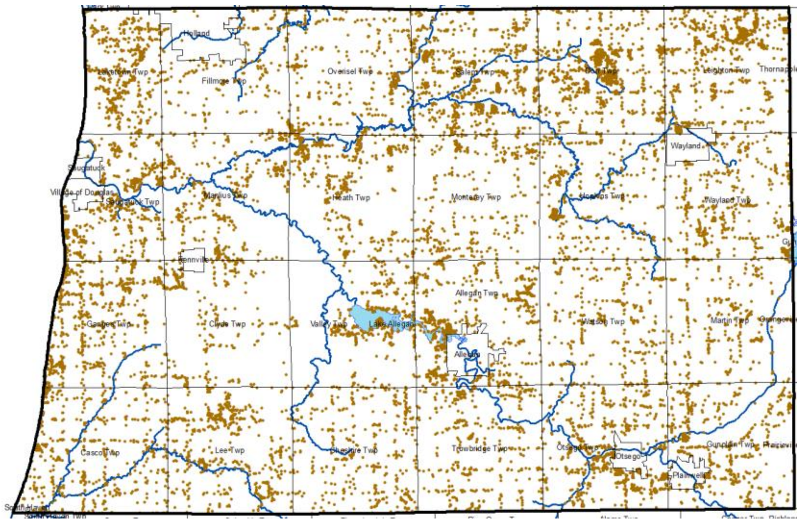
Irrigation $N_{IRRI} = 521$



Public Supply $N_{PS} = 896$



Industry $N_{NDUS} = 42$



Household $N_{HOSHOLD} = 13050$

Water Use Patterns

Screening-Level Water Use Model

A screening-level countywide water use model was developed using information contained in the *Wellogic* water well records and a few simplifying assumptions about pumping rates. Even though the actual pumping rates may vary significantly from those applied for this study, it is an effective way to estimate relative differences in pumping across space (and time). Again, the reported values are not meant to be exact or highly certain estimates.

The approach worked as follows:

- All compiled wells were classified as “domestic,” “irrigation,” “public supply,” or “industrial/commercial” (based on information provided in driller logs), and the pumping rates of different well types were assigned using calibrated “long-term average” pumping rates from the Phase II Ottawa County Water Resources Study (Curtis et al., 2018). These pumping rates are “effective” in that they represent the impact of different types of wells as if they are operating continuously, although in reality there may be daily or seasonal fluctuations (as well as periods when the pumping rate is zero). A thorough process of fine-tuning the pumping rates was completed using sophisticated computer simulations and large observational water level datasets.

- The calibrated pumping rates using in this analysis were: 13.5 GPM (gallons per minute) for irrigation wells; 8.0 GPM (gallons per minute); 13.5 GPM for industrial / commercial wells; and 0.65 GPM for domestic wells.

- Total water use was mapped township-by-township across the county by taking the number of wells (of a certain type) and multiplying by the appropriate pumping rate. Then total pumping from all water sectors was summed to get total water use. A similar approach was applied section-by-section across the county.

This approach was applied to the well network for present day (August 2020). It was also applied to the well network “snapshot” in 2000 and 2010 to get a sense of how water use has increased over the past two decades.

Water Use Patterns

Water Use (Present Day)

ALL Water Sectors

This slide shows the township-by-township results from the water use model for present day (Aug. 2020).

The townships estimated to be using the most groundwater are: Dorr Twp. (765 million gallons per year, or MGY), Lee Twp. (685 MGY), Ganges Twp. (673 MGY), Salem Township (669 MGY), and Casco Twp. (657 MGY).

Clyde and Valley Townships use the least amount of groundwater of all the townships (230 MGY and 236 MGY, respectively). All cities and villages (e.g., Holland, Allegan, etc.) use less than 70 MGY, with have using 45 MGY (Saugatuck, Douglas, Fenville, Ostego and Plainwell).

Millions of Gallons per Year (MGY)

- 0.00 - 100.00
- 100.01 - 275.00
- 275.01 - 450.00
- 450.01 - 625.00
- 625.01 - 765.00

Water Use Patterns

Water Use (Present Day)

ALL Water Sectors

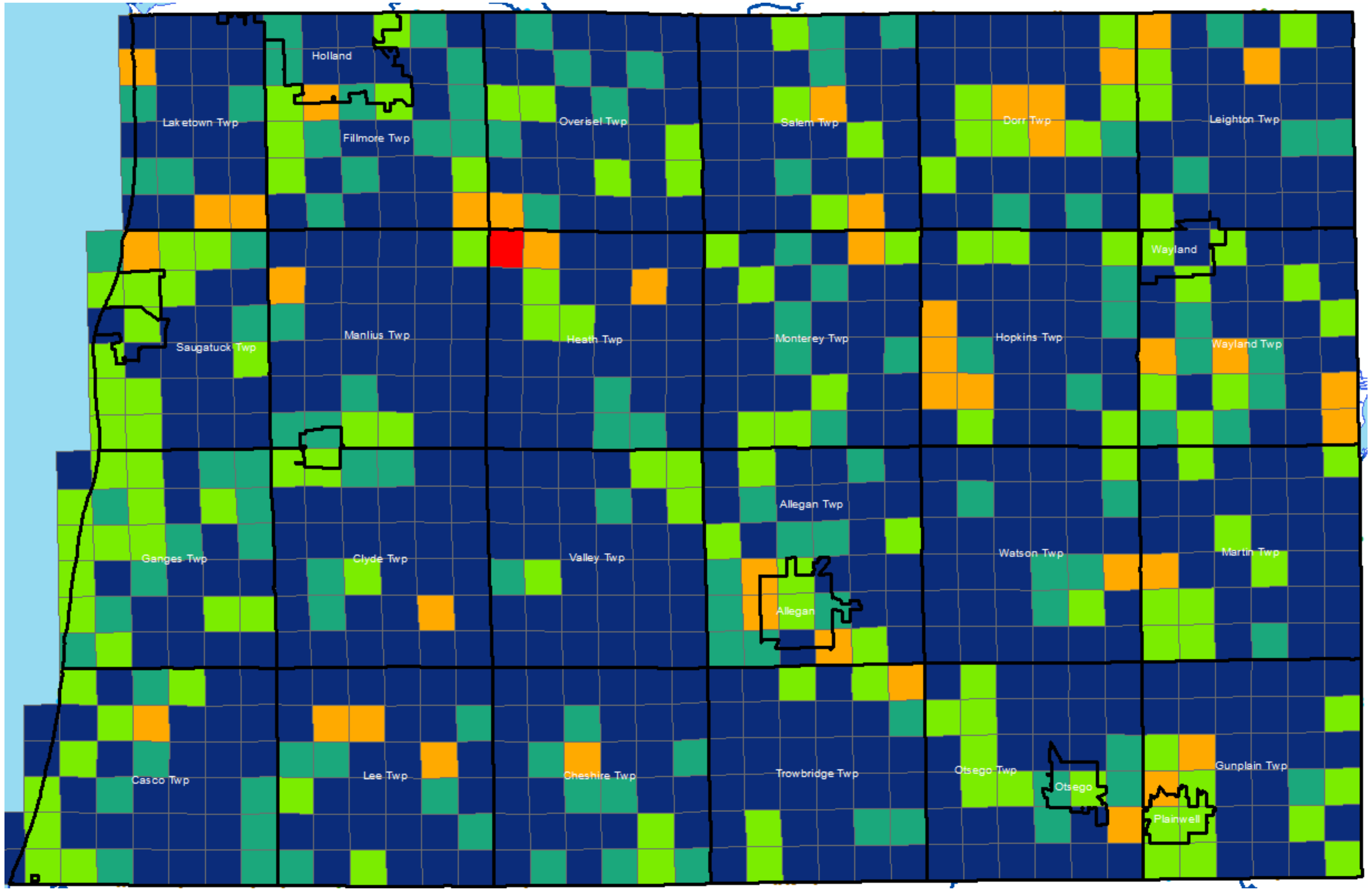
This slide shows the section-by-section results from the water use model for present day (Aug. 2020).

Not surprisingly, some of the water use “hot-spots” occur in sections inside / near population centers (many wells plus high-capacity public supply and/or industrial wells), e.g., Plainwell and Allegan. Holland is a notable exception, as the city uses surface water.

Other hot-spots can be seen in less densely populated / rural areas, e.g., Casco, Lee, Salem, and Dorr Townships.

Millions of Gallons per Year

- 0.00 - 0.10
- 0.11 - 5.00
- 5.01 - 25.00
- 25.01 - 75.00
- 75.01 - 135.00



Water Use Patterns

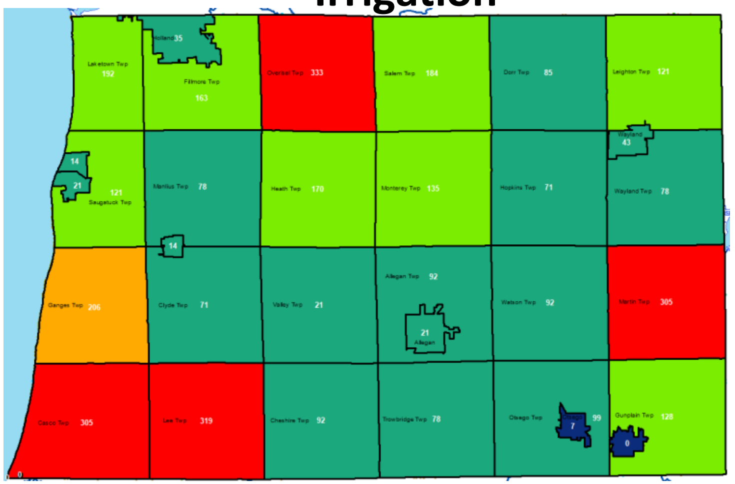
Water Use (Present Day)
By Water Sector

This slide shows township-by-township water use by sector: irrigation, public supply, industry / commercial, and household.

Groundwater use for industrial/commercial activities is low compared to the other sectors. Household water use is consistently moderate or high (between 100 and 300 MGY) and especially high (>300 MGY) in the northeast corner of the county (Dorr and Leighton Townships) – a result of the large number of domestic wells in that area.

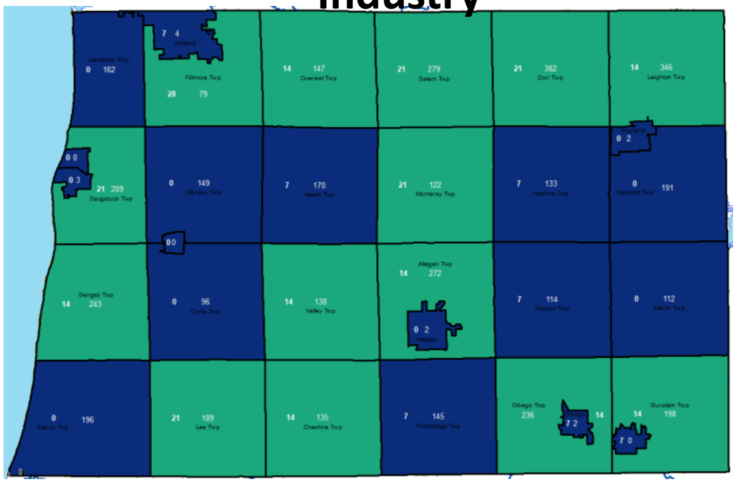
Groundwater use for irrigation is highest in Lee Overisel (333 MGY), Lee (319 MGY) Casco (305 MGY), and Martin (305 MGY) Townships.

Irrigation

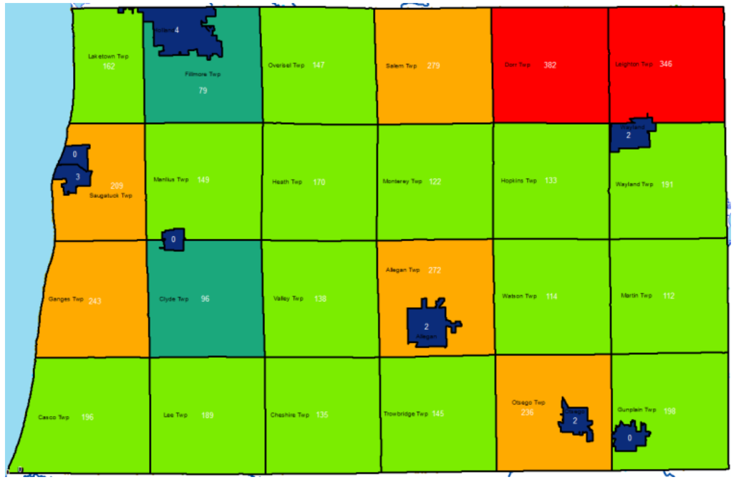


Public Supply

Industry



Household



Millions of Gallons per Year

- 0.00 - 10.00
- 10.01 - 100.00
- 100.01 - 200.00
- 200.01 - 300.00
- 300.01 - 382.00

Water Use Patterns

Water Use (Over Time)

ALL Water Sectors

This slide shows township-by-township total water use (all sectors) for different “snapshots” in time: the years 2000, 2010, and present day (Aug. 2020).

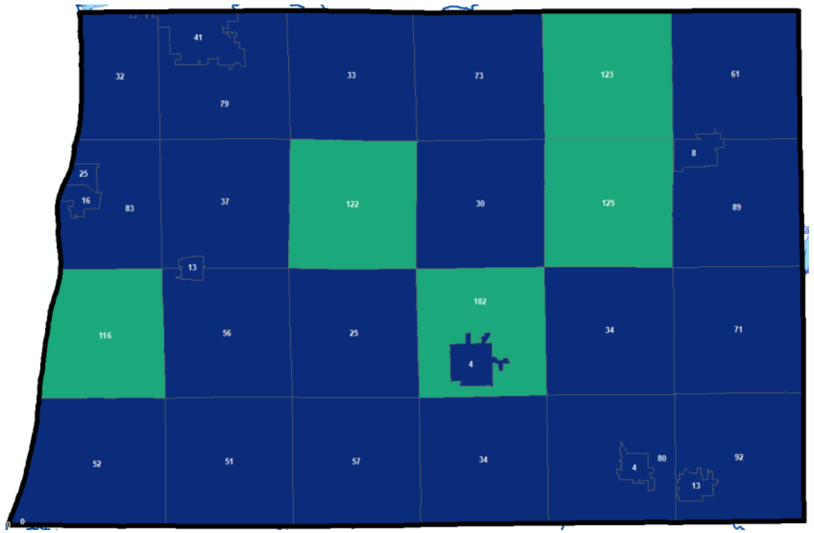
Clearly groundwater use has increased significantly over the past two decades, in virtually all parts of the county, but most significantly in the “outer” townships along the periphery of the county.

As previously mentioned, a significant number of wells were added to the Wellogic database during the 2000-2005 time period, which corresponds with the time during which Wellogic was first being used in the State of Michigan. It’s possible that there are wells missing from Wellogic prior to 2000. These wells would have been included in our spatial water use modeling, and therefore the water use presented here is likely to be an underestimate of actual water use.

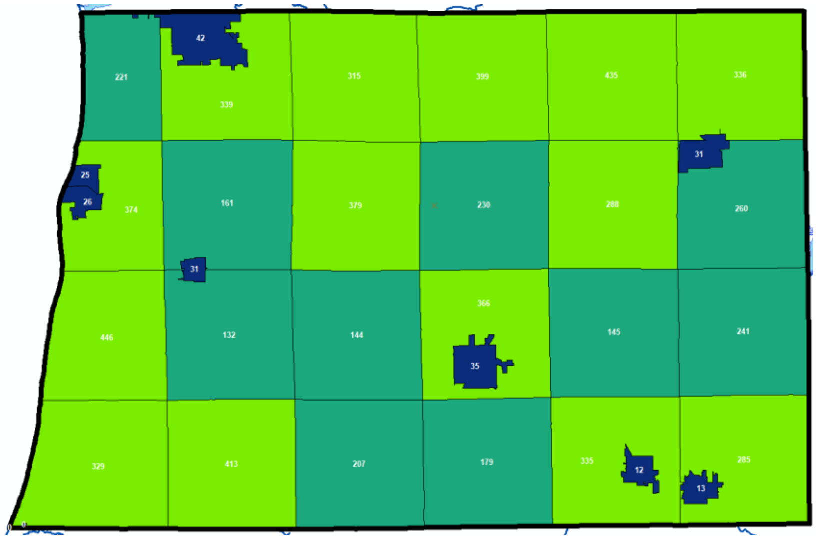
Millions of Gallons per Year

- 0.00 - 100.00
- 100.01 - 275.00
- 275.01 - 450.00
- 450.01 - 625.00
- 625.01 - 765.00

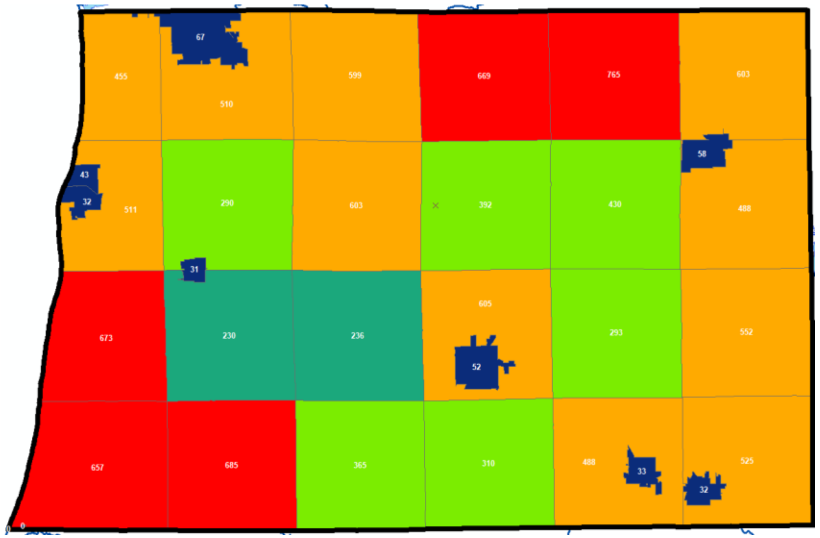
2000



2010



Present Day



Temporal Water Level Trends in High Water Use Areas

This slide highlights the areas of highest groundwater use in Allegan County presented on slide 66.

Long term sustainability can be best evaluated with long-term monitoring wells, but data from them is not available in the county and is prohibitively expensive to collect on a county-wide scale. However, Static Water Level (SWL) data from domestic wells in an area can be used to provide a screening-level evaluation of temporal water level trends. More specifically, SWL data (collected at the time of installation of a water well) analyzed over a sufficiently large area often includes representative dates (i.e., the area includes wells drilled in different decades). If the temporal decline is significantly larger than SWL spatial variability and measurement "noise" (seasonal water level fluctuations, location uncertainty of the well, etc.), a trend can be identified. But when the area is too large, the temporal decline can be hidden by spatial variability and noise. In other words, there is a tradeoff between space and time in the SWL temporal analysis.

Static water levels from *Wellogic* records were analyzed over time in the areas of highest groundwater use in Allegan County. The following slides present the results for the various townships highlighted here.

Temporal Water Level Trends in Areas of Growth

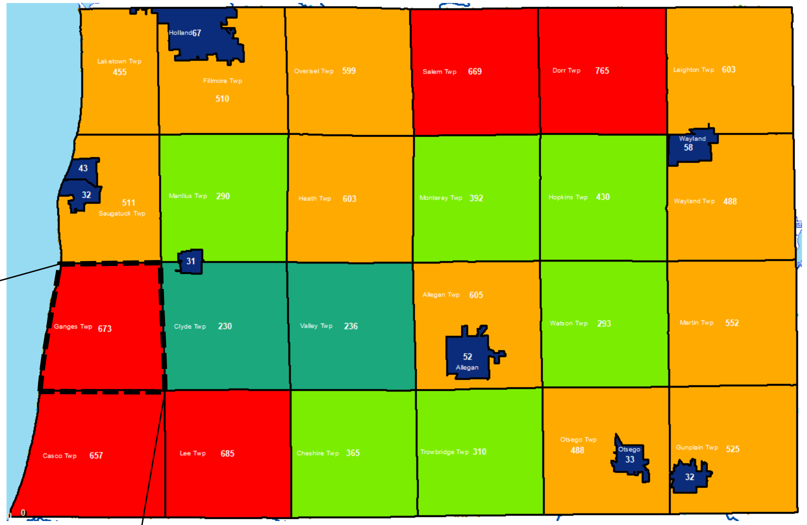
Ganges Township

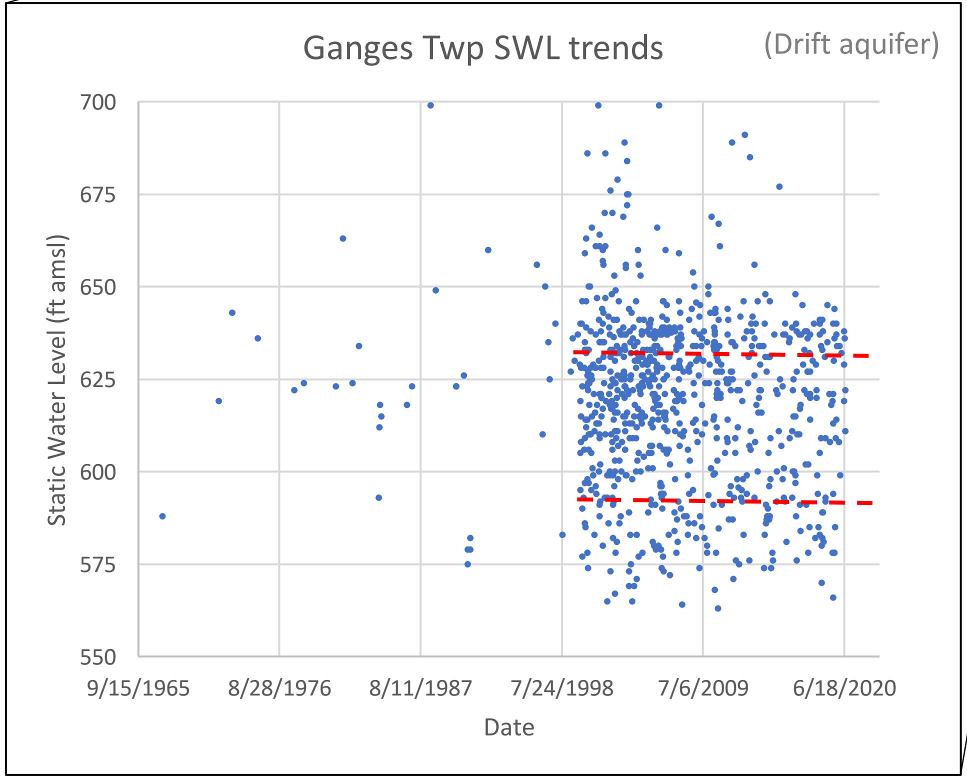
This slide shows SWL data over time for Ganges Township. Note that wells in Ganges Township are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer).

It’s possible there are two different “clouds” of data shown in the figure, for two different areas within the township and/or wells within the same area that are screen at different depths.

Note:

- There is a possibility of modest (5-10 ft) systematic SWL decline since 2000.
- There is not enough data prior to 2000 to make a determination.

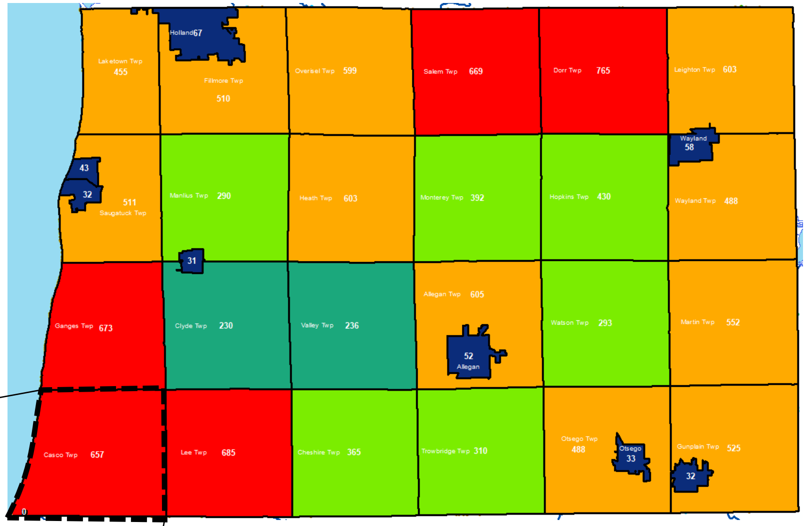




Temporal Water Level Trends in Areas of Growth

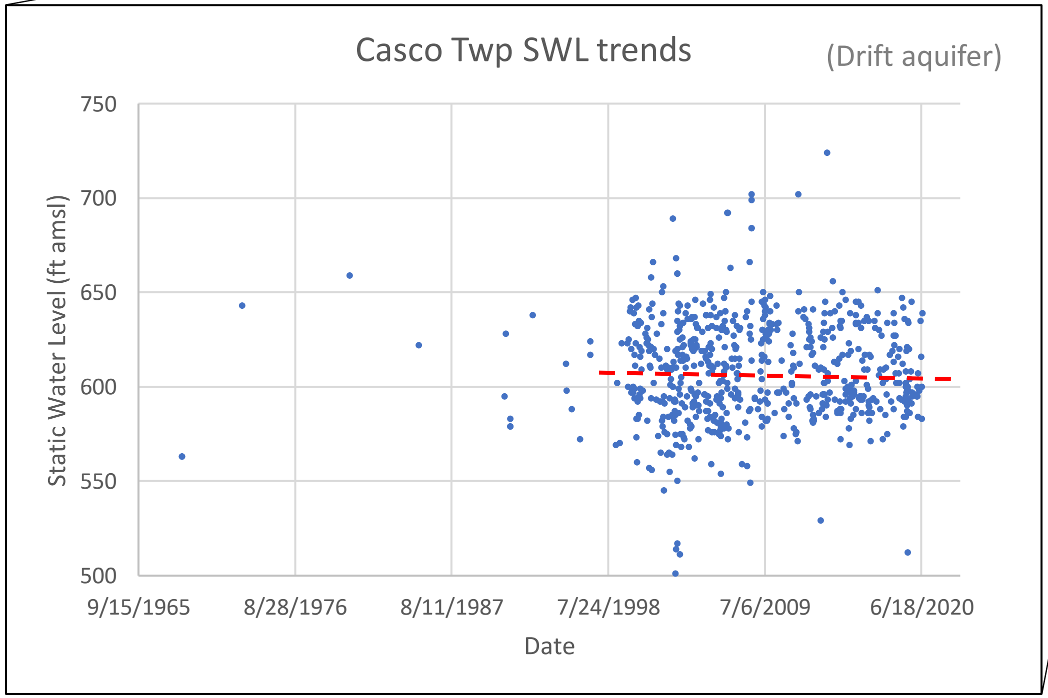
Casco Township

This slide shows SWL data over time for Casco Township. Note that wells in Casco Township are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer).



Note:

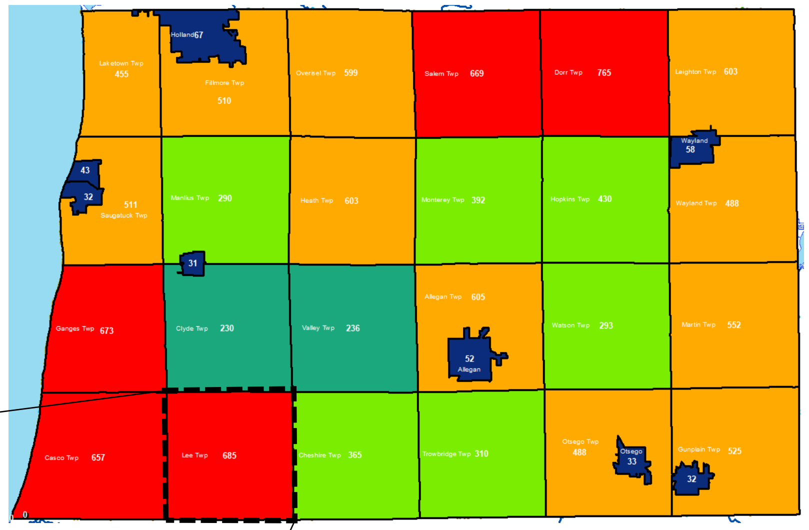
- There does not appear to be a significant temporal trend for the 2000-2020 time period.
- There is not enough data prior to 2000 to make a determination.



Temporal Water Level Trends in Areas of Growth

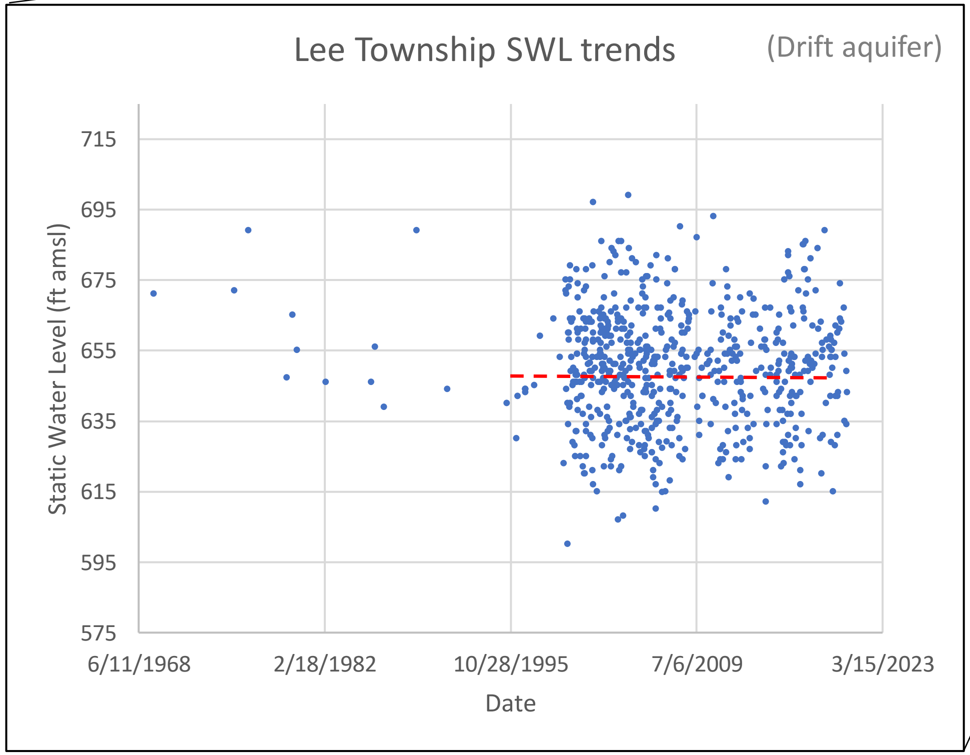
Lee Township

This slide shows SWL data over time for Lee Township. Note that wells in Lee Township are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer).



Note:

- There does not appear to be a significant temporal trend for the 2000-2020 time period.
- There is not enough data prior to 2000 to make a determination.

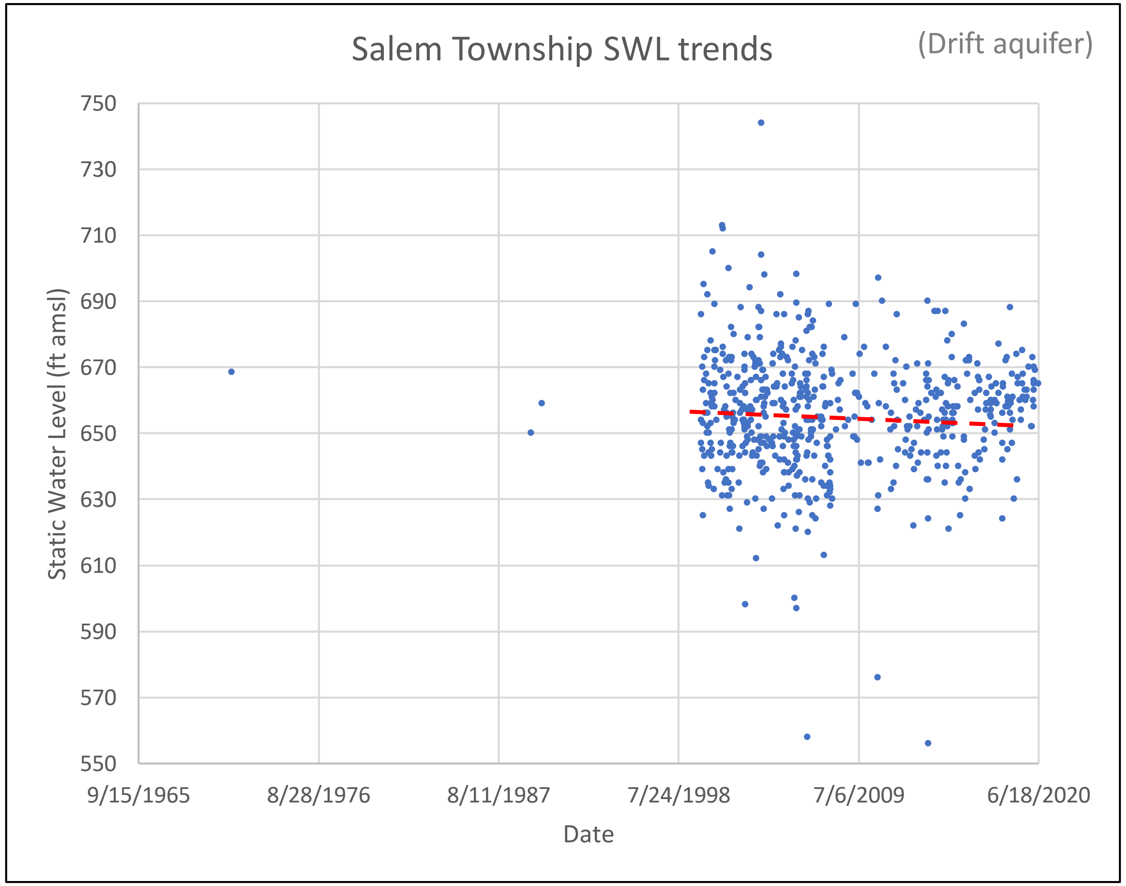


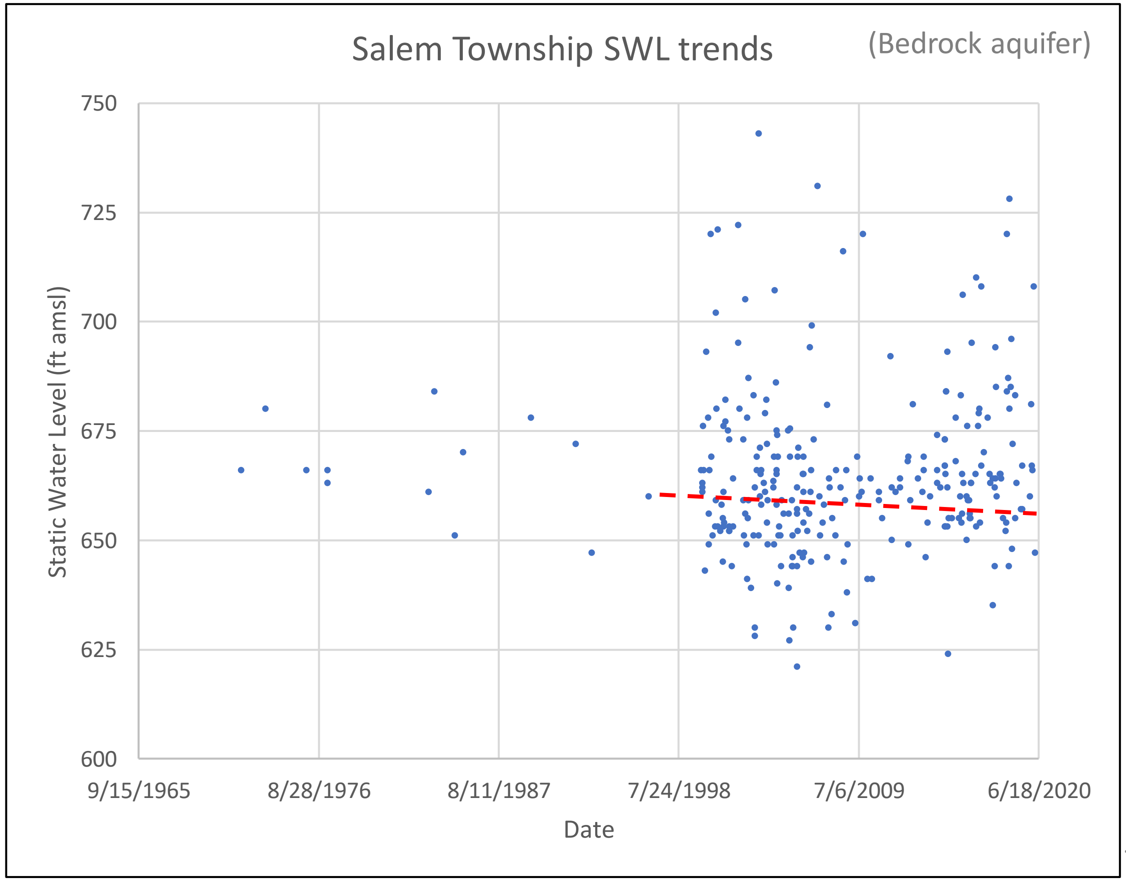
Temporal Water Level Trends in Areas of Growth

Salem Township

This slide shows SWL data over time for Salem Township. Note that wells in Salem Township are screened in both the glacial aquifer and deeper Marshall bedrock aquifer.

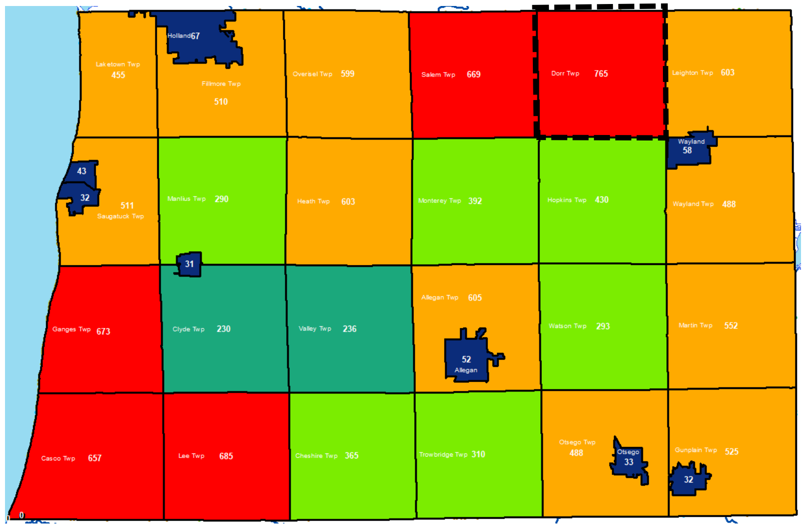
There is a possibility of modest (5-10 ft) systematic SWL decline since 2000, in both the glacial and bedrock aquifers. There is not enough data prior to 2000 to make a determination.





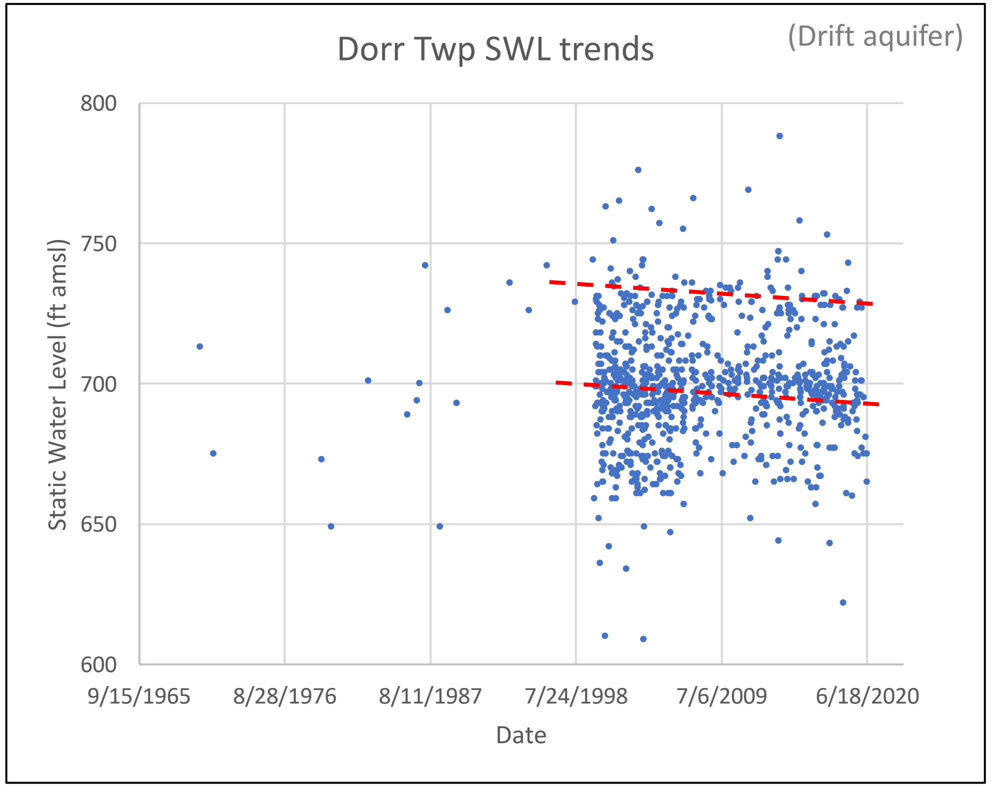
Temporal Water Level Trends in Areas of Growth

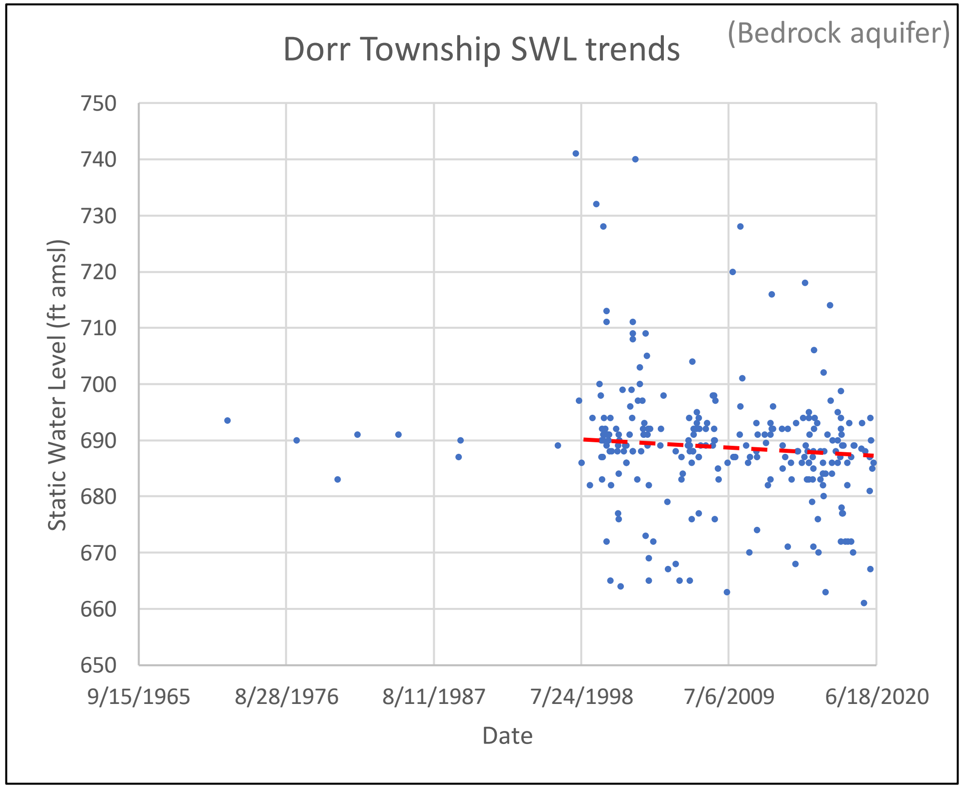
Dorr Township



This slide shows SWL data over time for Dorr Township. Note that wells in Dorr Township are screened in both the glacial aquifer and deeper Marshall bedrock aquifer. For the glacial layer, it is possible there are two different “clouds” of data shown in the figure, for two different areas within the township and/or wells within the same area that are screen at different depths.

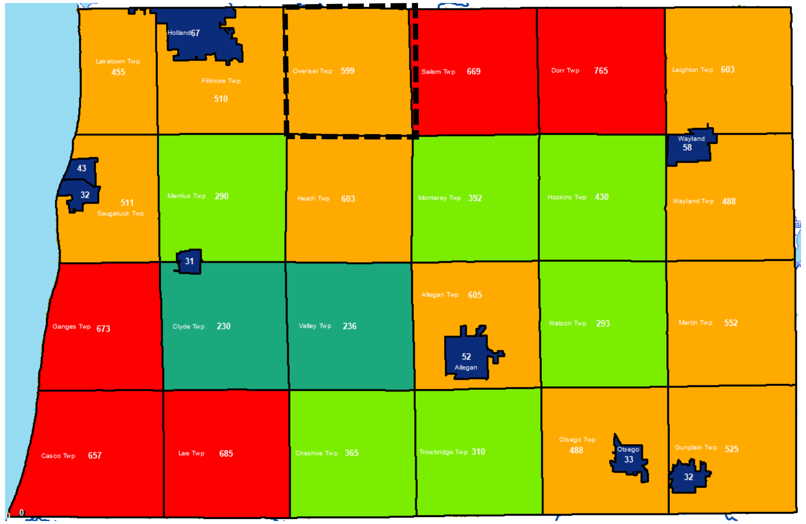
There is a possibility of modest (5-10 ft) systematic SWL decline since 2000, in both the glacial and bedrock aquifers. There is not enough data prior to 2000 to make a determination.





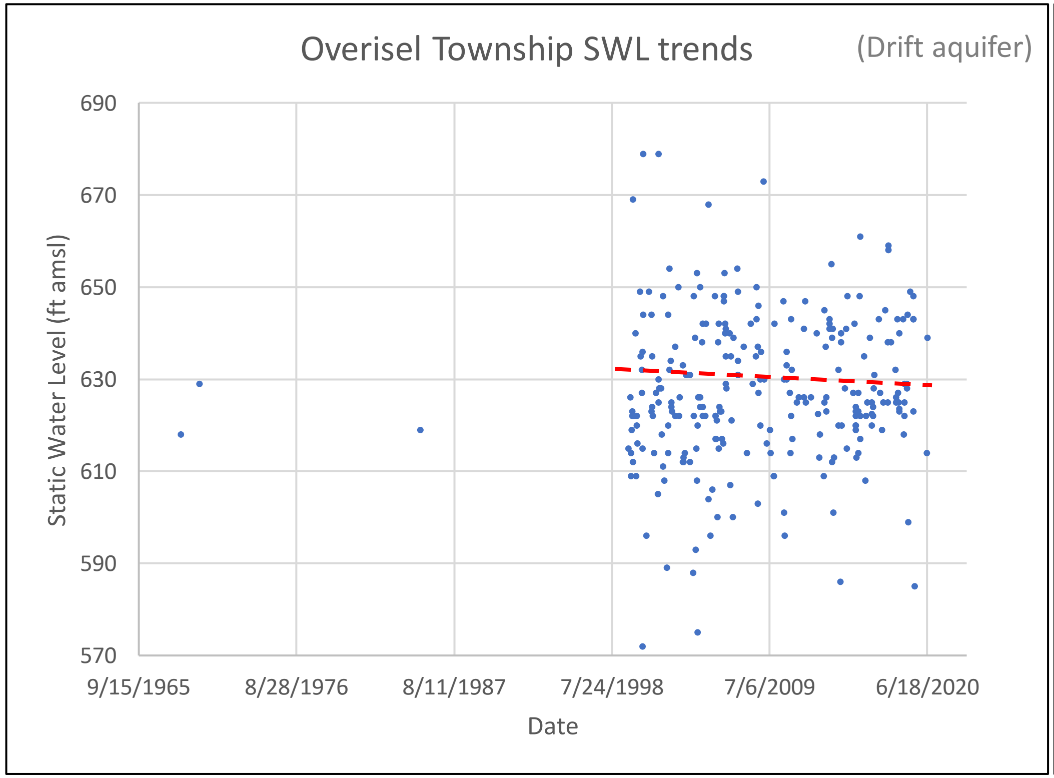
Temporal Water Level Trends in Areas of Growth

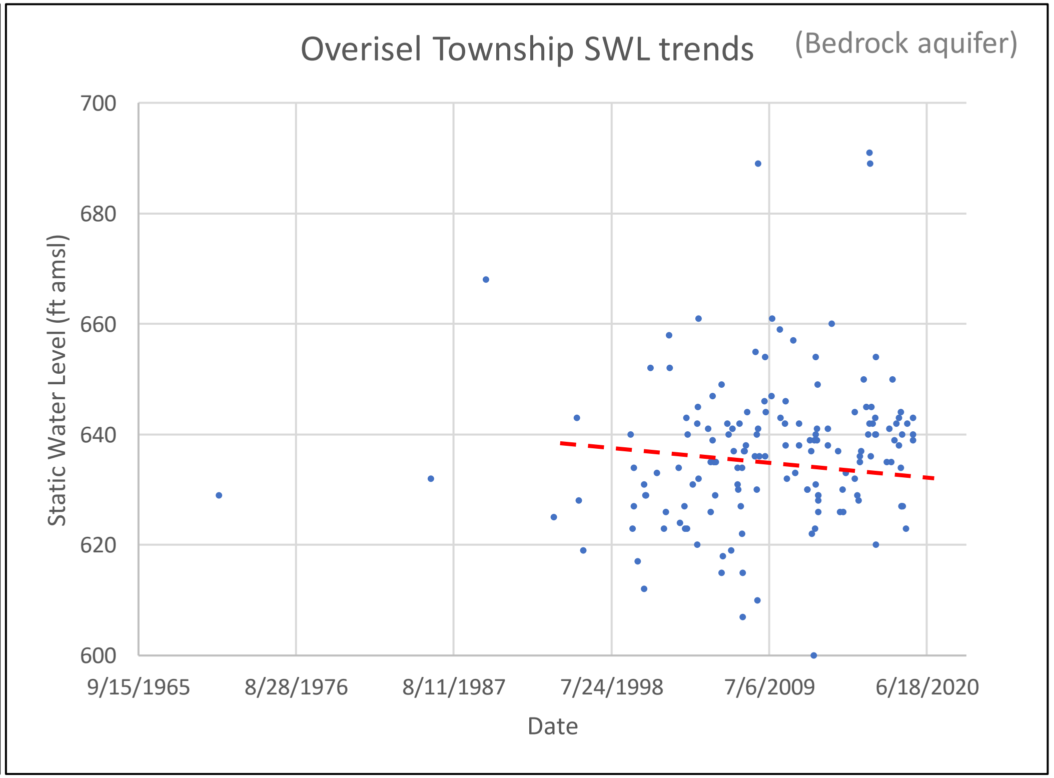
Overisel Township



This slide shows SWL data over time for Overisel Township. Note that wells in Dorr Township are screened primarily in the glacial aquifer, although some wells may terminate in the bedrock (the Marshall Sandstone and the Coldwater Shale formations interface in this area).

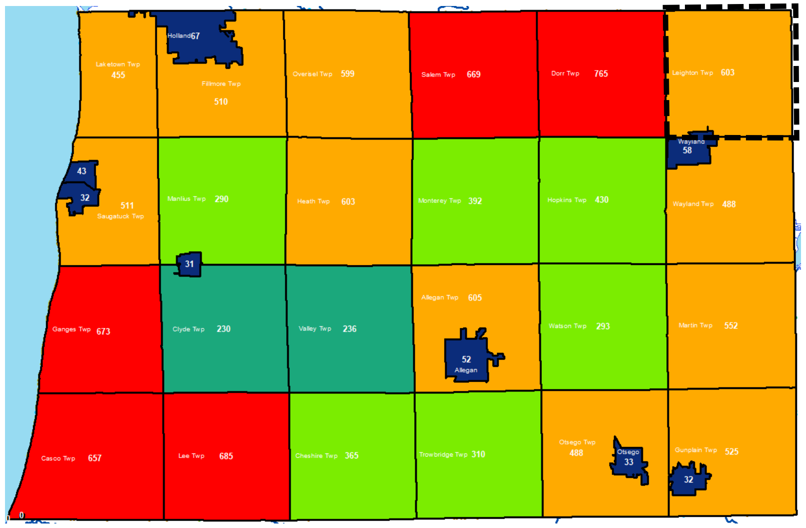
There is a possibility of modest (5-10 ft) systematic SWL decline since 2000 in the glacial aquifer. A more substantial SWL decline (~10 ft) is possible in the bedrock aquifer. There is not enough data prior to 2000 to make a determination in either case.





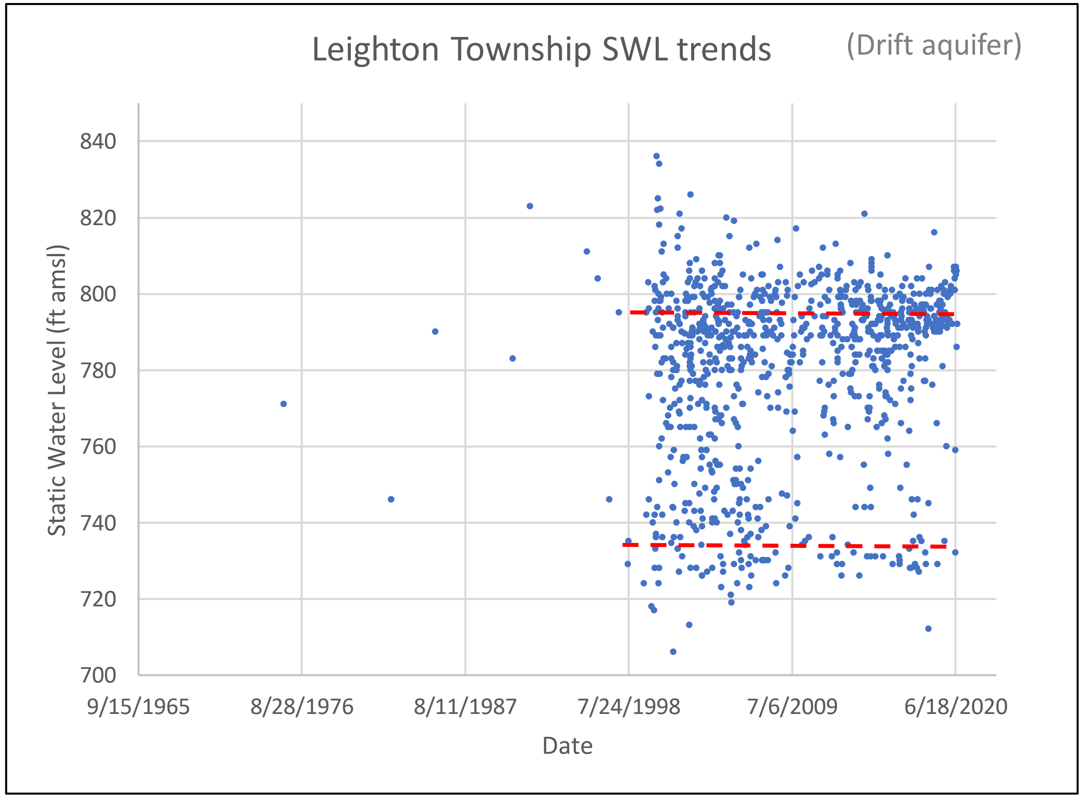
Temporal Water Level Trends in Areas of Growth

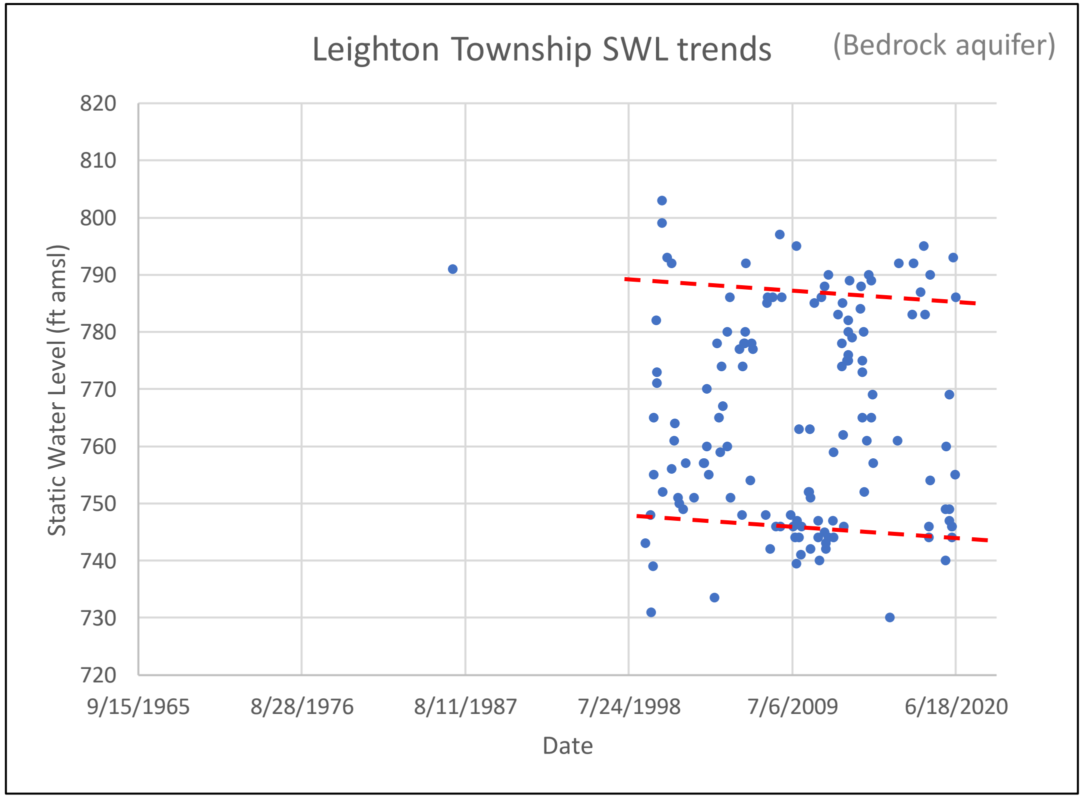
Leighton Township



This slide shows SWL data over time for Leighton Township. Note that wells in Leighton Township are screened in both the glacial aquifer and deeper Marshall bedrock aquifer. It is possible there are two different “clouds” of data shown in the figures, for two different areas within the township and/or wells within the same area that are screen at different depths.

There is a possibility of modest (5-10 ft) systematic SWL decline since 2000 in the bedrock aquifer. An overall trend is not observed for the glacial aquifer. There is not enough data prior to 2000 to make a determination in either aquifer.





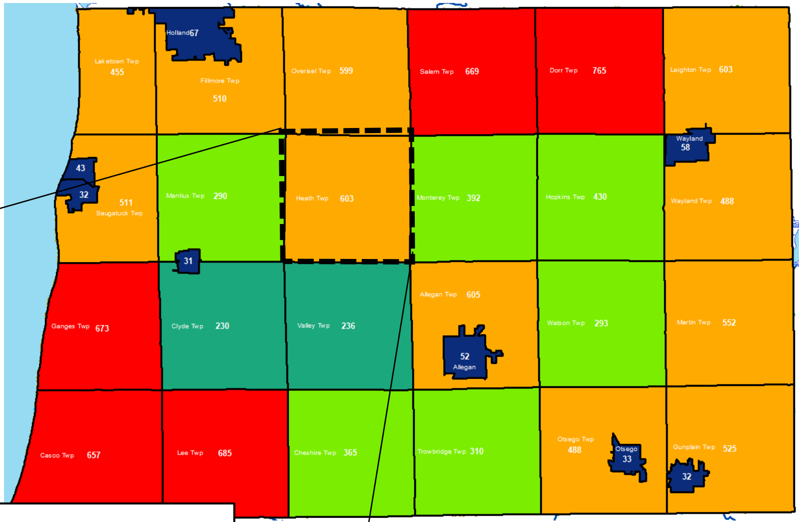
Temporal Water Level Trends in Areas of Growth

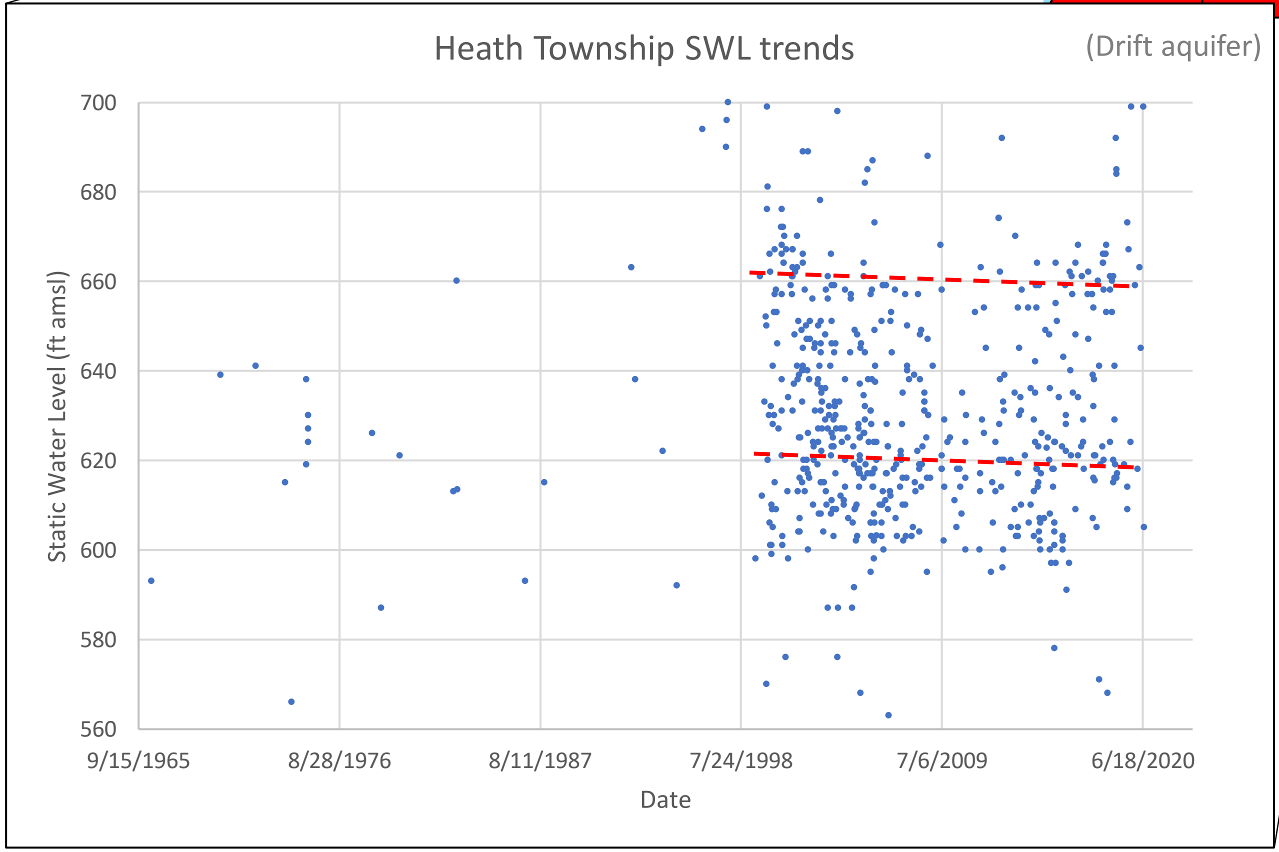
Heath Township

This slide shows SWL data over time for Heath Township. Note that wells in Heath Township are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer). It is possible there are two different "clouds" of data shown in the figure, for two different areas within the township and/or wells within the same area that are screen at different depths.

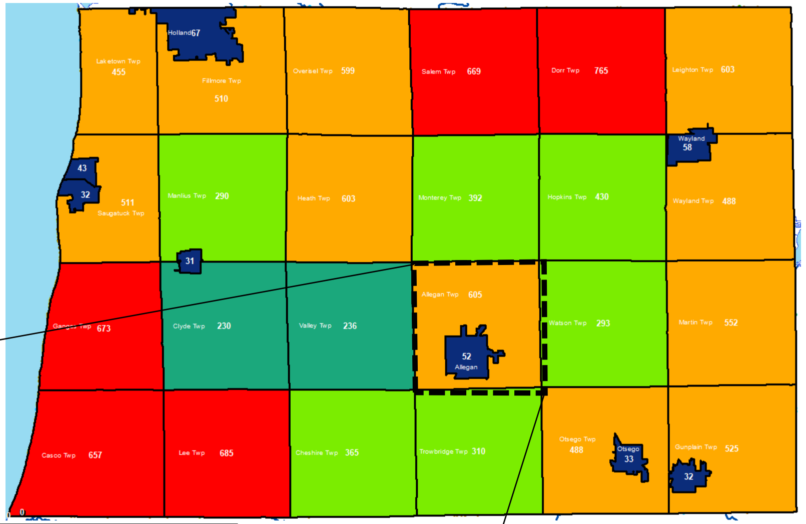
Note:

- There is a possibility of modest (~5 ft) systematic SWL decline since 2000
- There is not enough data prior to 2000 to make a determination.



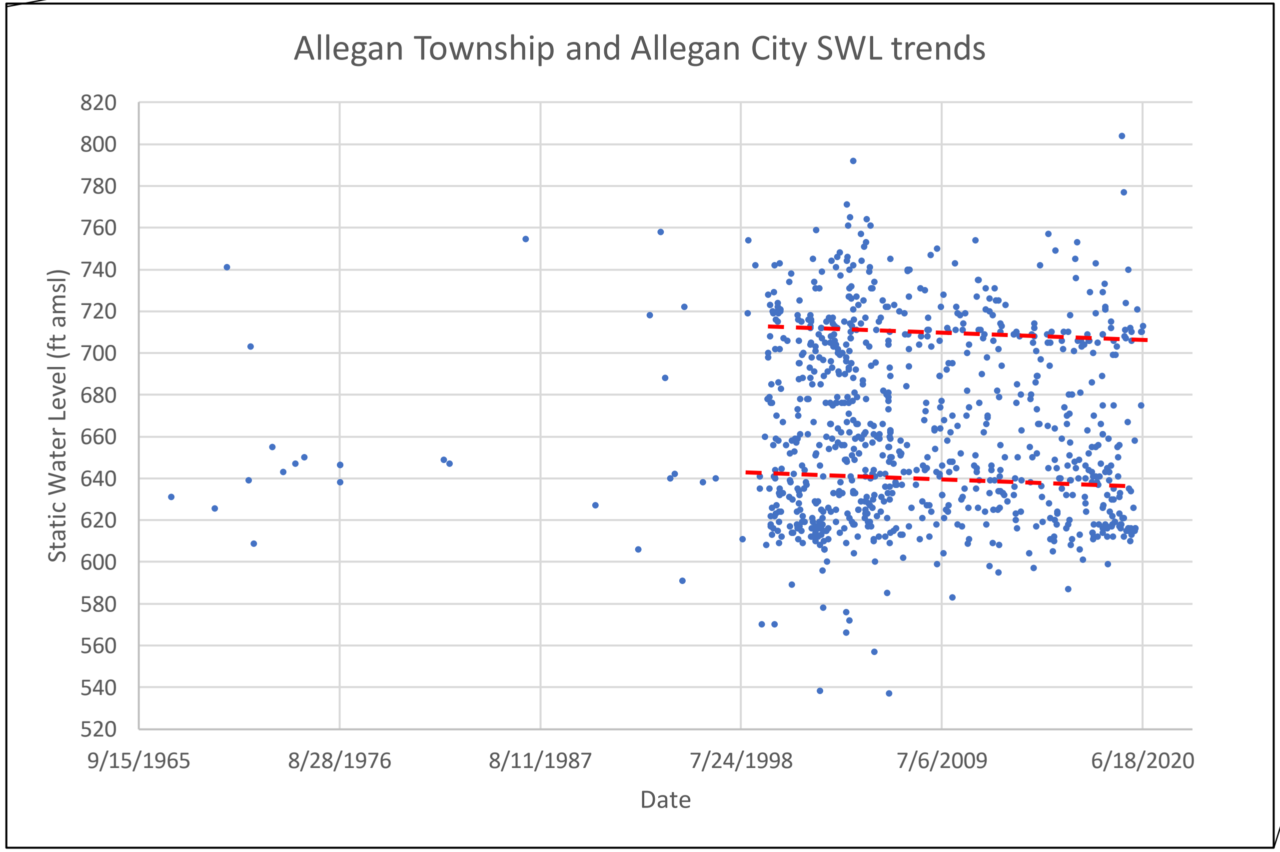


Temporal Water Level Trends in Areas of Growth



Allegan Township

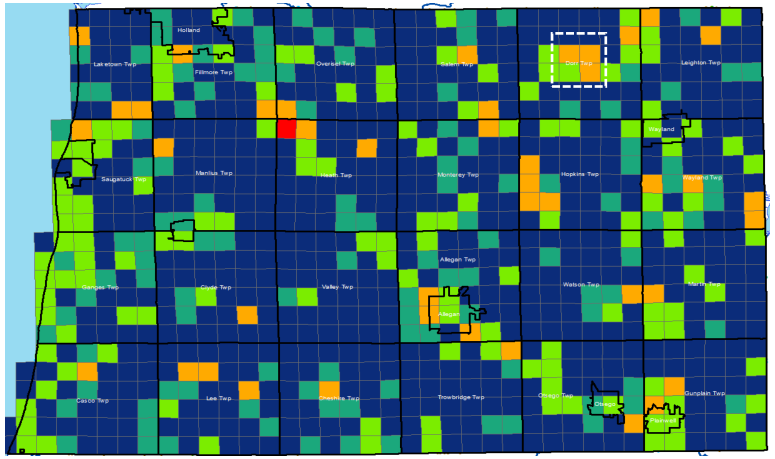
This slide shows SWL data over time for Allegan Township. Note that wells in Allegan Township are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer).



Note:

- It is possible there are two different “clouds” of data shown in the figure, for two different areas within the township and/or wells within the same area that are screen at different depths.
- For both clouds, there is a possibility of modest (5-10 ft) systematic SWL decline since 2000.
- There is not enough data prior to 2000 to make a determination.

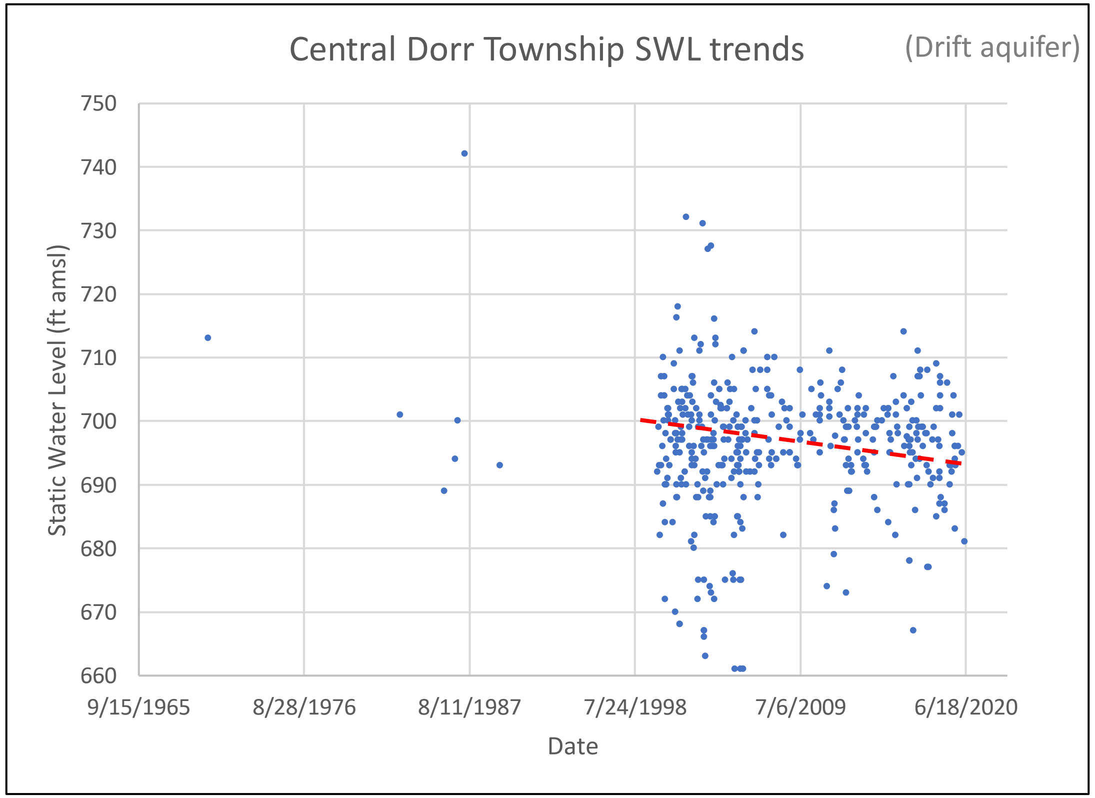
Temporal Water Level Trends in Areas of Growth

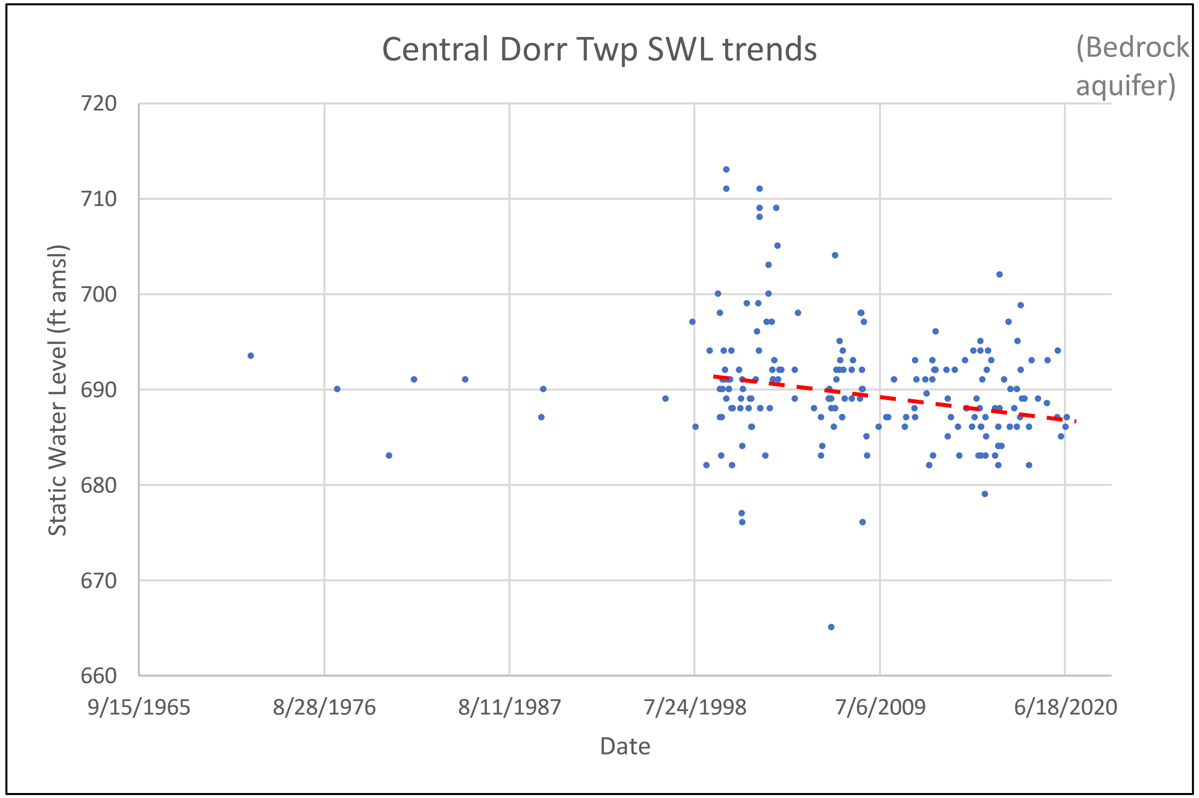


Central Dorr Township

This slide (and the slides that immediately follow) present results from temporal trend analysis of SWL sub-set (sub-township level) to reduce some of the SWL noise (due to SWL variability across space) but still have enough data points for a meaningful analysis. The results shown here are for central Dorr Township – a “hot-spot” water use area identified in the section-by-section water use analysis.

There appears to asystematic SWL decline of 5-10ft since 2000, in both the glacial and bedrock aquifers. There is not enough data prior to 2000 to make a determination.

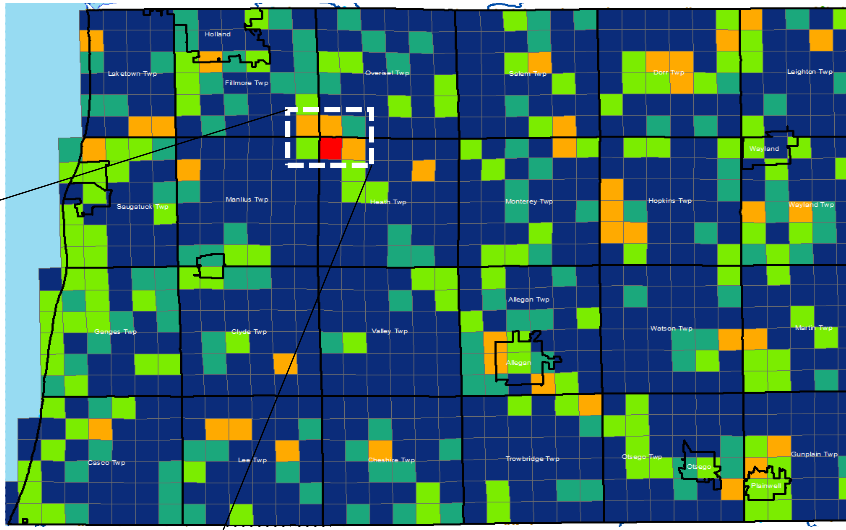




Temporal Water Level Trends in Areas of Growth

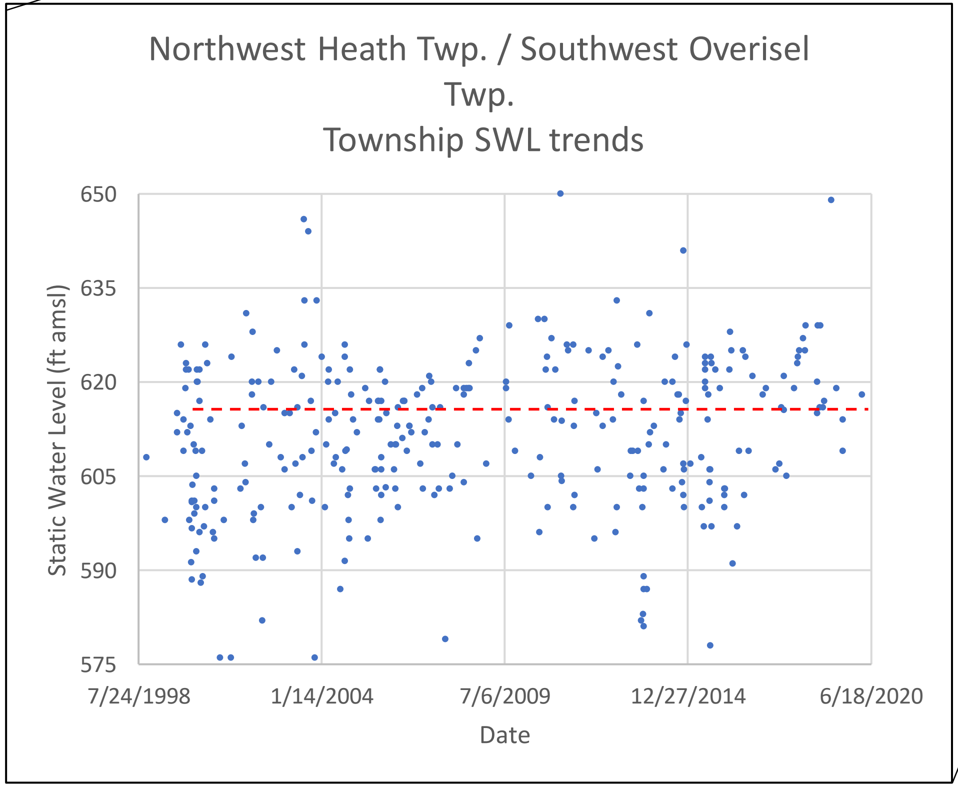
Northwest Heath Twp / Southwest Overisel Twp

This slide shows SWL data over time for northwest Heath Twp. / southwest Overisel Twp. Note that wells in this area are screened almost exclusively in the glacial aquifer (the Marshall Sandstone and the Coldwater Shale formations interface in this area).



Note:

- There does not appear to be a significant temporal trend for the 2000-2020 time period.
- There is not enough data prior to 2000 to make a determination.



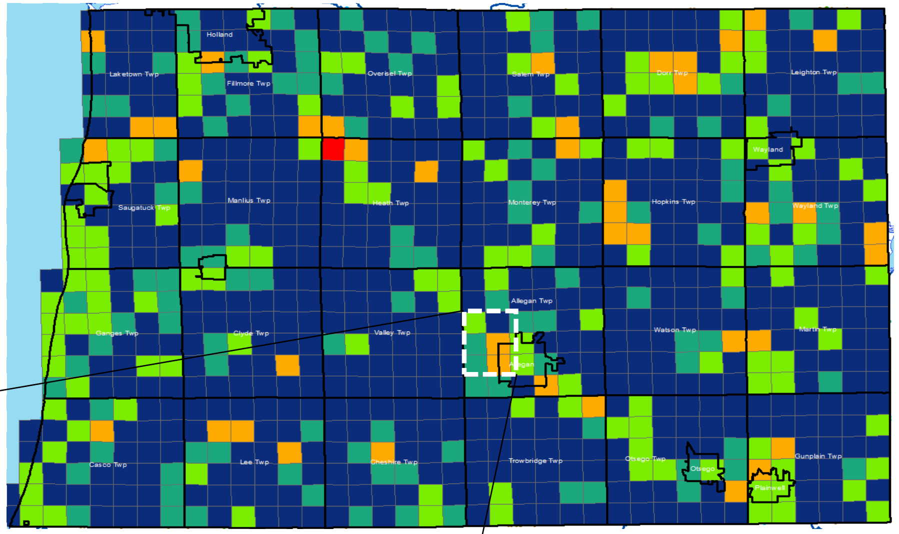
Temporal Water Level Trends in Areas of Growth

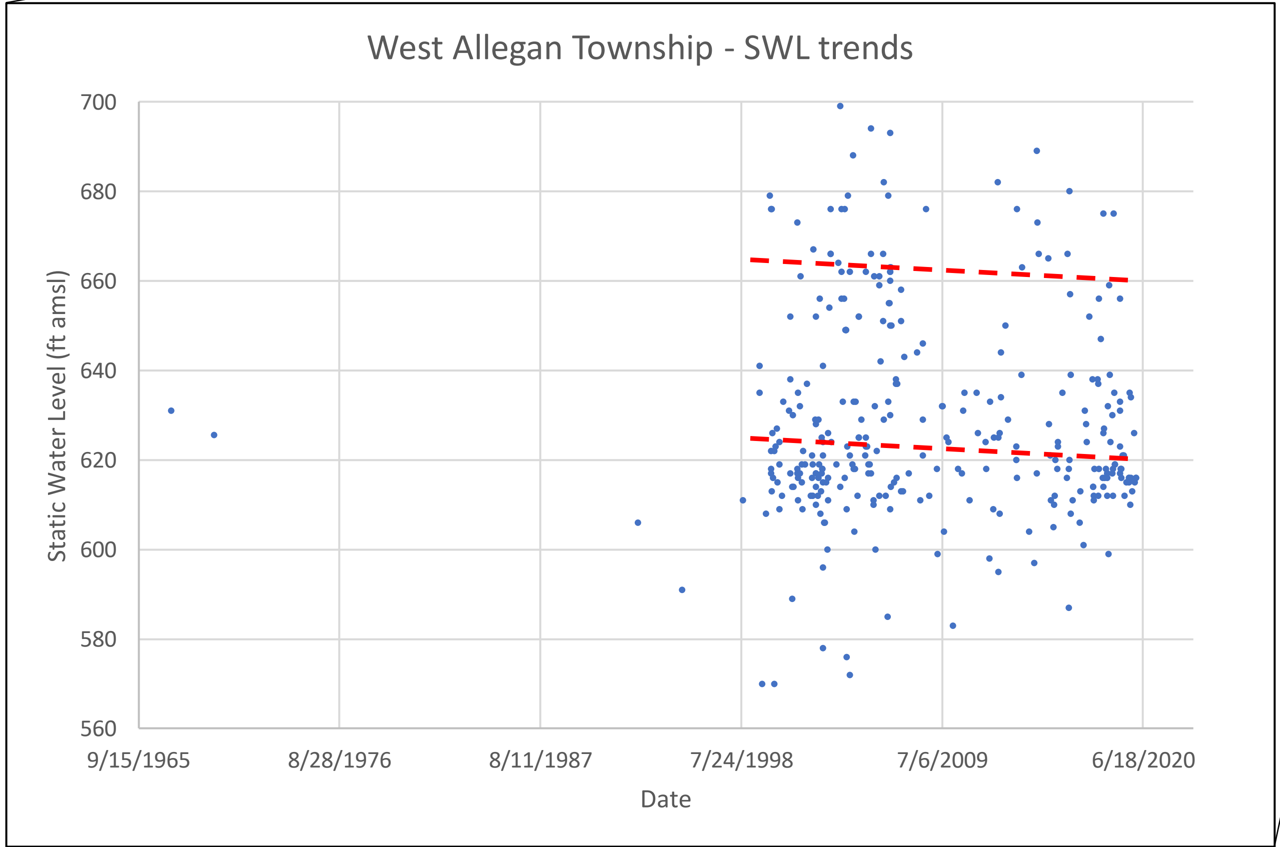
West-central Allegan Township

This slide shows SWL data over time for west-central Allegan Twp. Note that wells in this area are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer). It is possible there are two different “clouds” of data shown in the figure, for two different areas within the township and/or wells within the same area that are screen at different depths.

There is a possibility of modest (~5 ft) systematic SWL decline since 2000 for both clouds of data.

There is not enough data prior to 2000 to make a determination.

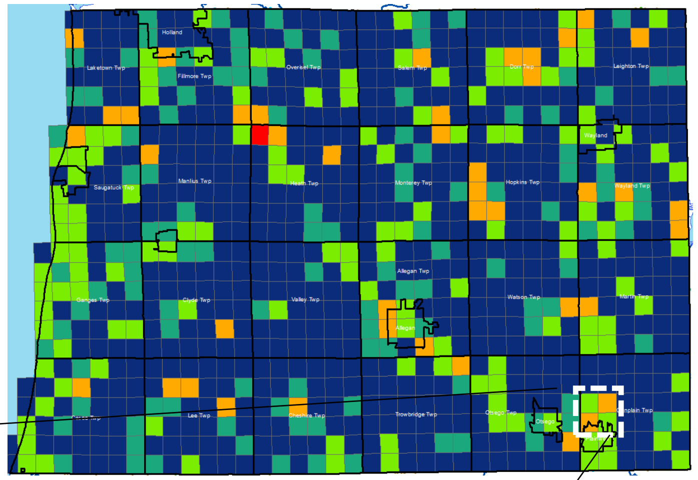




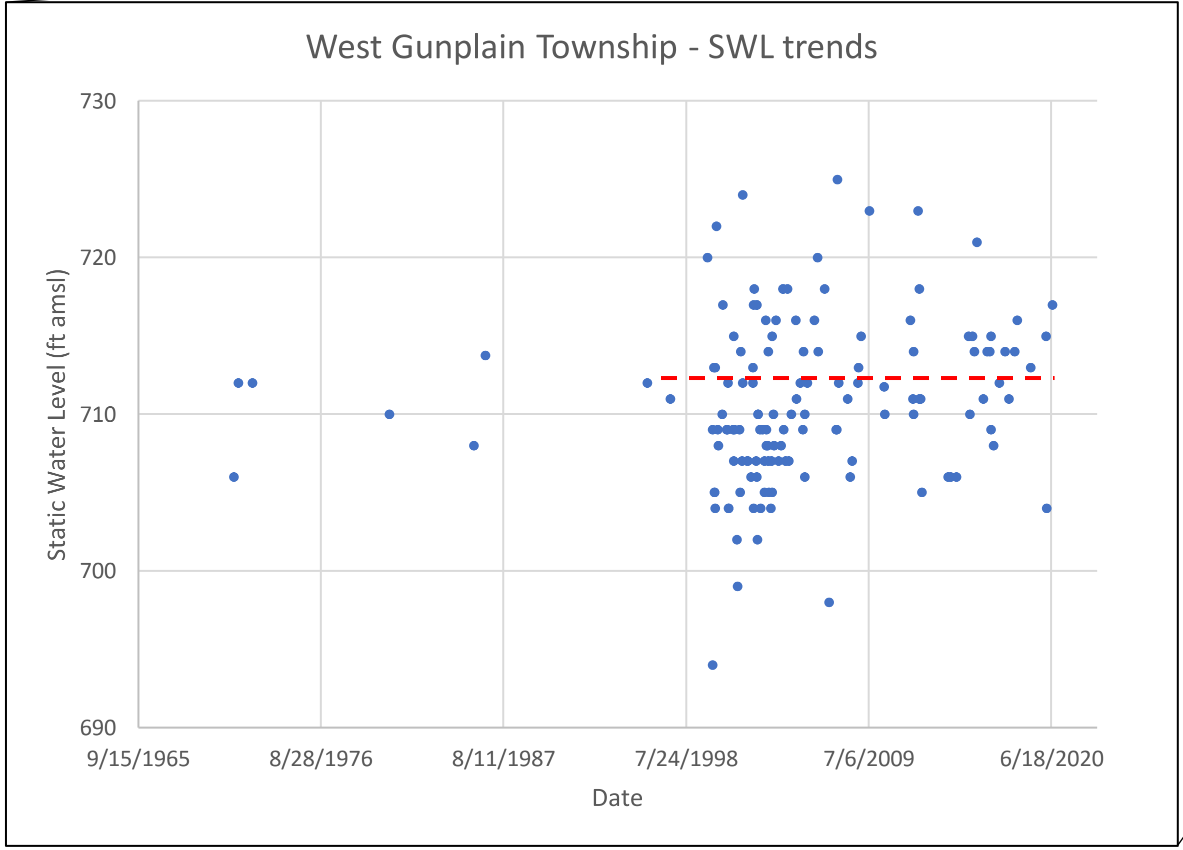
Temporal Water Level Trends in Areas of Growth

Western Gun Plain Township

This slide shows SWL data over time for western Gunplain Twp. Note that wells in Gunplain Township are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer).



Note:
- There does not appear to be a significant temporal trend for the 2000-2020 time period.
- There is not enough data prior to 2000 to make a determination.



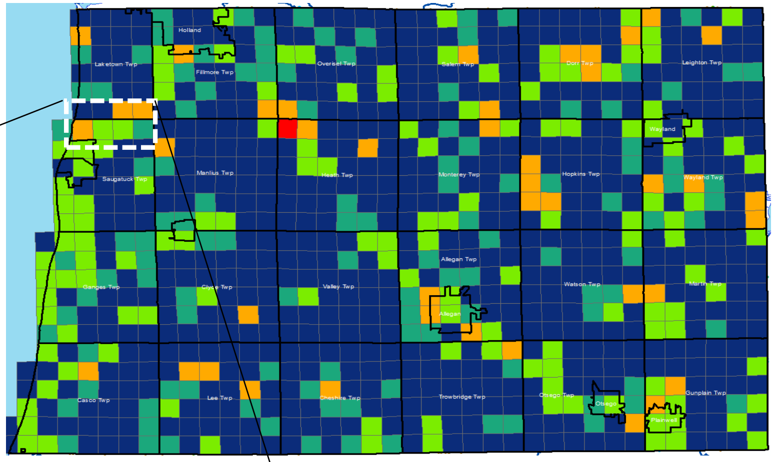
Temporal Water Level Trends in Areas of Growth

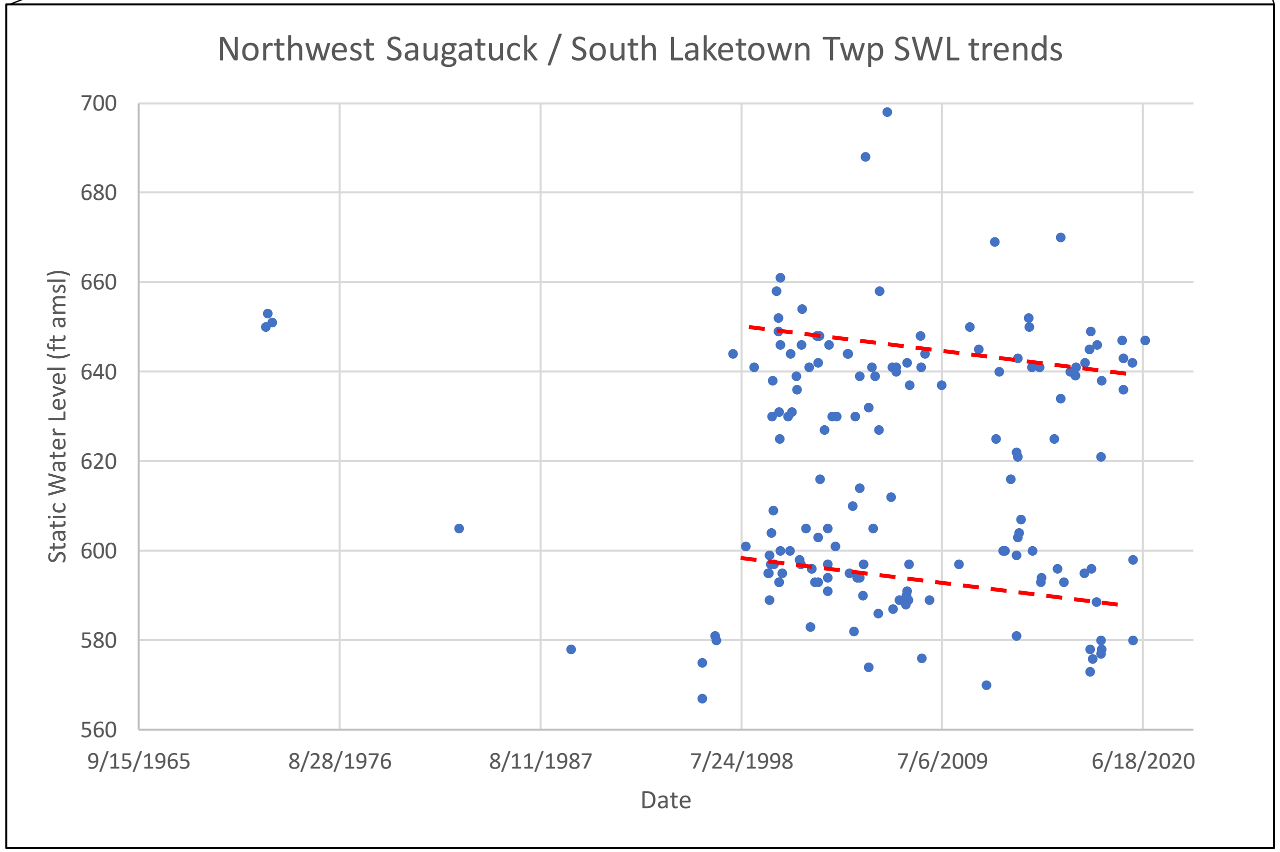
Northwest Saugatuck / South Laketown Twp

This slide shows SWL data over time for northwest Saugatuck Twp. / south Laketown Twp. Note that wells in this area are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer). It is possible there are two different “clouds” of data shown in the figure, for two different areas within the township and/or wells within the same area that are screen at different depths (above and below a “clay layer”).

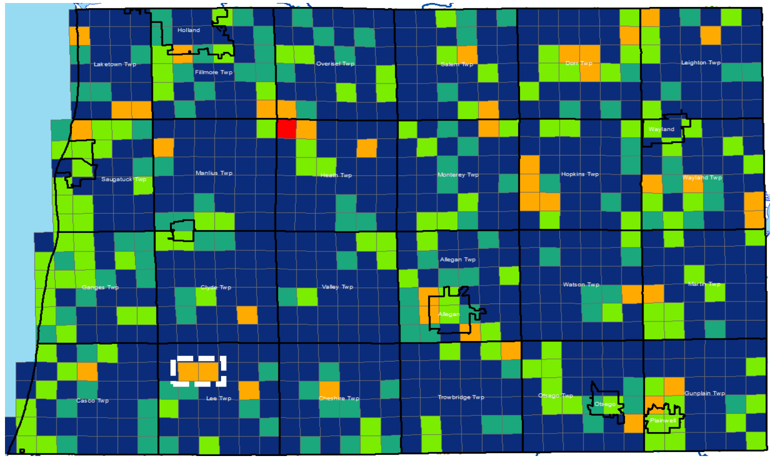
Note:

- For the time period of 2000-2020, both clouds of data show a possible systematic decline of 10-15 ft.
- There is not enough data prior to 2000 to make a determination.





Temporal Water Level Trends in Areas of Growth

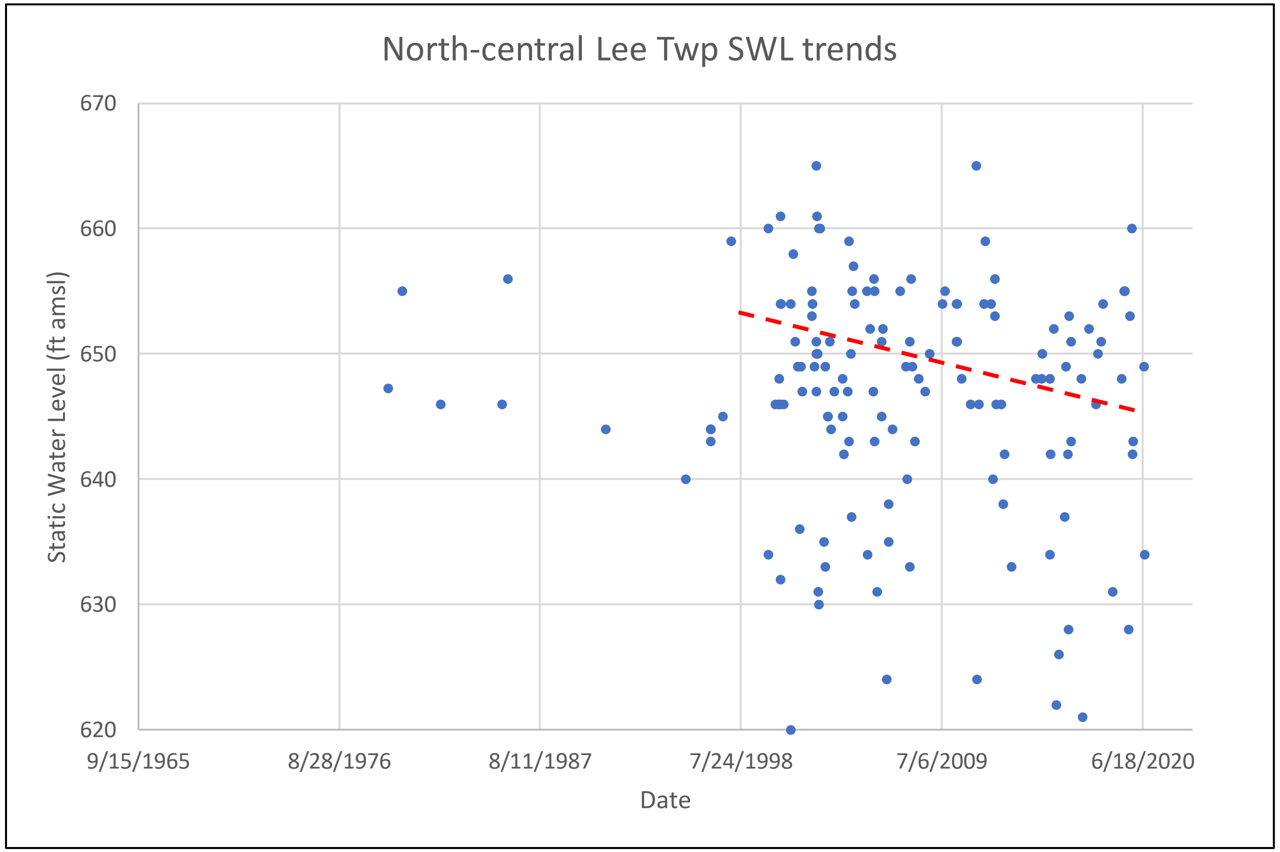


North-central Lee Twp

This slide shows SWL data over time for north-central Lee Twp. Note that wells in this area are screened in the glacial aquifer (Coldwater Shale underlies the glacial aquifer).

Note:

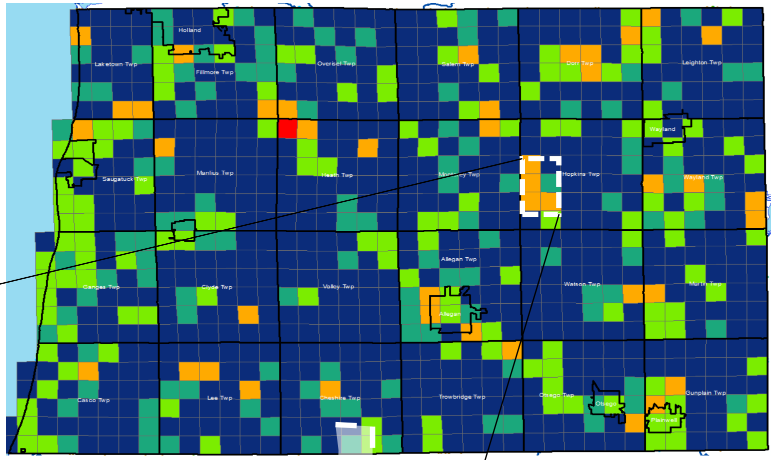
- There is a possibility of modest (5-10 ft) systematic SWL decline since 2000
- There is not enough data prior to 2000 to make a determination.



Temporal Water Level Trends in Areas of Growth

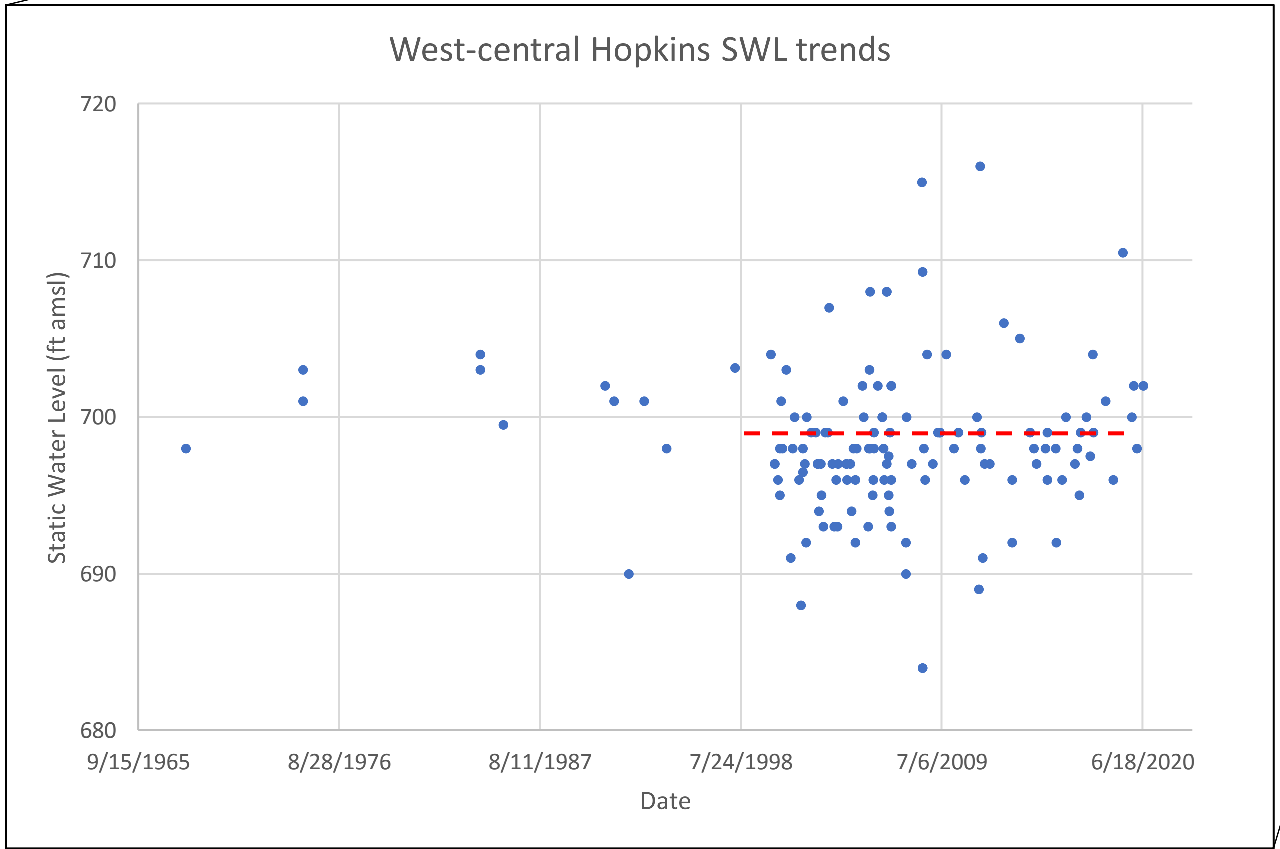
West-central Hopkins Twp

This slide shows SWL data over time for west-central Hopkins Twp. wells in Dorr Township are screened primarily in the glacial aquifer, although some wells may terminate in the bedrock (the Marshall Sandstone and the Coldwater Shale formations interface in this area).



Note:

- There does not appear to be a significant temporal trend for the 2000-2020 time period.
- There is not enough data prior to 2000 to make a determination.



Key Messages from Temporal SWL Trend Analysis

Recall that, if the temporal decline is significantly larger than SWL spatial variability and measurement “noise” (seasonal water level fluctuations, location uncertainty of the well, etc.), a trend can be identified. But when the area is too large, the temporal decline can be hidden by spatial variability and noise.

In general, there does not appear to be large-scale declines (e.g., township-wide) that are observed in neighboring Ottawa County, or at least the average decline is not significantly larger than the spatial variability. There are hints of systematic decline, especially at smaller scales (e.g., section scales), but these must be confirmed with long-term monitoring and local surveys (e.g. in parts of Dorr Twp., northern Saugatuck / southern Lake town Twps., and parts of Allegan Twp.). Even at the section-scale, spatial variability is still significant and can “overshadow” potential temporal trends.

Allegan County Groundwater Study

Task 3 – Water Quality Analysis

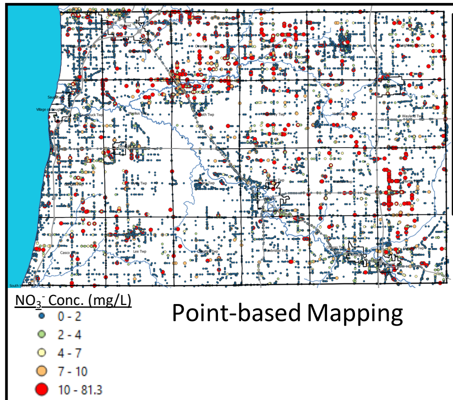
Hydrosimulatics INC.

Task 3 – Executive Summary

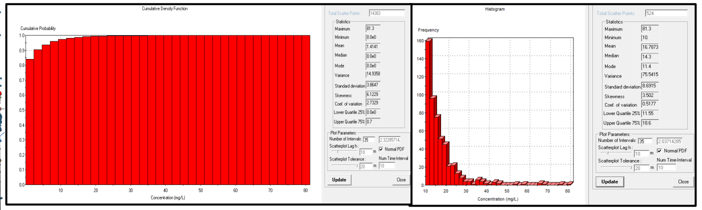
In Task 3, we characterized the groundwater quality across Allegan County. We processed, sorted, and filtered thousands of water quality samples from the *WaterChem* statewide database to map spatial patterns and statistically analyze different chemical constituents of groundwater, including nitrate, chloride, sodium, iron, lead, arsenic and manganese. Point-based maps showing sample concentrations as different colors / symbols sizes were created, as well as graphical representations of the frequency distributions (histograms) and cumulative distribution functions (CDF). Township-based countywide maps of 50th and 75th percentile concentrations were generated to give a sense of the average (median) and above-average concentrations found in different areas. For chemicals with enough data - nitrate and chloride - section-based maps were also created.

For the different chemicals, the median and 75th percentile concentrations for each township were normalized by the Maximum Contaminant Level (MCL) (or Secondary MCL, when appropriate) to create a "water quality index". A water quality "severity index" was generated for all chemical parameters for which a water quality index (WQI) was computed. A "primary" severity index was calculated by summing the WQI for the contaminants known to adversely impact human health: nitrate, lead, and arsenic (i.e., those with a MCL or Action Level). A similar "secondary" severity index was computed for chemicals with non-mandatory water quality standards: chloride and iron (there was not enough data to create a water quality index for sodium and manganese). Cheshire Township ranks highest in terms of primary water quality severity index - due to the high arsenic concentrations – followed by Overisel Twp., Martin Twp., and Holland City (primarily because high nitrate concentrations). The townships of Hopkins, Watson, Fillmore, and Dorr also have high-ranking primary water quality severity indexes. Ganges Townships ranks highest in terms of secondary water quality severity index – due to high iron concentrations – followed by Holland City (relatively high iron and chloride concentrations), Clyde Township, and Otsego Township (high iron concentrations). The townships of Valley, Gunplain, Saugatuck, and Martine also have high-ranking secondary water quality severity indexes.

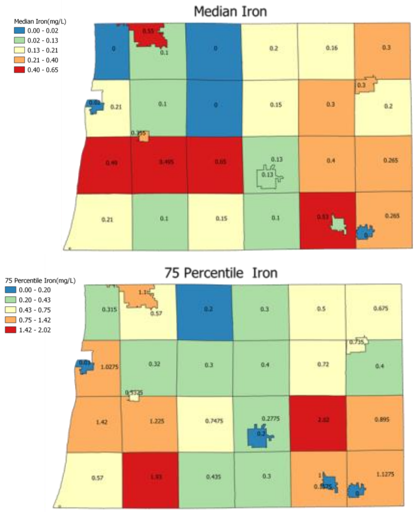
We also mapped the locations of known or potential sites of groundwater contamination obtained from the Environmental Mapper tool from the Department of Energy, Great Lakes, and Energy. In our analysis, we identified two (2) known PFAS sites, 78 sites of environmental concern, 168 leaky underground storage tanks (LUSTs), 165 underground storage tanks, 41 landfills / waste handlers, and 94 oil / gas wells.



Point-based Mapping



Countywide Statistical Analysis of Point Concentration Data



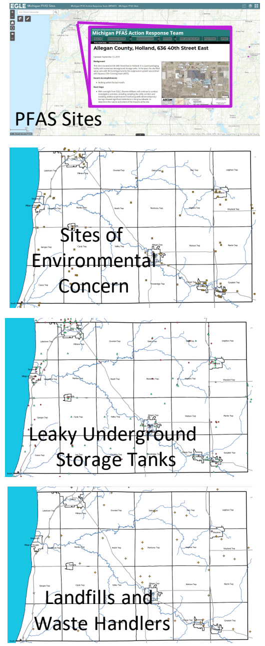
Aggregated Spatial Analyses

Water Quality Severity Rankings

Township/Village	PRIMARY Water Quality Severity Index
Cheshire	2.54
Overisel	1.29
Martin	1.25
Holland City	1.23
Hopkins	1.20
Watson	1.15
Fillmore	1.12
Dorr	1.07
Leigthon	1.04
Allegan City	0.96
Casco	0.91
Laketown	0.89
Monterey	0.83
Wayland City	0.81
Wayland Twp	0.80
Saugatuck	0.67
Saugatuck City	0.60
Salem	0.55
Clyde Twp.	0.54
Heath	0.50
Otsego	0.50
Ganges	0.43
Allegan	0.41
Gunplain	0.35
Plainwell City	0.23
Valley	0.22
Manlius	0.20
Lee	0.18
Trowbridge	0.17
Douglas City	0.13
Fenvillle City	0.13
Otsego City	0.09

Township/Village	SECONDARY Water Quality Severity Index
Ganges	6.44
Holland City	6.09
Clyde	5.83
Otsego	5.18
Valley	4.73
Gunplain	4.73
Saugatuck	4.25
Martin	4.04
Hopkins	3.61
Wayland City	3.54
Leigthon	3.31
Fenvillle City	3.31
Casco	2.68
Fillmore	2.52
Dorr	2.29
Wayland Twp	2.06
Cheshire	2.03
Monterey	1.89
Lee	1.89
Salem	1.79
Manlius	1.52
Allegan	1.45
Trowbridge	1.43
Watson	1.41
Allegan City	1.28
Heath	1.16
Laketown	1.15
Otsego City	1.13
Overisel	1.04
Douglas City	0.58
Saugatuck City	0.47
Plainwell City	0.29

Maps of Contamination Sites



Statewide Water Quality Database

The Drinking Water Analysis Laboratory was established under the authorization of the Michigan Safe Drinking Water Act, 1976 PA 399, as amended (Act 399), and the United States Environmental Protection Agency (USEPA) and is certified by “The Laboratory Certification Program”. Results from the analyses completed at the Drinking Water Analysis Laboratory are stored in the *WaterChem* database maintained by the State of Michigan.

Michigan State University (MSU) geocoded the statewide Waterchem database under a jointly funded MSU-DEQ water resources partnership.

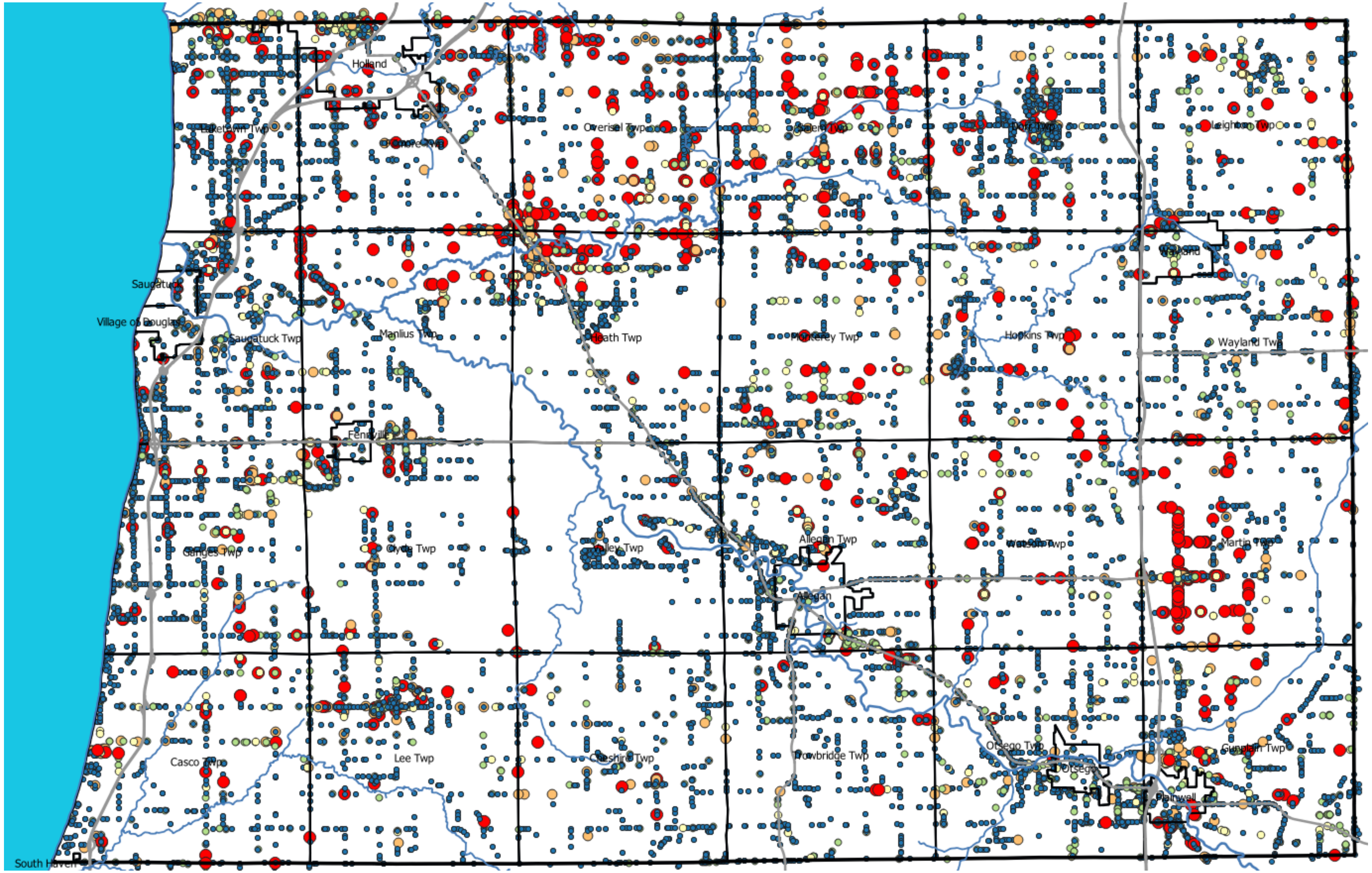
This geocoded database, now containing 30 years of analytical data (1983-2012), offers an unique opportunity to significantly improve the understanding of the spatial (geographic) and statistical patterns of water quality in Michigan’s groundwater.

Nitrate Concentrations (NO_3^-)

This slide shows the distribution of nitrate point concentration data (water quality samples at approximate well locations) in Allegan County. Note that the large red circles indicate samples with concentrations above the Maximum Contaminant Level (MCL) – legally enforceable standards – set by the United States Environmental Protection Agency (EPA).

Samples with concentrations above the MCL are found throughout the county. Townships with notable visual "clusters" of samples above the MCL include: Overisel, Salem, Heath, Martin, Gunplain, and Manlius (especially along its northern and northwestern township border).

Approximately 4% of the data shown here have concentrations above the MCL for nitrate. The next slides provides a full set of statistics for the nitrate point concentration data.



NO_3^- Conc. (mg/L)

- 0 - 2
- 2 - 4
- 4 - 7
- 7 - 10
- 10 - 81.3

Nitrate MCL: 10 mg/L

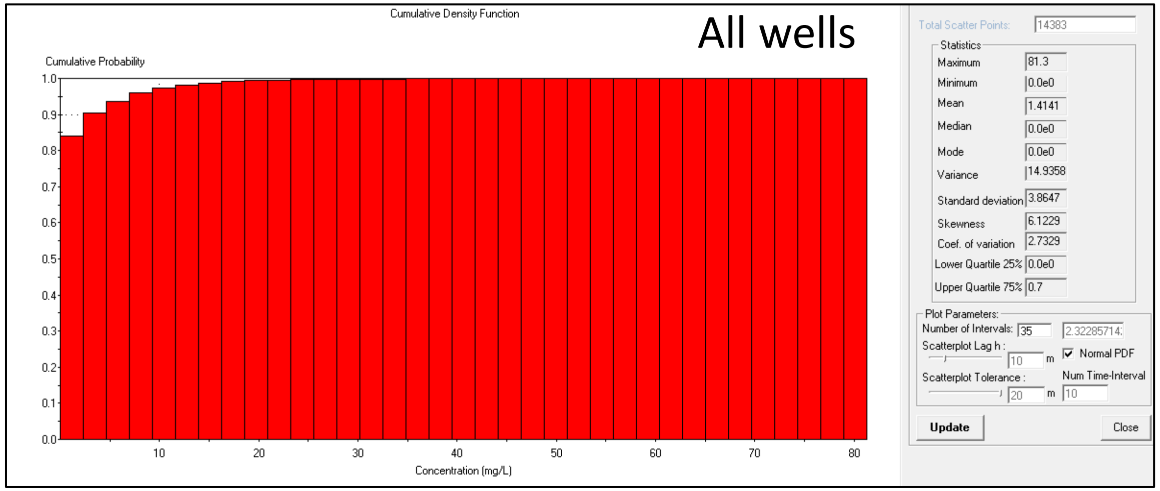
Nitrate Concentrations (NO_3^-)

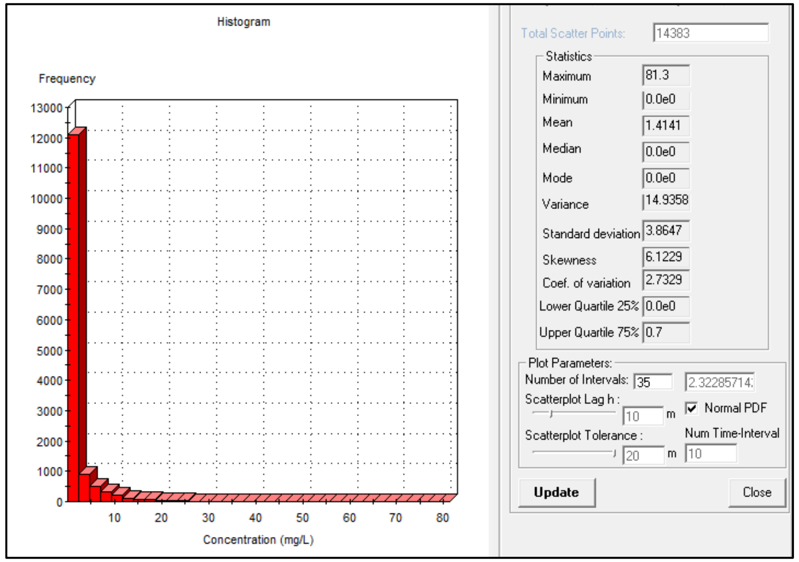
Aggregated Statistical Analysis

Countywide CDF and Histograms

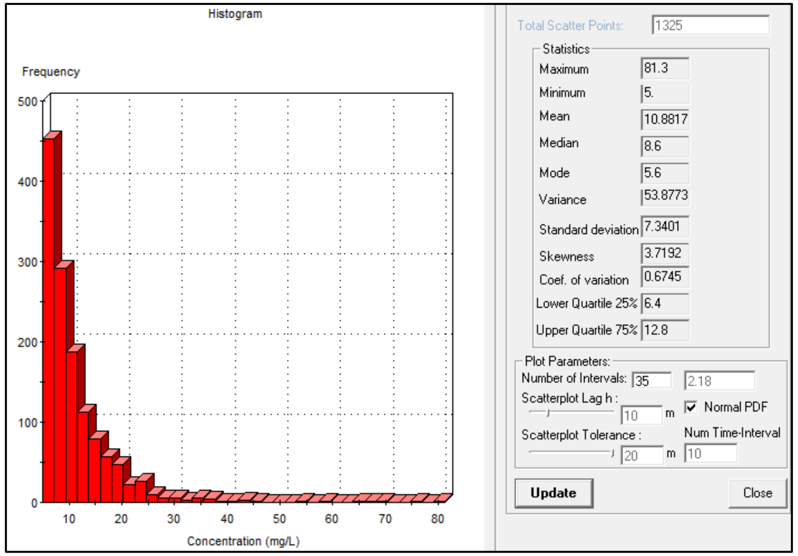
COUNTYWIDE STATISTICS, NITRATE CONCENTRATIONS:

- Number of Data Points: 14,383
- Min: 0
- Max: 81.3 mg/L
- Mode: 0 (no detection)
- Mean: 1.41 mg/L
- Median: 0 (no detection)
- Standard Deviation: 3.86 mg/L

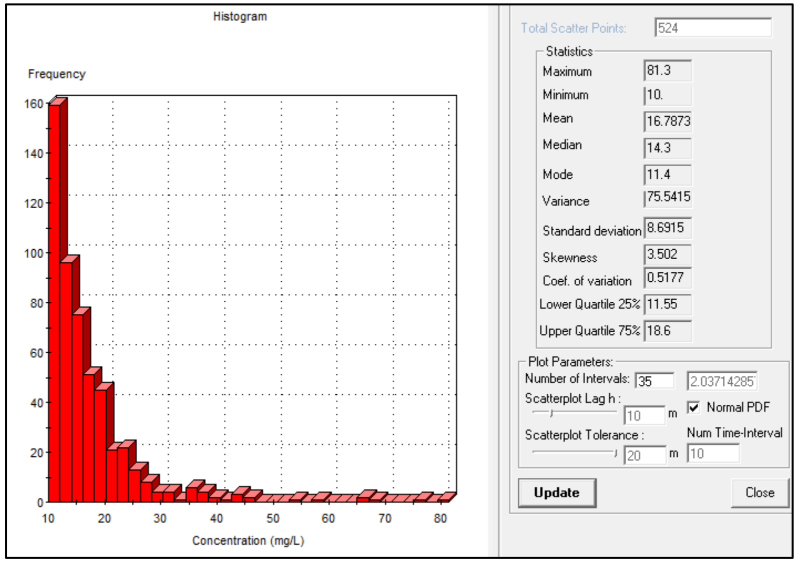




All Wells



Wells with NO_3^- > 5 mg/L



Wells with NO_3^- > 10 mg/L

Nitrate MCL: 10 mg/L

Nitrate Concentrations (NO_3^-)

Aggregated Spatial Analysis

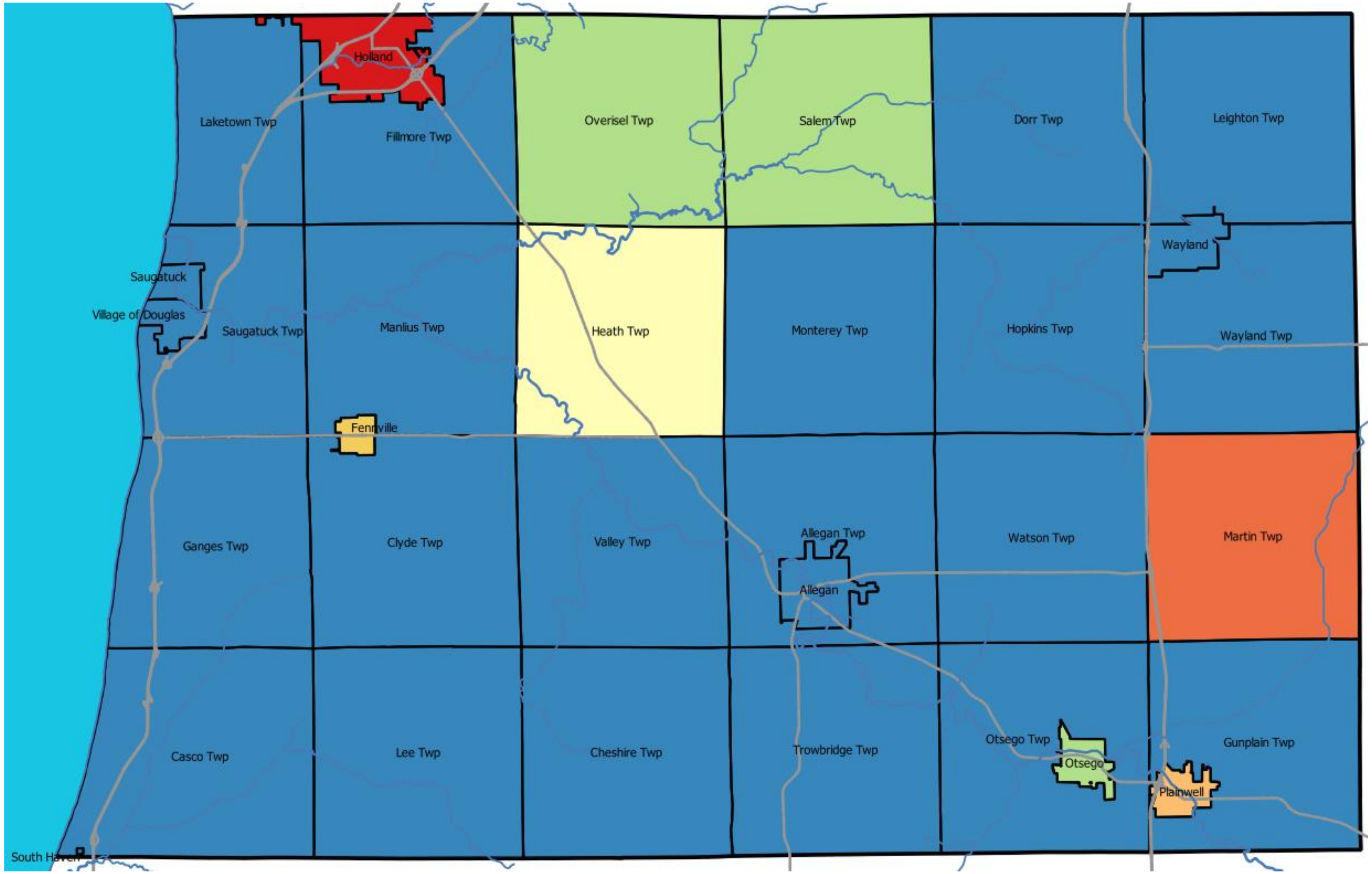
Township-by-township

Median (50th *Percentile)* Concentrations

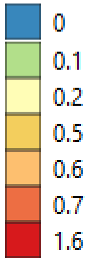
Township-wide "percentile concentrations" were computed for 50th and 75th percentiles. The 50th and 75th percentiles give a sense of the average (median) and above-average concentrations, respectively. For example, for a subset of data within a given township, 25% of the nitrate data in that townships have concentrations that are above the computed 75th percentile concentration.

This slide presents the results for 50th percentile concentrations for nitrate. In most of the townships / city limits, the 50th percentile concentration is 0 mg/L (i.e., at least half of the samples were "no detect"). As expected from the point data analysis, Overisel, Salem, Heath and Martin Townships have elevated median concentrations.

The cities of Holland, Fenville, Ostego and Plainwell also show elevated median concentrations, likely an artifact of samples with higher concentrations in these areas having a more significant impact on the statistical calculation because of the fewer number of total samples in these areas.



Median Nitrate (mg/L)



Nitrate MCL: 10 mg/L

Nitrate Concentrations (NO_3^-)

Aggregated Spatial Analysis

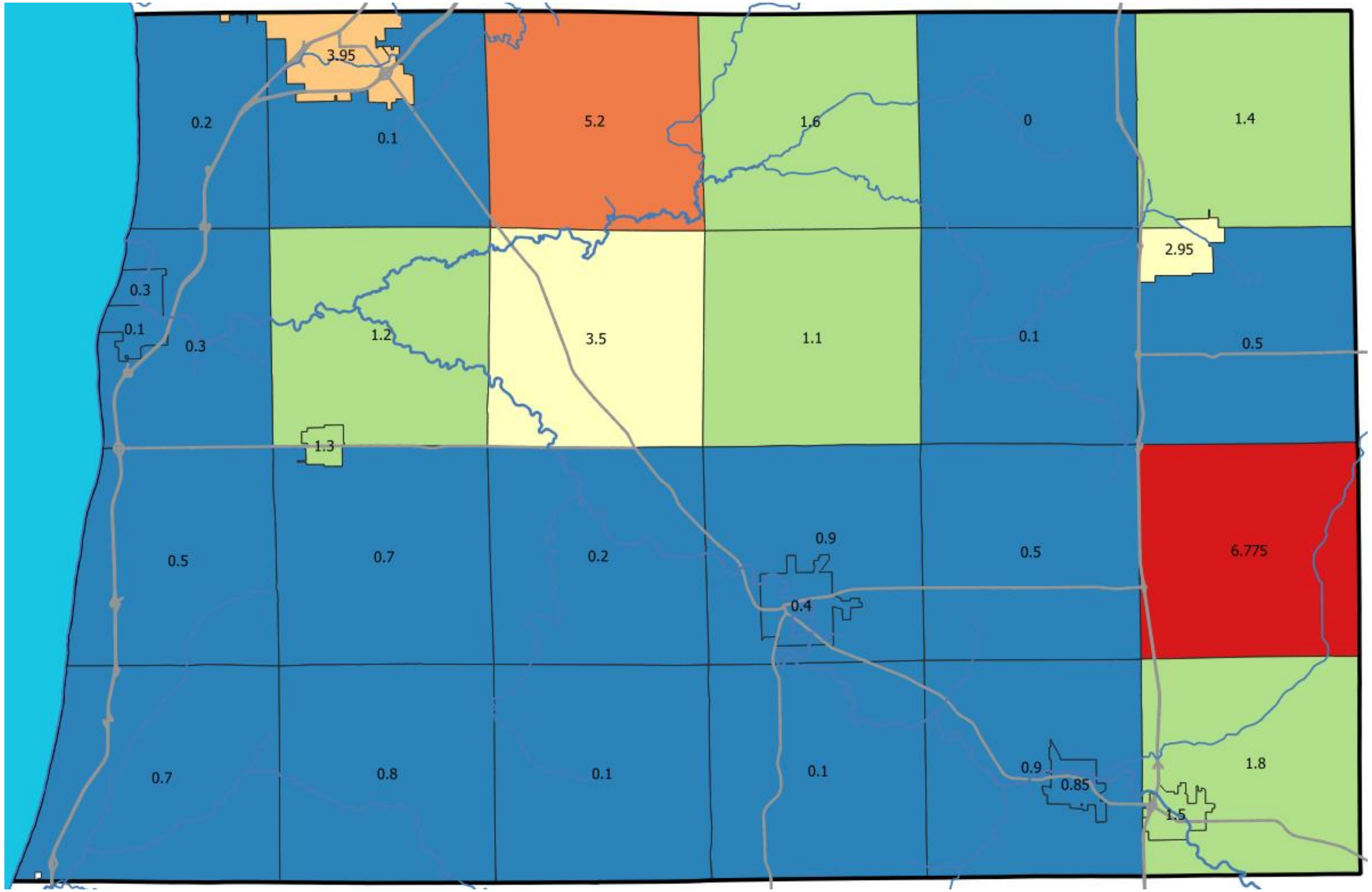
Township-by-township

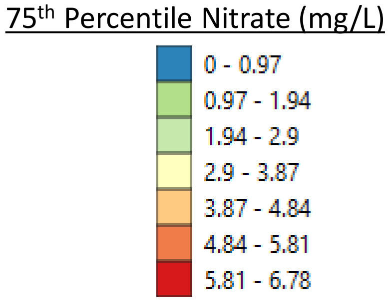
75th Percentile Concentrations

This slide presents the results for 75th percentile concentrations for nitrate. (The numbers in each township are the 75th percentile concentration.)

Again, in many of the townships / city limits, the 75th percentile concentration is 0 mg/L. As expected from the point data analysis, Overisel, Heath and Martin Townships have the highest 75th percentile concentrations (5.2, 3.5, and 6.8 mg/L, respectively). The cities of Holland and Wayland also have elevated 75th percentile concentrations (3.95 and 2.95 mg/L, respectively).

Note that a significant number of points were available for analysis. In other words, the fact that 25% of the data points in some townships are above 1mg/L (and in some cases approaching or even exceeding half the MCL for nitrate) suggests that a real problem may exist.





Nitrate MCL: 10 mg/L

Nitrate Concentrations (NO_3^-)

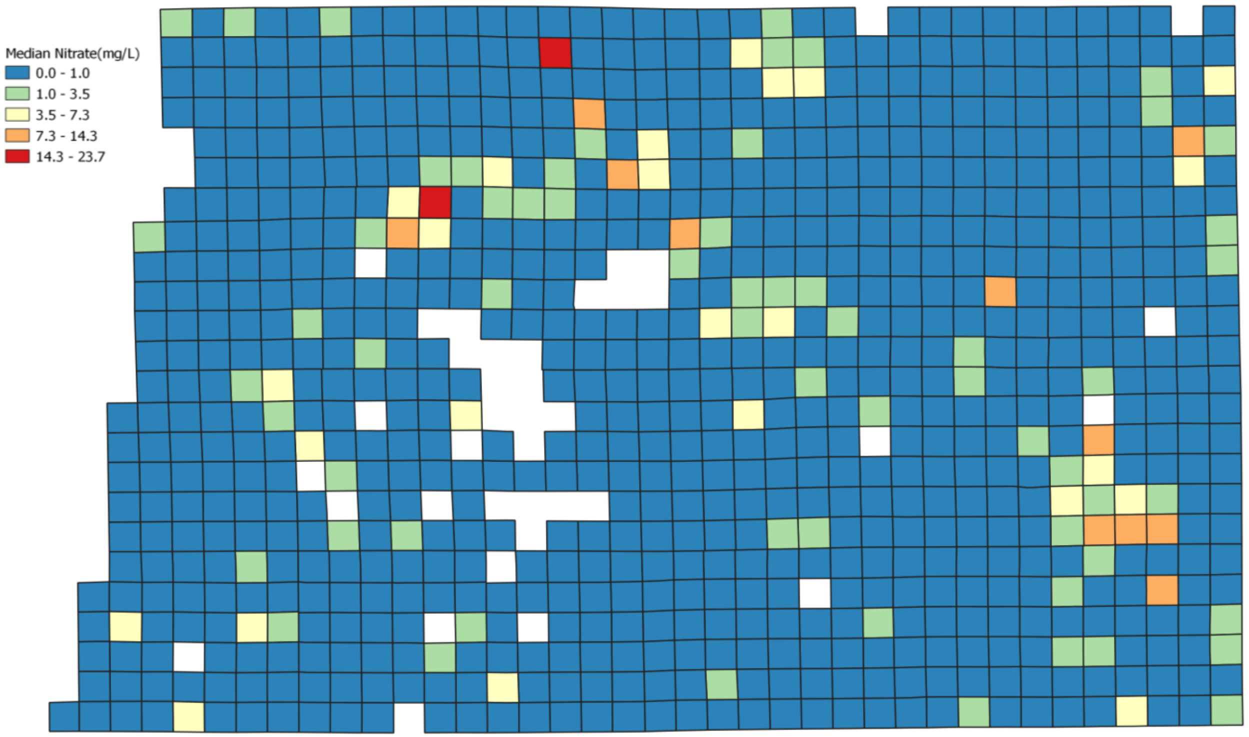
Aggregated Spatial Analysis

Section-by-Section

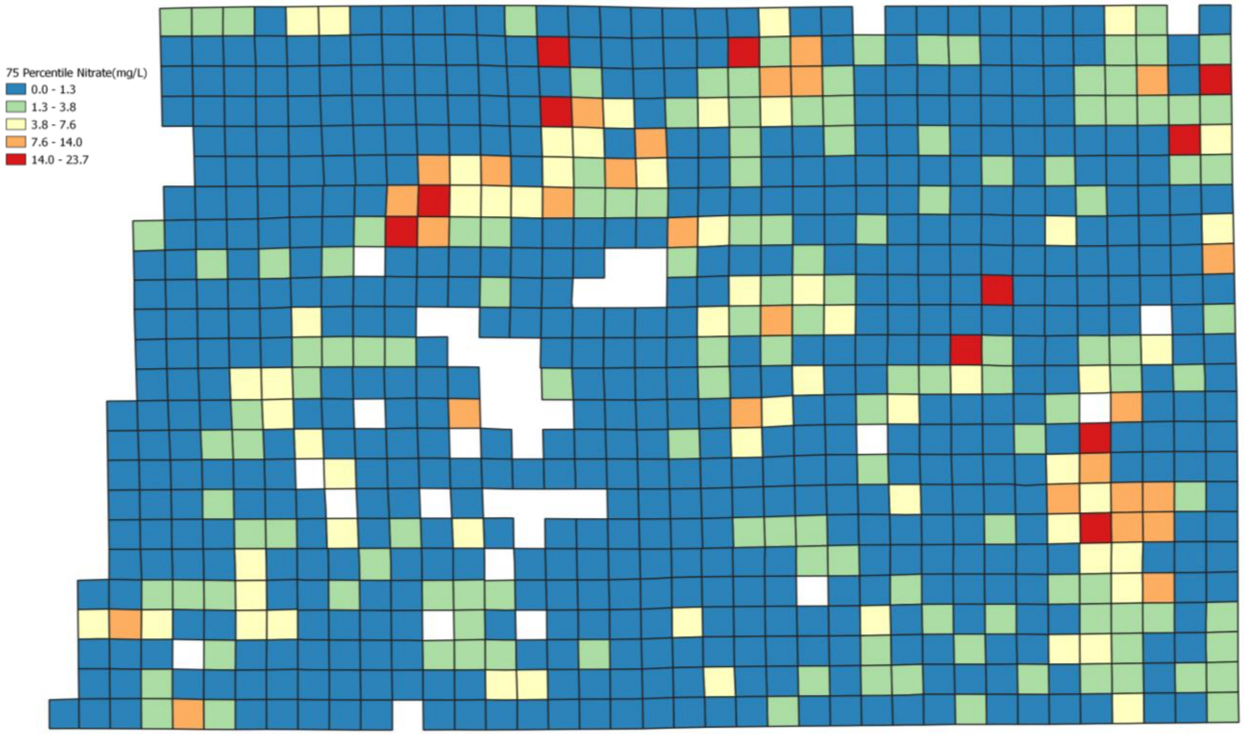
Median & 75th Percentile Concentrations

There was enough nitrate point concentration data available across the county to perform a similar analysis on a section-by-section basis. The results are shown below for both the 50th and 75th percentiles ("blank" or "missing" sections are sections where no data were available). This map may help to prioritize further data sampling or analysis within townships or cities / villages of concern. However, data density varies from section-to-section, so the computed percentile concentrations may be skewed toward higher values in areas with fewer total samples (again, higher samples in these have more impact relative to areas with more total samples).

Median Nitrate

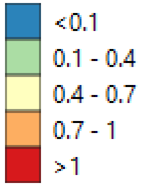


75 Percentile Nitrate



Nitrate MCL: 10 mg/L

Nitrate Concentrations (NO_3^-)



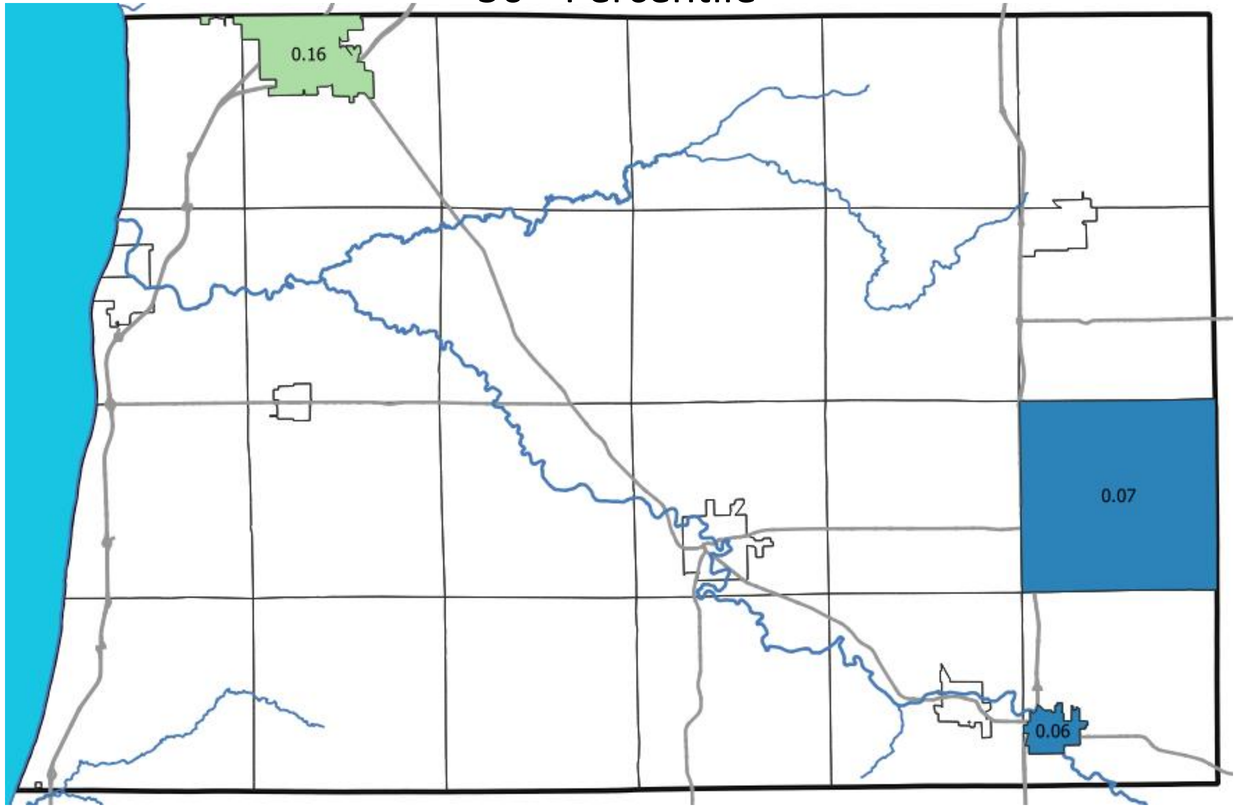
Water Quality Indices

Township-by-township

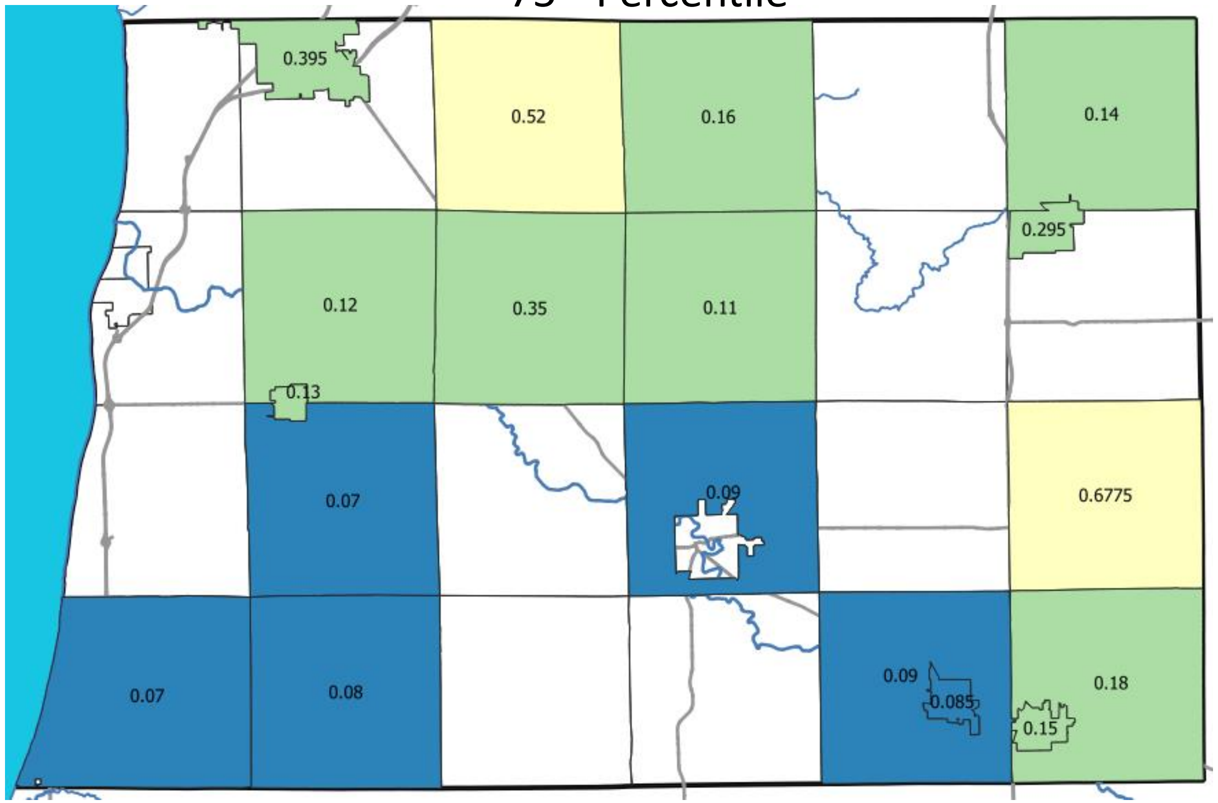
The median and 75 percentile concentrations for each township were normalized by the nitrate Maximum Contaminant Level (MCL) of 10 mg/L to create a "nitrate water quality index". The results are shown here. (Townships with median and/or 75th percentile concentrations of zero also have a nitrate water quality index of zero.)

The water quality index is used to develop multi-chemical "water quality severity indexes" for each township and city / village in Allegan County (see slide 120).

50th Percentile



75th Percentile



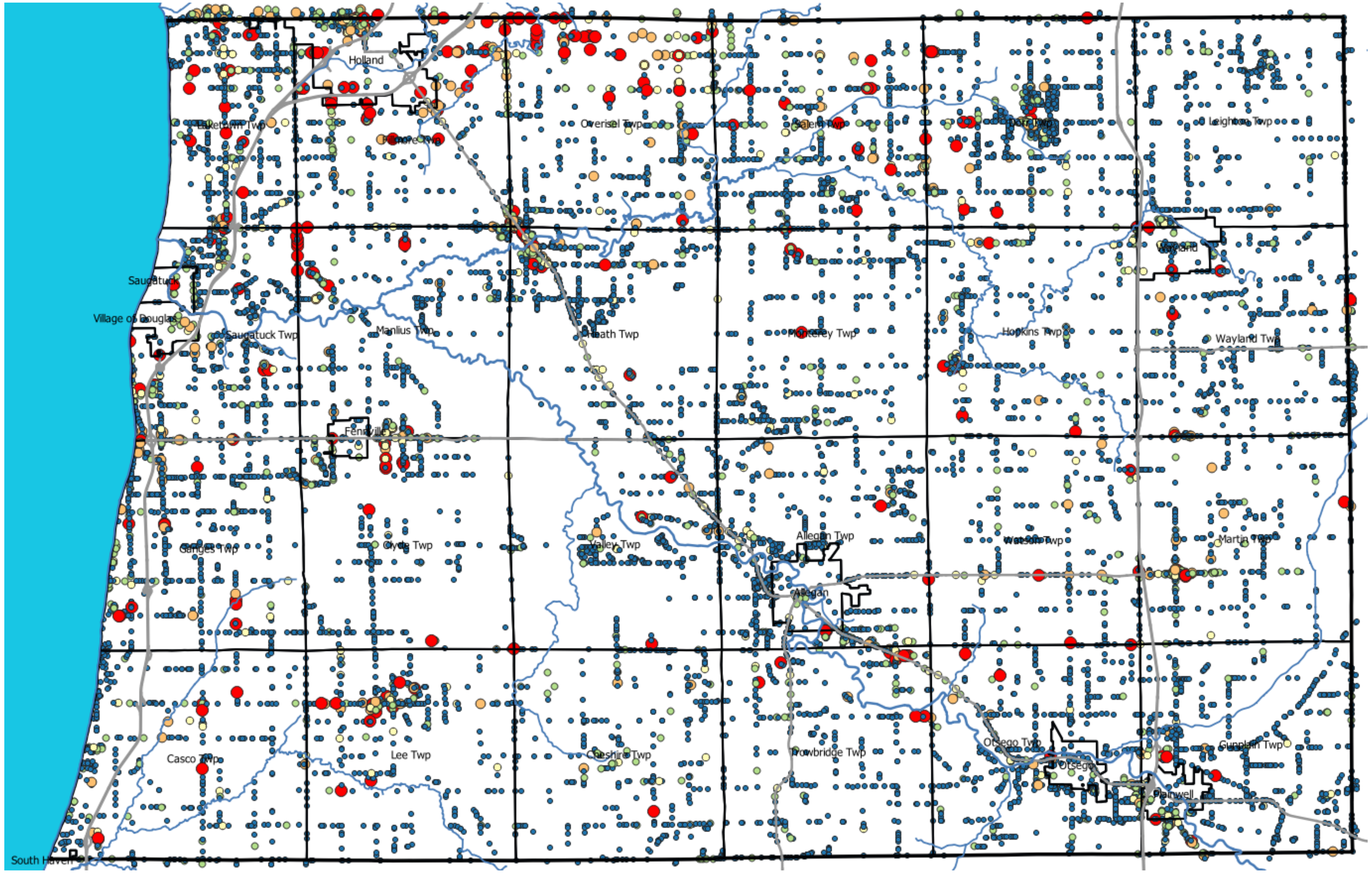
Nitrate MCL: 10 mg/L

Chloride Concentrations (Cl^-)

This slide shows the distribution of chloride point concentration data (water quality samples at approximate well locations) in Allegan County. Note that the large red circles indicate samples with concentrations above the Secondary Maximum Contaminant Level (SMCL) of 250 mg/L set by the US Environmental Protection Agency (EPA). SMCLs are non-mandatory guidelines to assist public water systems manage their drinking water for aesthetic considerations (e.g., taste, color, odor). Contaminants are not considered to present a risk to human health at the SMCL.

Samples with concentrations above the SMCL are found throughout the county, although most townships appear to have only a handful of elevated samples relative to the number of samples with low concentrations. Fillmore Twp., Overisel Twp. – and to a lesser degree, Laketown, Salem, Lee Townships – have notable visual “clusters” of samples above the SMCL.

Approximately 2% of the data shown here are above the SMCL. The next slide provides a full set of statistics for the chloride point concentration data.



Cl^- Conc. (mg/L)

- 0 - 50
- 50 - 100
- 100 - 150
- 150 - 250
- 250 - 2098

Chloride SMCL: 250 mg/L

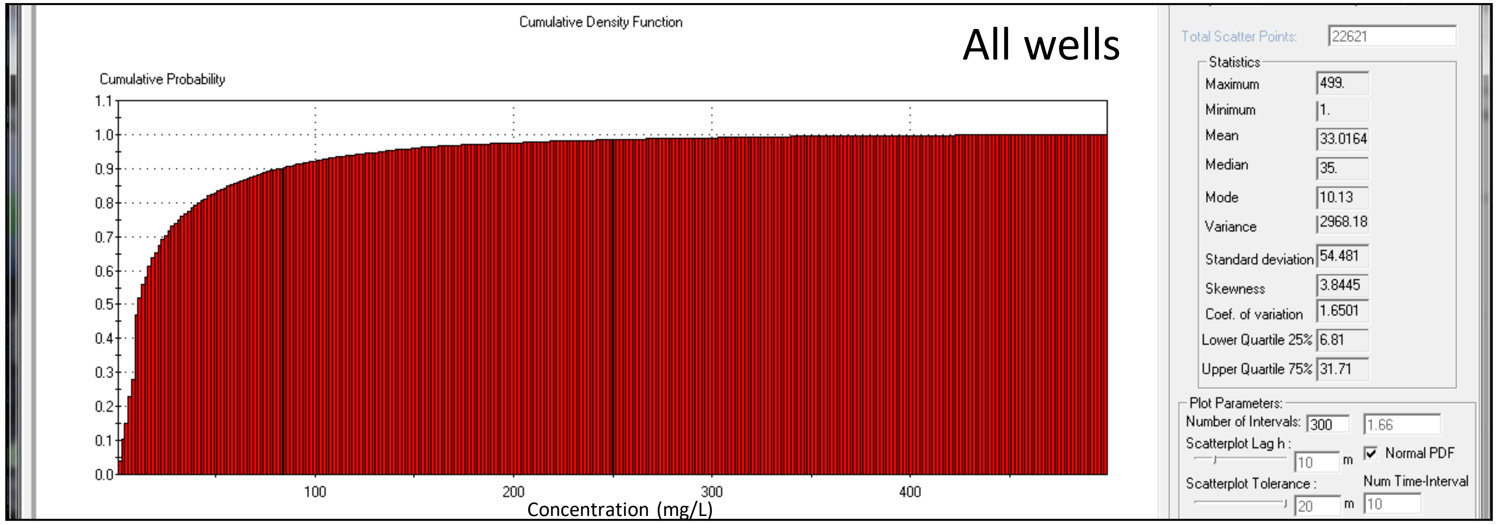
Chloride Concentrations (Cl^-)

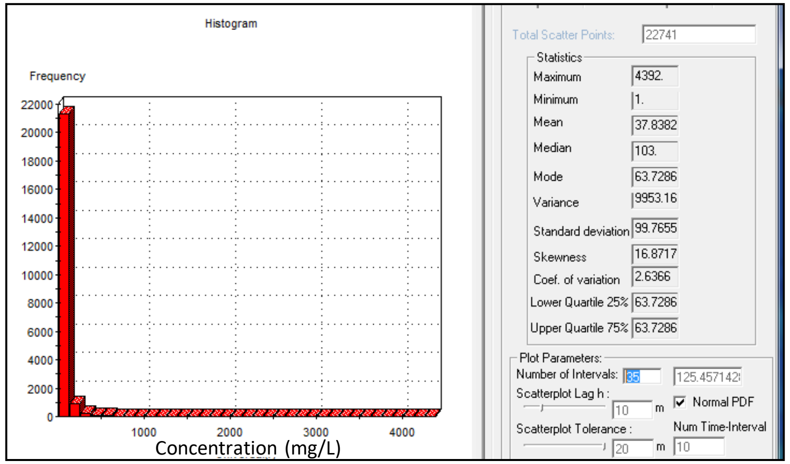
Aggregated Statistical Analysis

Countywide CDF and Histograms

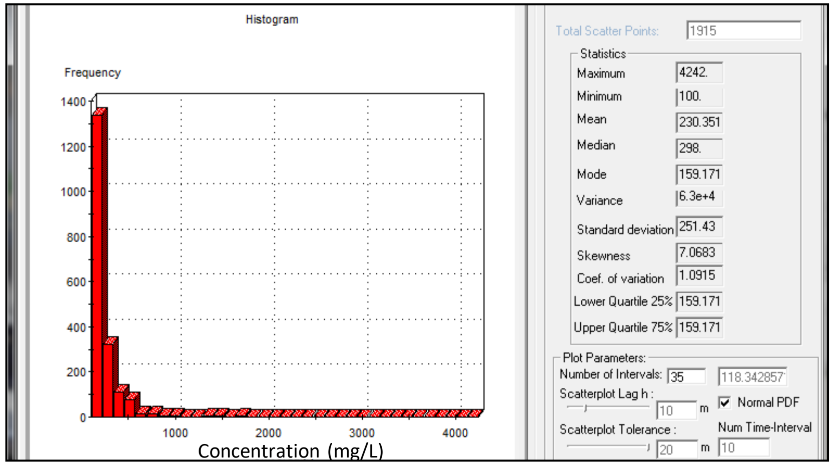
COUNTYWIDE STATISTICS, CHLORIDE CONCENTRATIONS:

- Number of points: 22,741
- Min: 0
- Max: 499 mg/L
- Mode: 10.13 mg/L
- Mean: 33 mg/L
- Median 35 mg/L
- Standard Deviation: 54.5 mg/L

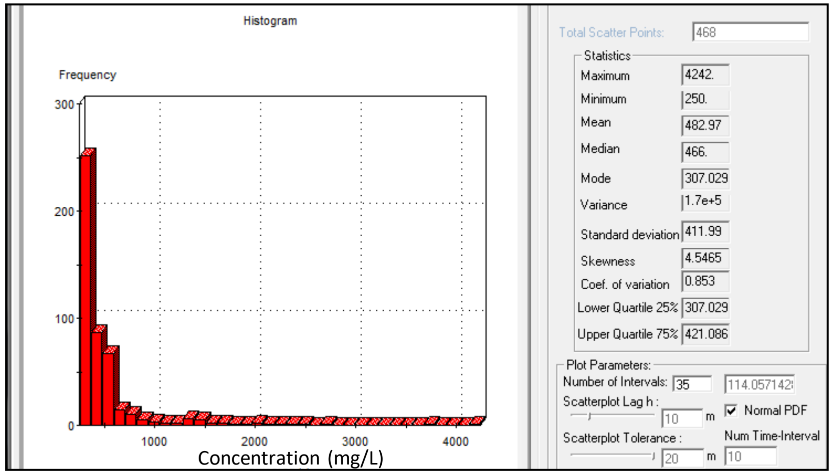




All Wells



Wells with Cl > 100 mg/L



Wells with Cl > 250 mg/L

Chloride Secondary MCL: 250 mg/L

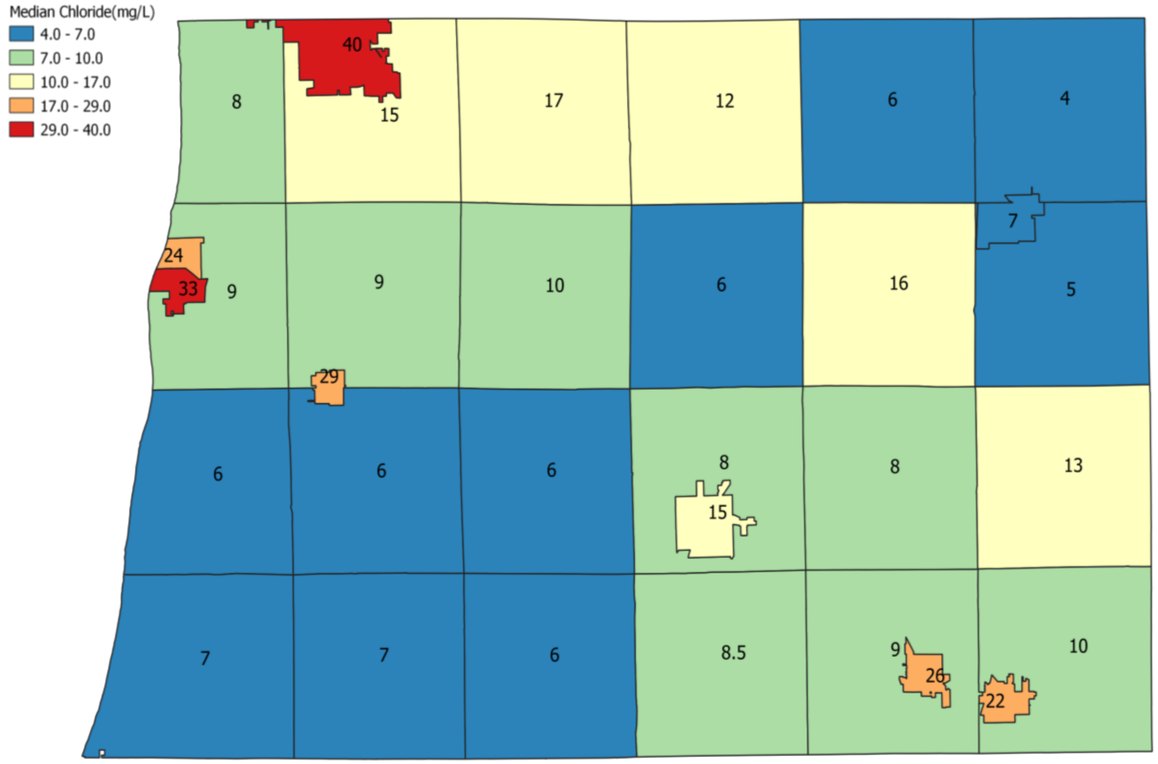
Chloride Concentrations (Cl^-)

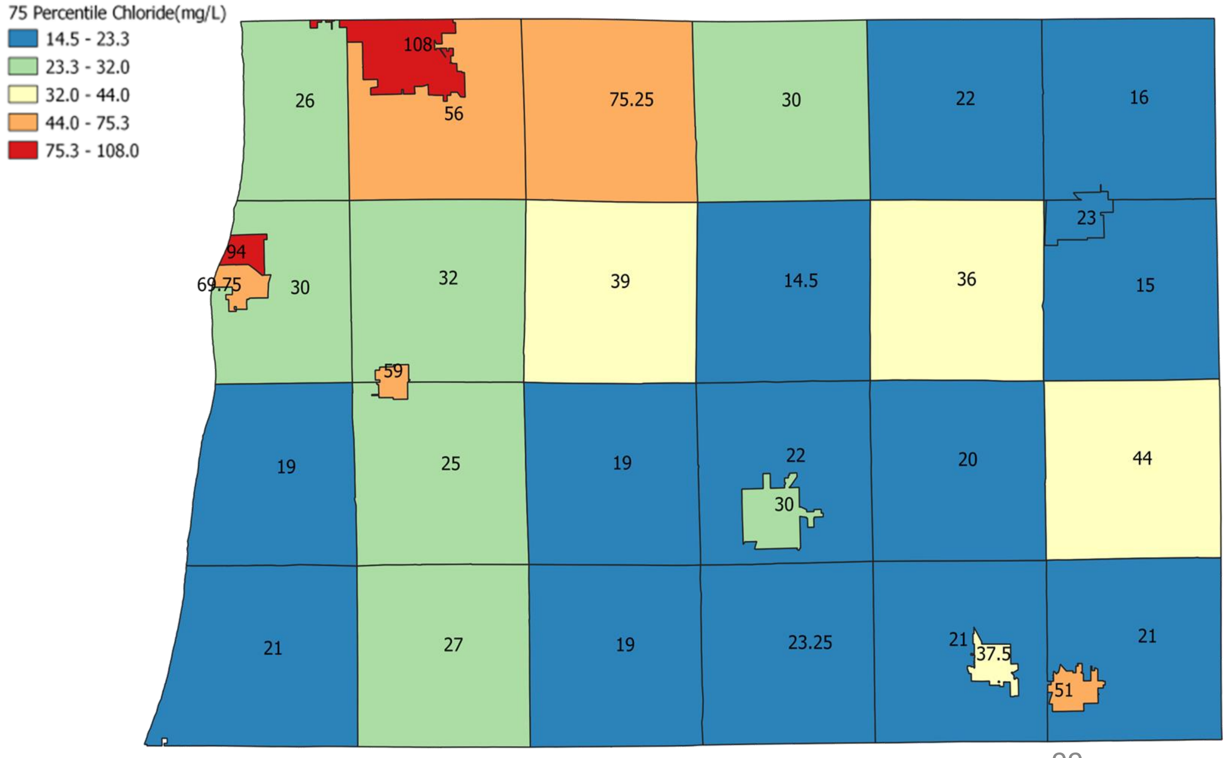
Aggregated Spatial Analysis

Township-by-township

Median (50^{th} *Percentile)* and *75^{th} Percentiles* Concentrations

This slide presents the results for 50^{th} and 75^{th} percentile concentrations for chloride. For both percentiles, the townships / cities with the highest concentrations are generally found in the northwest portion of the county (e.g., Fillmore Township, Holland City, Overisel, City of Saugatuck, City of Douglas, etc.). Some townships (e.g., Martin) and cities in the southeastern portion of the county also have relatively higher 50^{th} percentile concentrations, and in some places higher 75^{th} percentile concentrations (e.g., cities of Allegan, Ostego, and Plainwell). Note that, for all townships and cities, and for both percentiles, the concentrations are well below the SMCL for chloride, but are considered elevated relative to natural concentrations expected in groundwater (typically 15 mg/L or less).





Chloride Secondary MCL: 250 mg/L

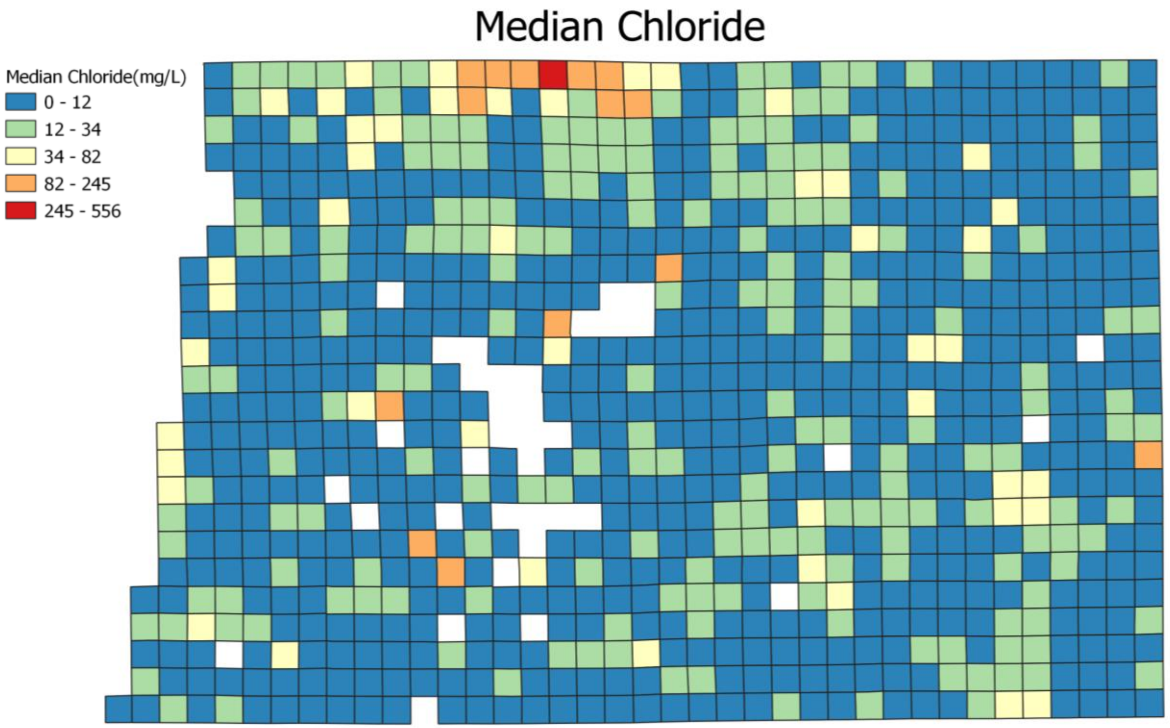
Chloride Concentrations (Cl^-)

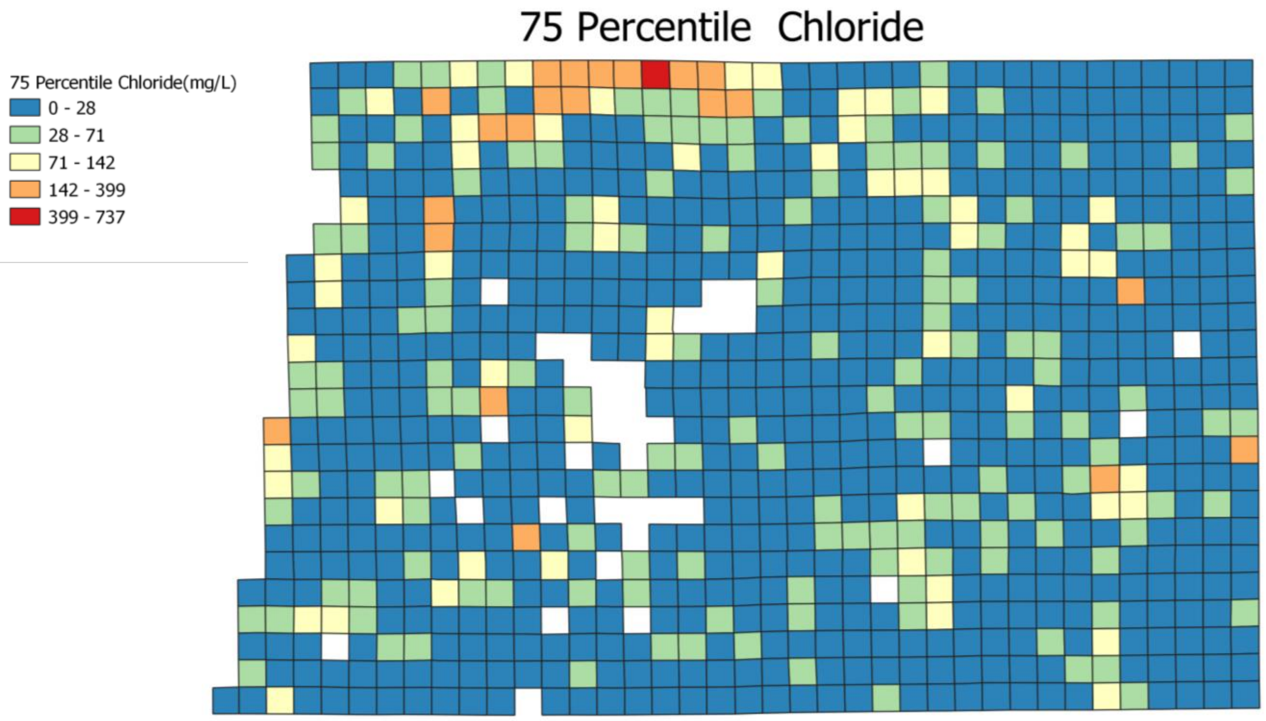
Aggregated Spatial Analysis

Section-by-section

Median (50th *Percentile)* and *75th Percentiles* Concentrations

Similarly to nitrate, there was enough chloride point concentration data available across the county to perform a similar analysis on a section-by-section basis. The results are shown below for both the 50th and 75th percentiles.





Chloride Secondary MCL: 250 mg/L

Chloride Concentrations (Cl^-)

WQ Index

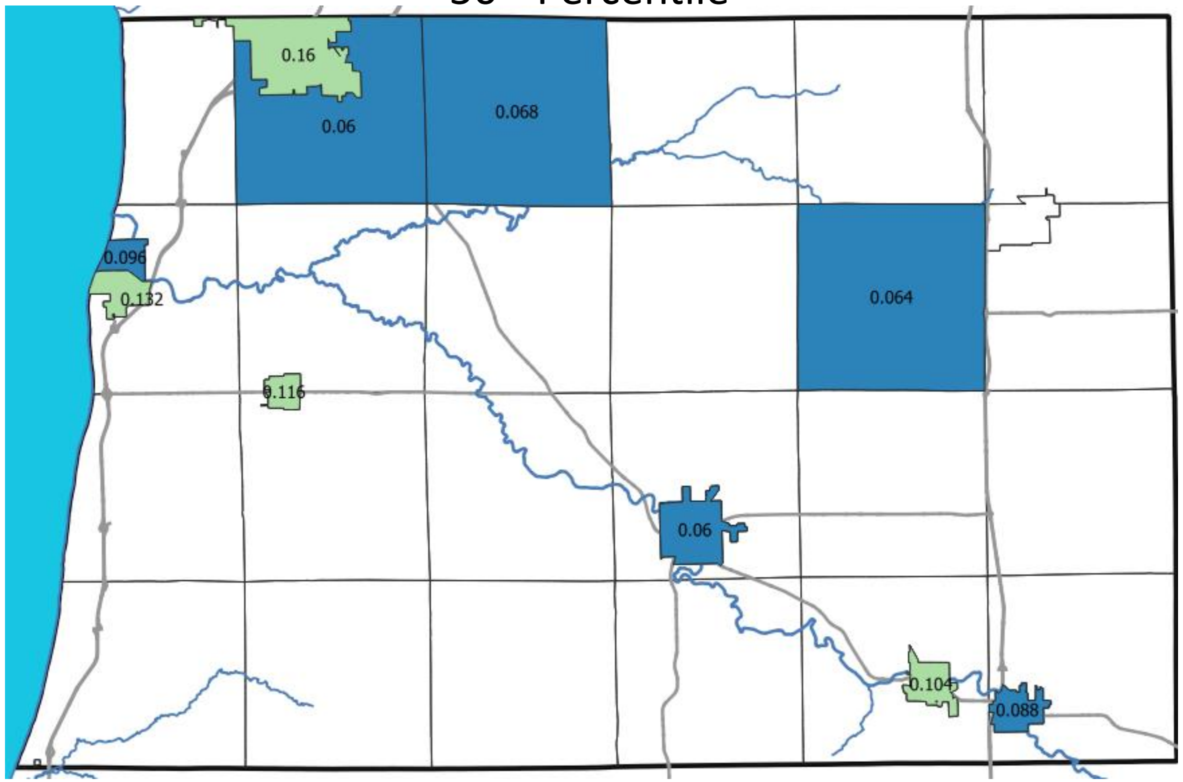
- <0.1
- 0.1 - 0.4
- 0.4 - 0.7
- 0.7 - 1
- >1

Water Quality Indices

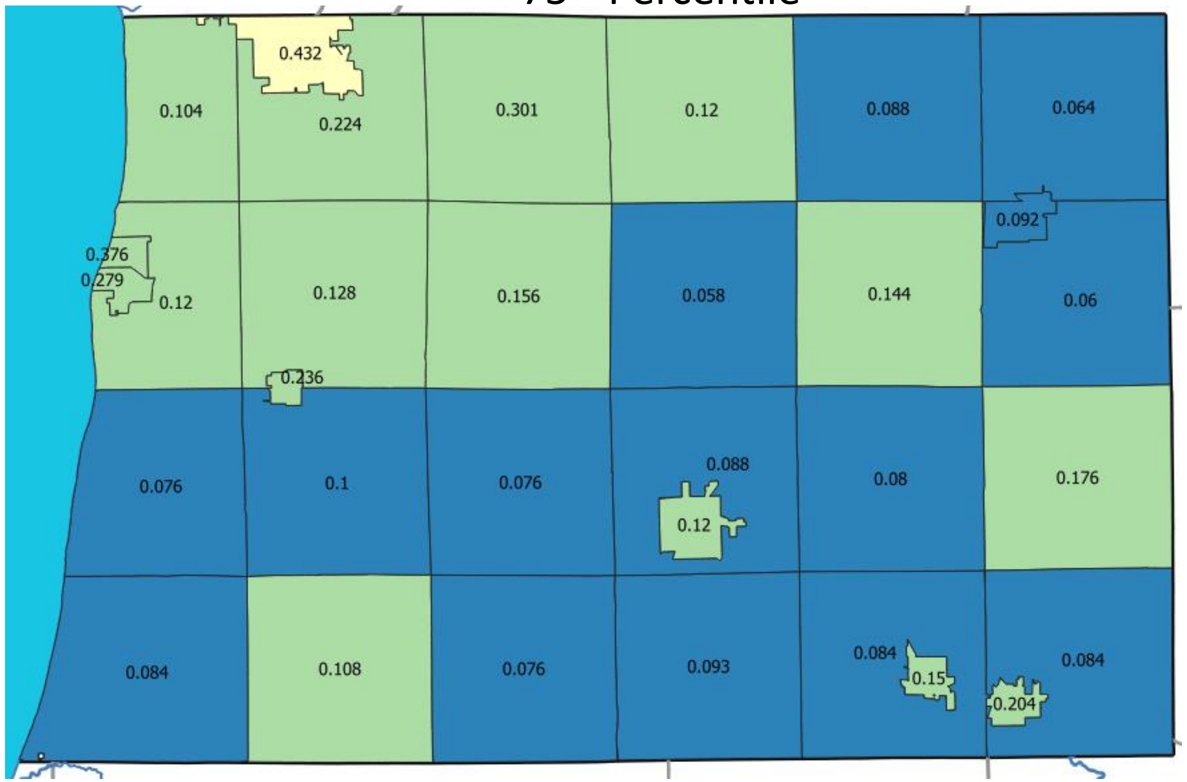
Township-by-township

The median and 75 percentile concentrations for each township were normalized by the chloride Secondary Maximum Contaminant Level (SMCL) of 250 mg/L so create a “chloride water quality index”. The results are shown here. (Townships with median and/or 75th percentile concentrations of zero also have a chloride water quality index of zero.)

50th Percentile



75th Percentile



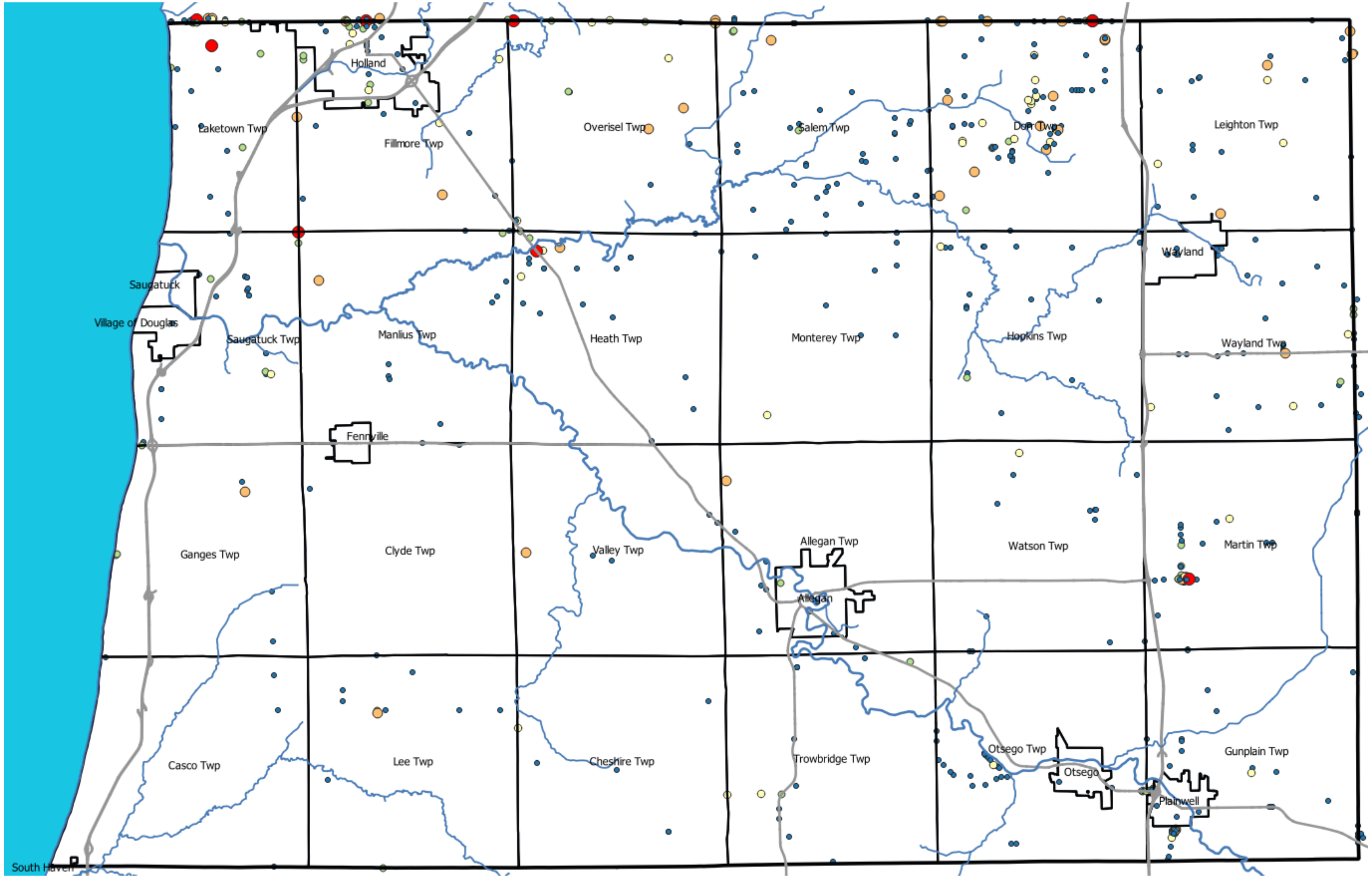
Chloride Secondary MCL: 250 mg/L

Sodium Concentrations (Na^+)

This slide shows the distribution of sodium point concentration data (water quality samples at approximate well locations) in Allegan County. There is no established MCL or SMCL or sodium, but the relationship between aesthetic quality ("saltiness") of sodium is similar to that of chloride (hence the same concentration color scheme for the data points for sodium and chloride).

Clearly, there are relatively few data points for sodium concentration across the county. Most of the samples that are available have low concentrations (<150mg/L).

Approximately 1.4% of the data shown here are above the 250mg/L. The next slide provides a full set of statistics for the chloride point concentration data.



Na^+ Conc. (mg/L)

- 0 - 50
- 50 - 100
- 100 - 150
- 150 - 250
- 250 - 2098

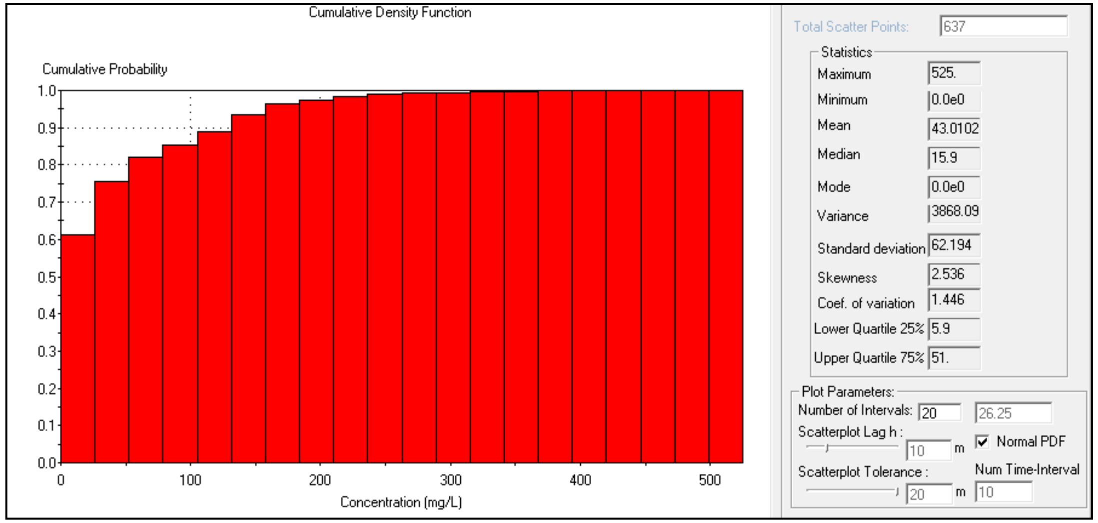
Sodium Concentrations (Na^+)

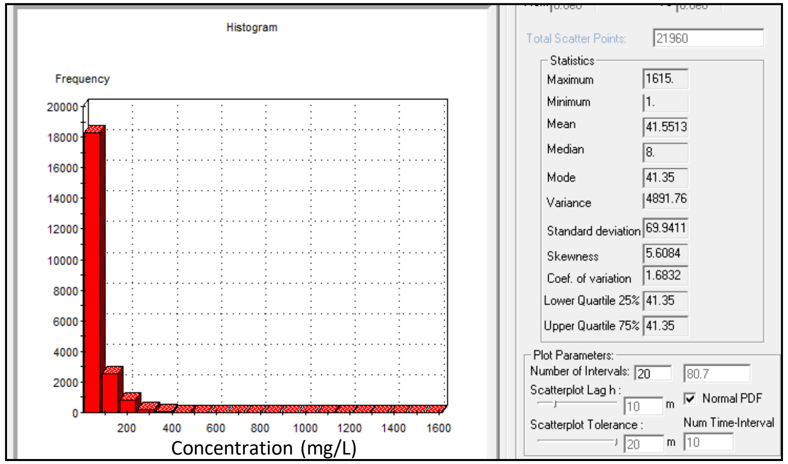
Aggregated Statistical Analysis

Countywide CDF and Histograms

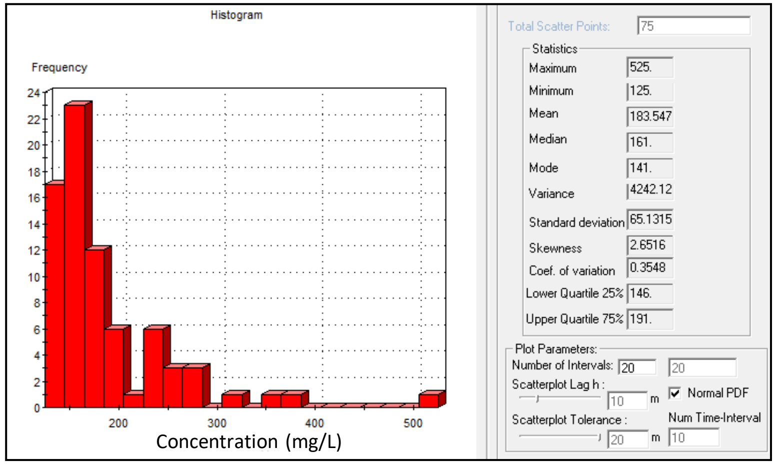
COUNTYWIDE STATISTICS, SODIUM CONCENTRATIONS:

- Number of Points: 637
- Min: 0
- Max: 525 mg/L
- Mode: 0 (no detection)
- Mean: 43.0 mg/L
- Median 15.9 mg/L
- Standard Deviation: 62.2 mg/L

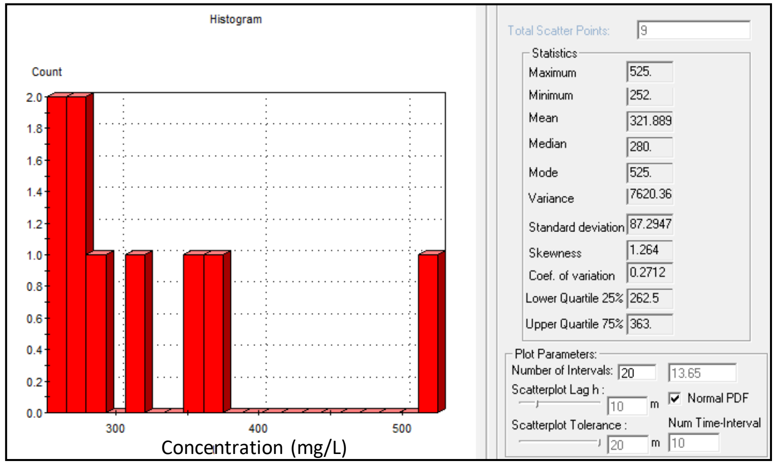




All Wells



Wells with Na > 125 mg/L



Wells with Na > 250 mg/L

Sodium Concentrations (Na^+)

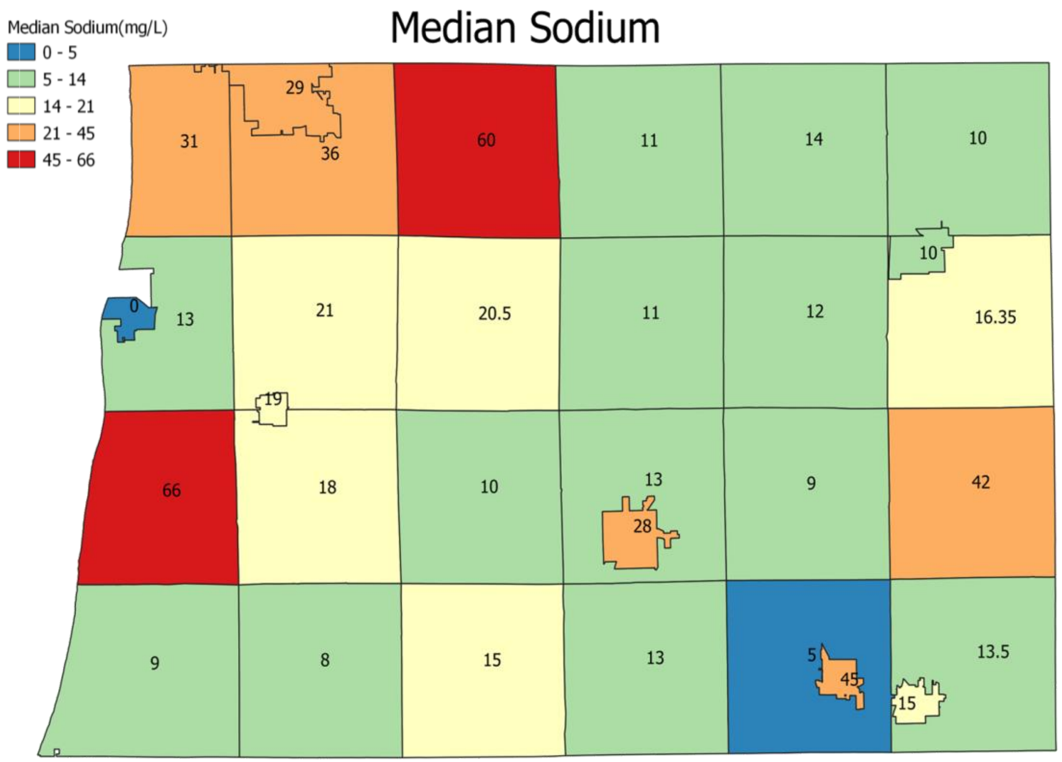
Aggregated Spatial Analysis

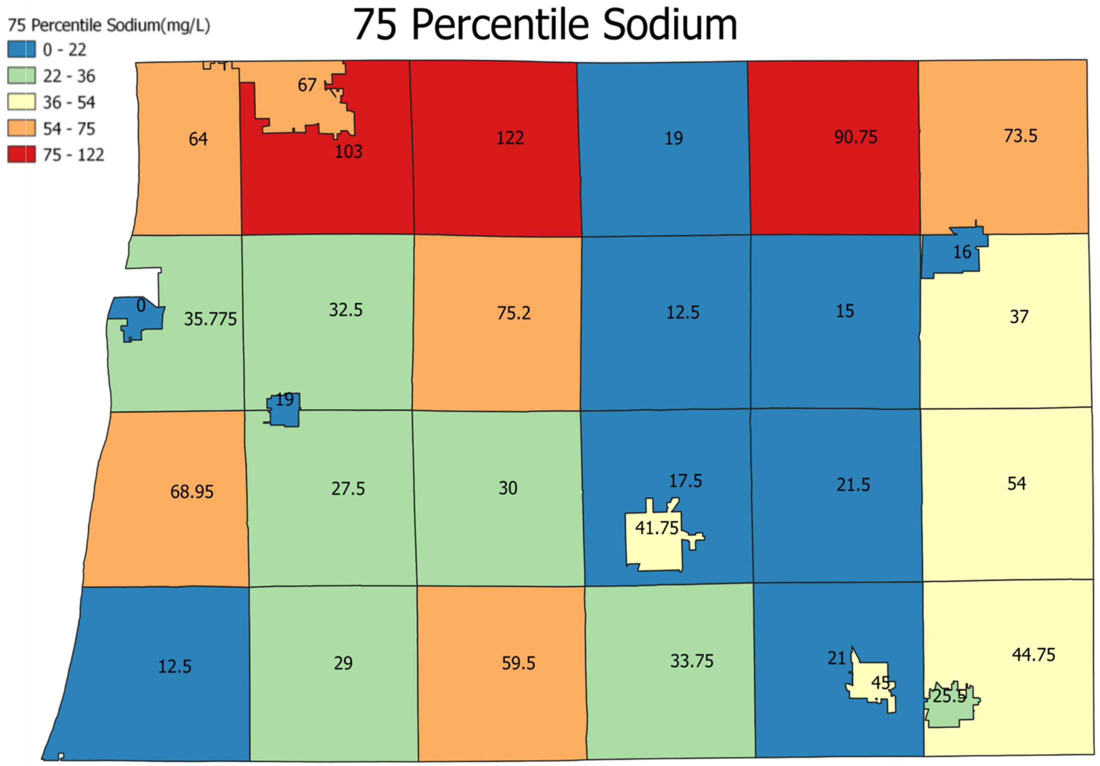
Township-by-township

Median (50th *Percentile)* and *75th Percentiles* Concentrations

This slide presents the results for 50th and 75th percentile concentrations for sodium. For both percentiles, the highest concentrations are generally along the county's northern boundary, e.g., Fillmore Township, Holland City, Overisel, Dorr and Leighton Twp. Ganges Township is notable for having some of the highest concentrations for both the 50th and 75th percentiles. Concentrations are generally lower in the eastern-central townships (e.g., Monterey, Hopkins, and Watson Twps.).

Compared to chloride, the township-by-township percentile analyses for sodium yield much higher concentrations. Recall that this is (at least in part) due to samples with higher concentrations having a more significant impact on the calculation because of the significantly fewer number of total samples used in the analysis.





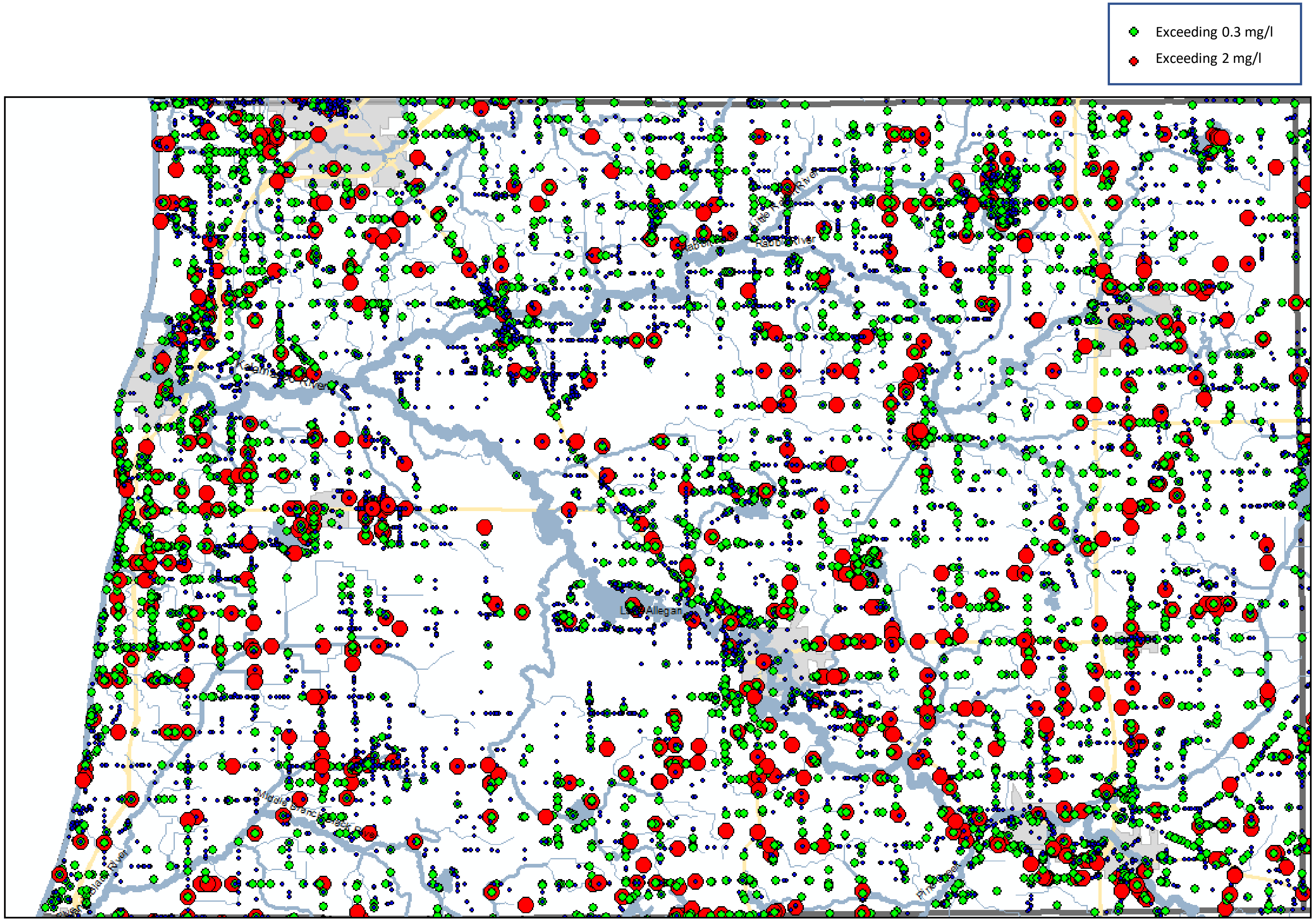
Note: Because there is no established SMCL for sodium, a water quality index was not created for each township / city / village.

Iron Concentrations (Fe)

This slide shows the distribution of iron point concentration data in Allegan County. Note that the large green and red circles indicate samples with concentrations above the SMCL.

The map shows that significant Iron exceedances occur throughout Allegan County. On a regional scale, the iron patterns and the degree of elevation in concentrations in different areas are statistically similar. On a local scale, the iron concentration pattern is extremely heterogeneous. Iron concentration varies dramatically over very short distances; elevated iron concentrations occur in seemingly random pockets.

Approximately 36% of the data shown here are above the SMCL. The next slides provide a full set of statistics for the iron point concentration data.



Iron Secondary MCL: 0.3 mg/L

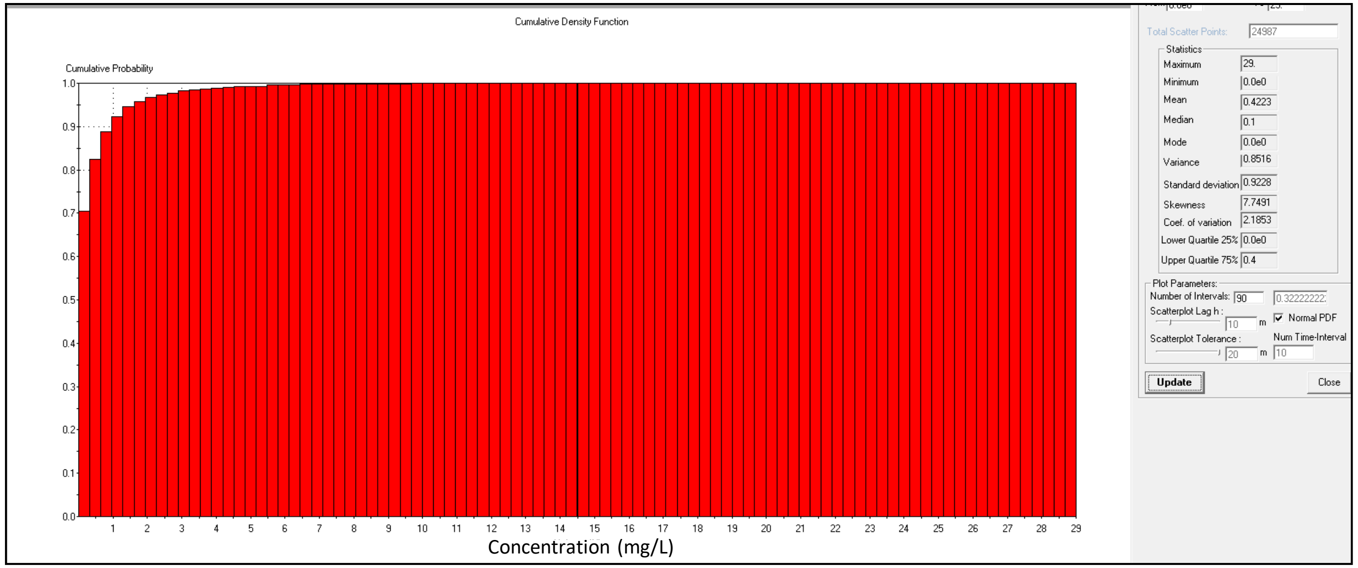
Iron Concentrations (Fe)

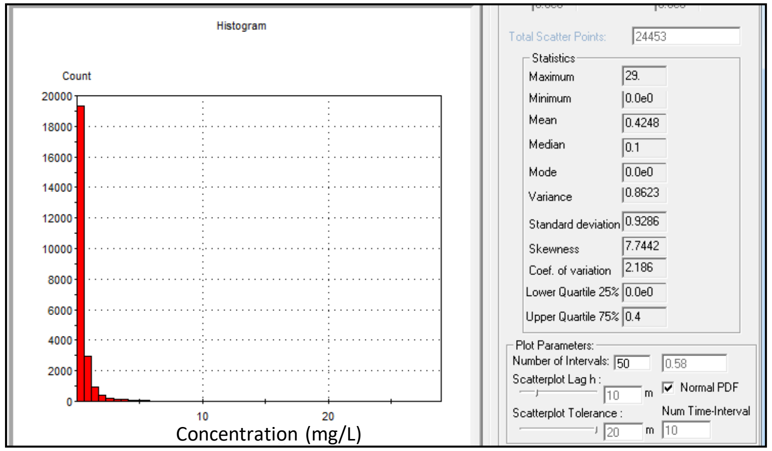
Aggregated Statistical Analysis

Countywide CDF and Histograms

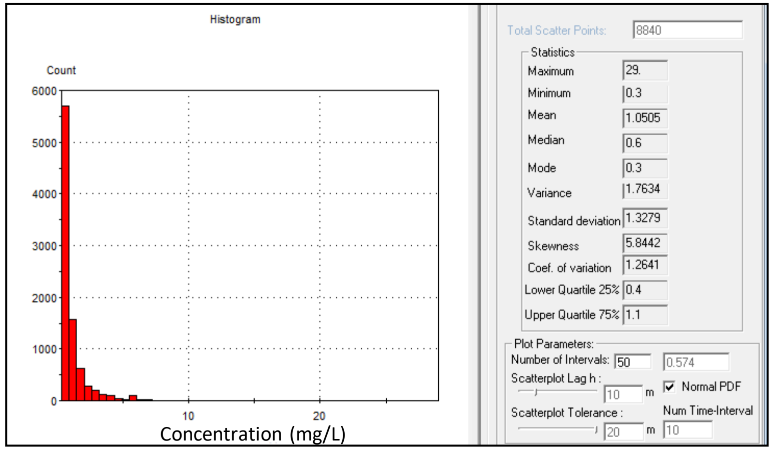
COUNTYWIDE STATISTICS,IRON CONCENTRATIONS:

- Number of Points: 24,479
- Min: 0
- Max: 29 mg/L
- Mode: 0 (no detection)
- Mean: 0.42 mg/L
- Median 0.1 mg/L
- Standard Deviation: 0.92 mg/L

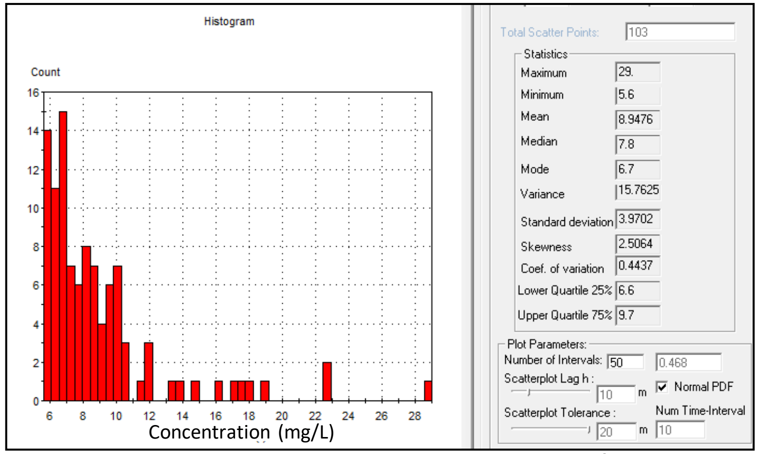




All Wells



Wells with Fe > 0.3 mg/L



Wells with Fe > 5.6 mg/L

Iron Secondary MCL: 0.3 mg/L

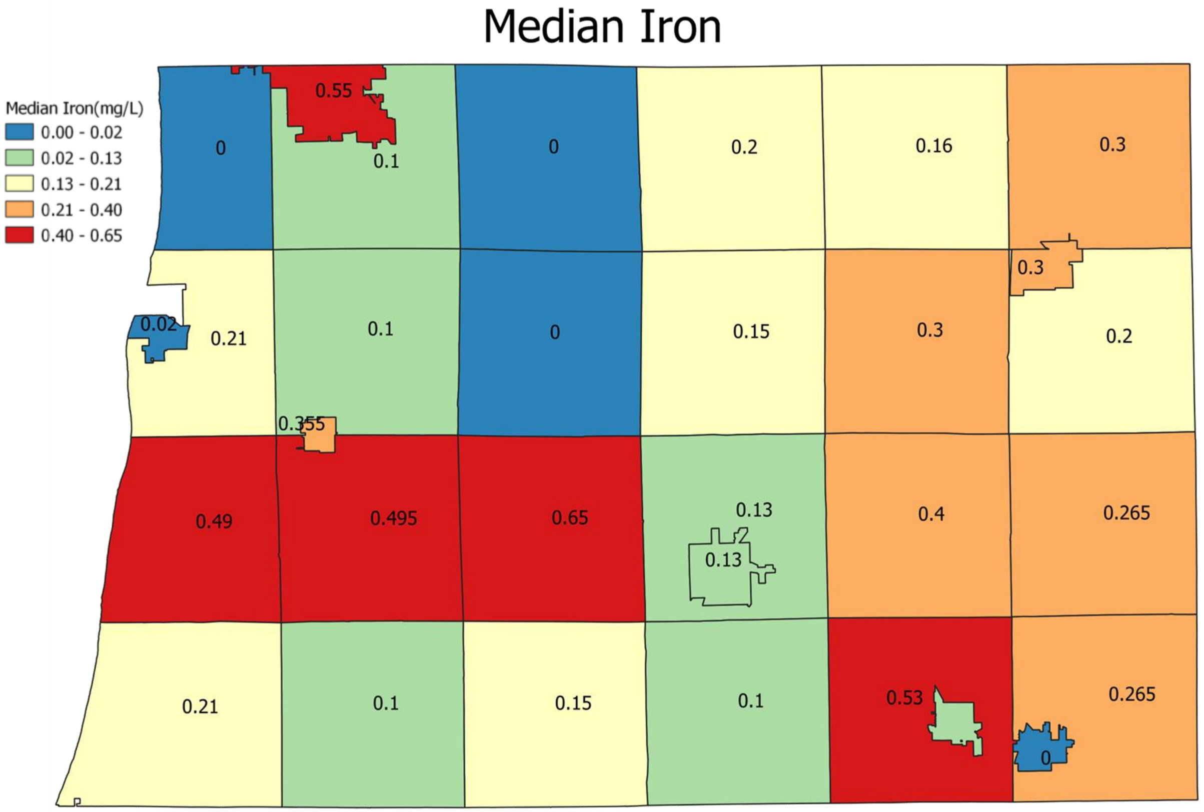
Iron Concentrations (Fe)

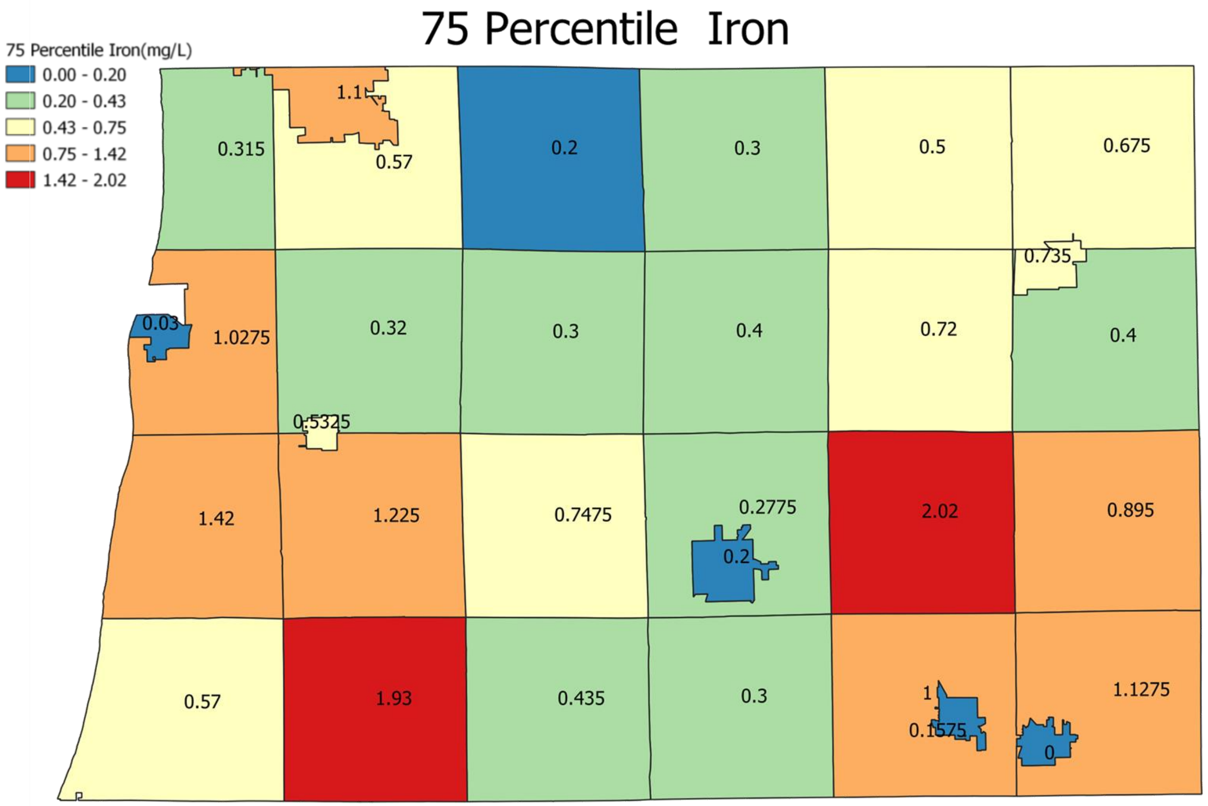
Aggregated Spatial Analysis

Township-by-township

Median (50th *Percentile)* and *75th Percentiles* Concentrations

This slide presents the results for 50th and 75th percentile concentrations for iron. For the 50th percentile, the areas with the highest concentrations (0.4-0.65mg/L) include the City of Holland, Ganges Twp., Clyde Twp., Valley Twp., and Otsego Twp. The areas with the highest 75th percentile concentrations are Lee Township (1.93mg/L) and Watson Township (2.02mg/L). The City of Holland, Saugatuck Twp., Ganges Twp., Clyde Twp., Otsego Twp., Martin Twp., and Gunplain Township also have high 75th percentile concentrations (0.75-1.42 mg/L).





Iron Secondary MCL: 0.3 mg/L

Iron Concentrations (Fe)

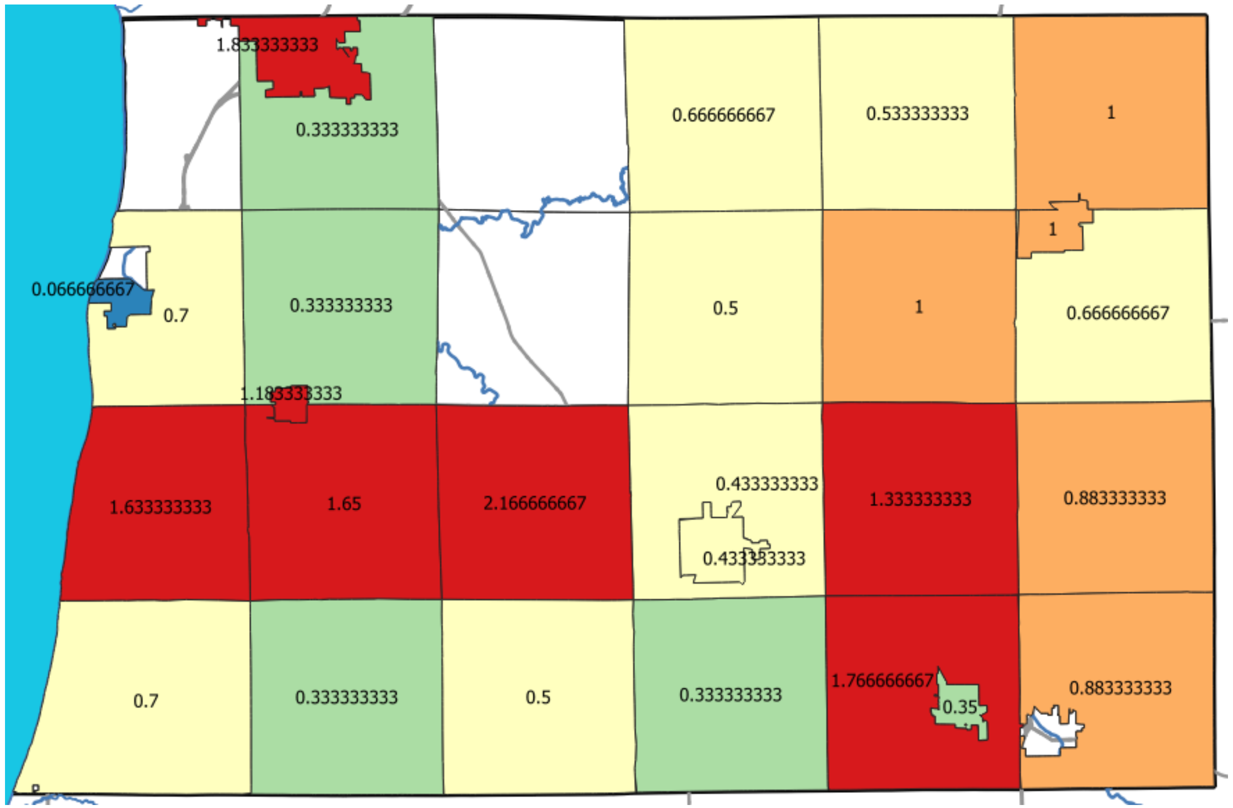
WQ Index
- <0.1
- 0.1 - 0.4
- 0.4 - 0.7
- 0.7 - 1
- >1

Water Quality Indices

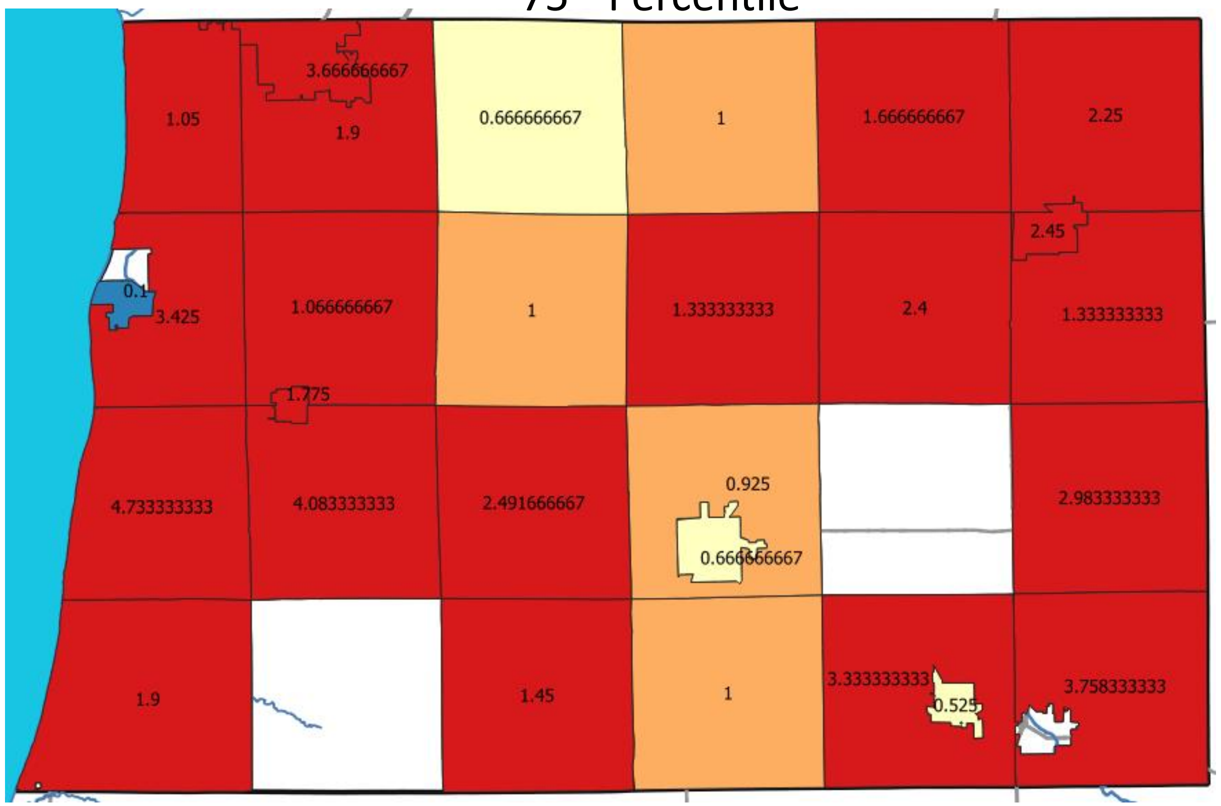
Township-by-township

The median and 75 percentile concentrations for each township were normalized by the iron Secondary Maximum Contaminant Level (SMCL) of 0.3 mg/L to create an "iron water quality index". The results are shown here. (Townships with median and/or 75^{th} percentile concentrations of zero also have an iron water quality index of zero.)

50^{th} Percentile



75^{th} Percentile



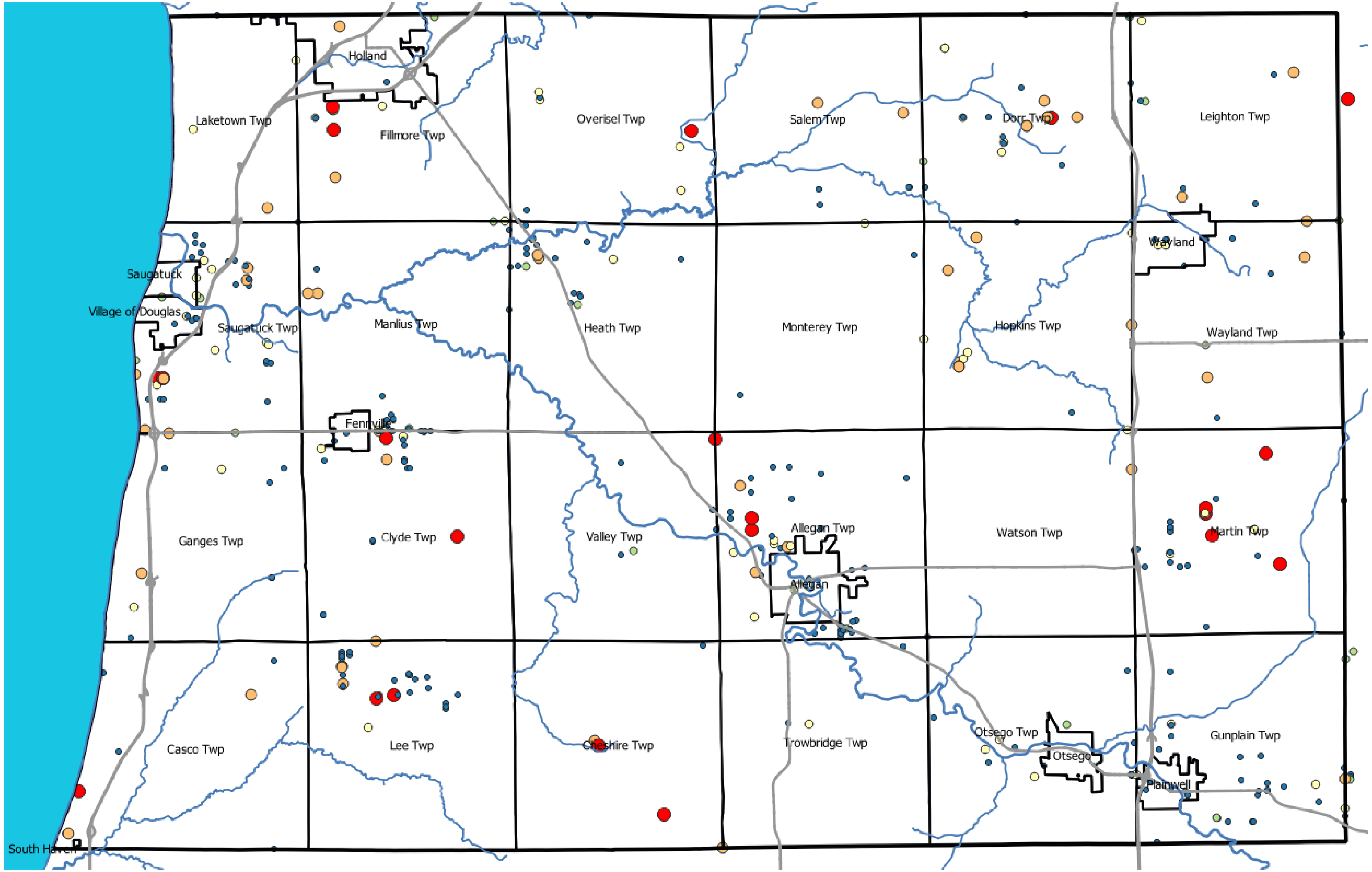
Iron Secondary MCL: 0.3 mg/L

Arsenic Concentrations (As)

This slide shows the distribution of arsenic point concentration data in Allegan County. Note that the large red circles indicate samples with concentrations above the Maximum Contaminant Level (MCL) of 0.010 mg/L.

Samples with concentrations above the MCL are found in a few isolated across the county. Townships with at least one sample above the MCL include: Fillmore, Overisel, Dorr, Saugatuck, Clyde, Allegan, Martin, Casco, Lee, and Cheshire.

Approximately 6.7% of the data shown here are above the MCL. The next slide provides a full set of statistics for the arsenic point concentration data.



As Conc. (mg/L)

- 0 - 0.001
- 0.001 - 0.0025
- 0.0025 - 0.005
- 0.005 - 0.01
- 0.01 - 0.064

Arsenic MCL: 0.010 mg/L

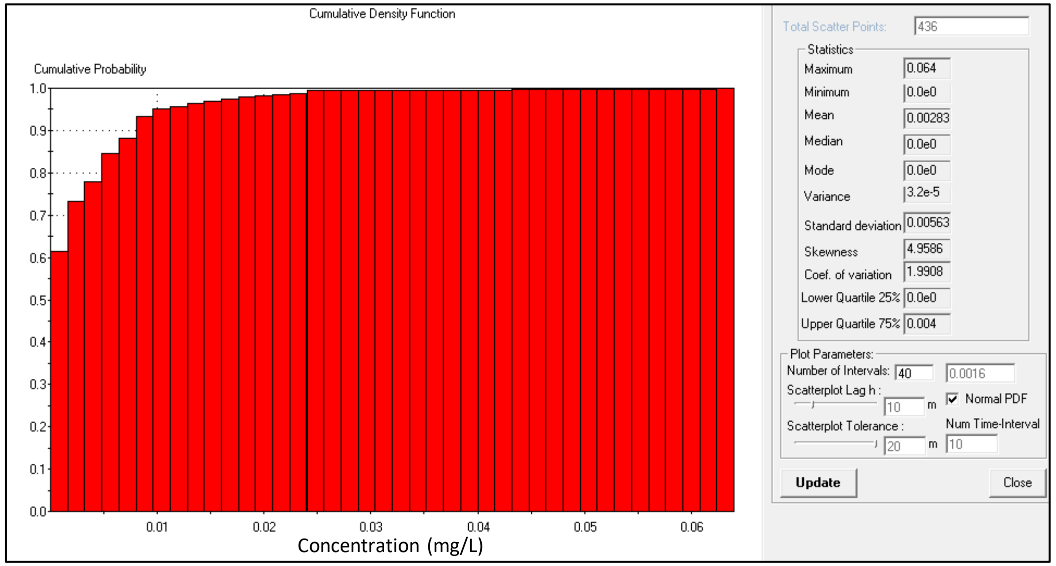
Arsenic Concentrations (As)

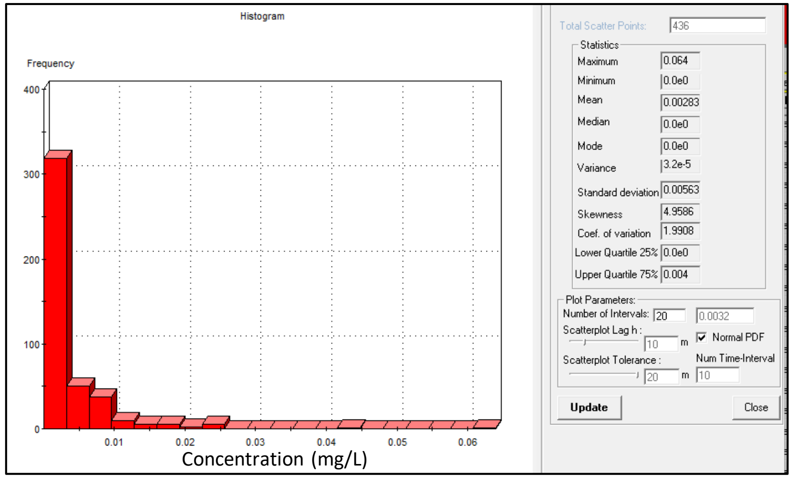
Aggregated Statistical Analysis

Countywide CDF and Histograms

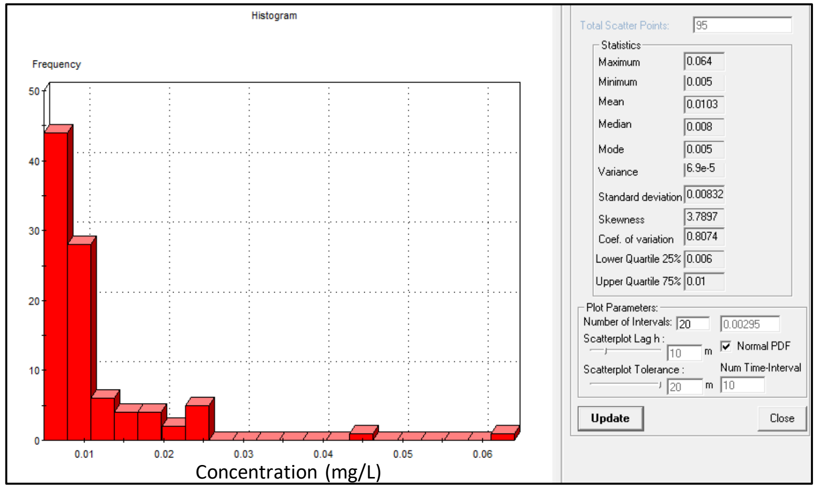
COUNTYWIDE STATISTICS, ARSENIC CONCENTRATIONS:

- Number of points: 436
- Min: 0
- Max: 0.064 mg/L
- Mode: 0 (no detection)
- Mean: 0.00283 mg/L
- Median: 0 (no detection)
- Standard Deviation: 0.00563 mg/L

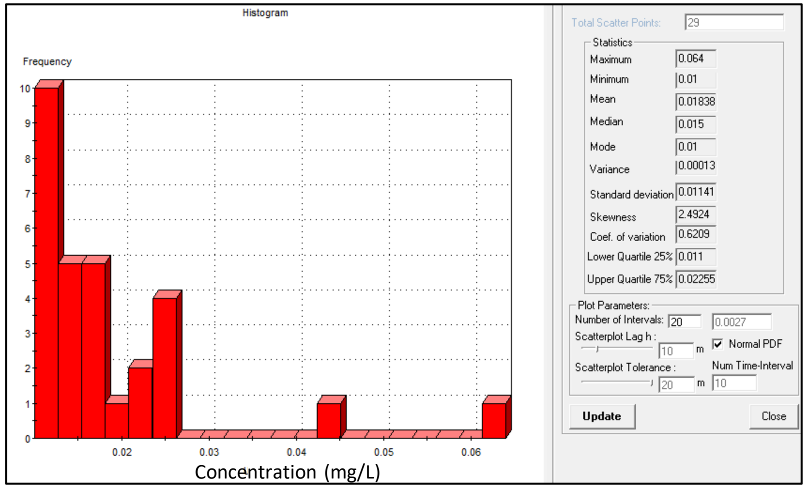




All Wells



Wells with As > 0.005 mg/L



Wells with As > 0.010 mg/L

Arsenic MCL: 0.010 mg/L

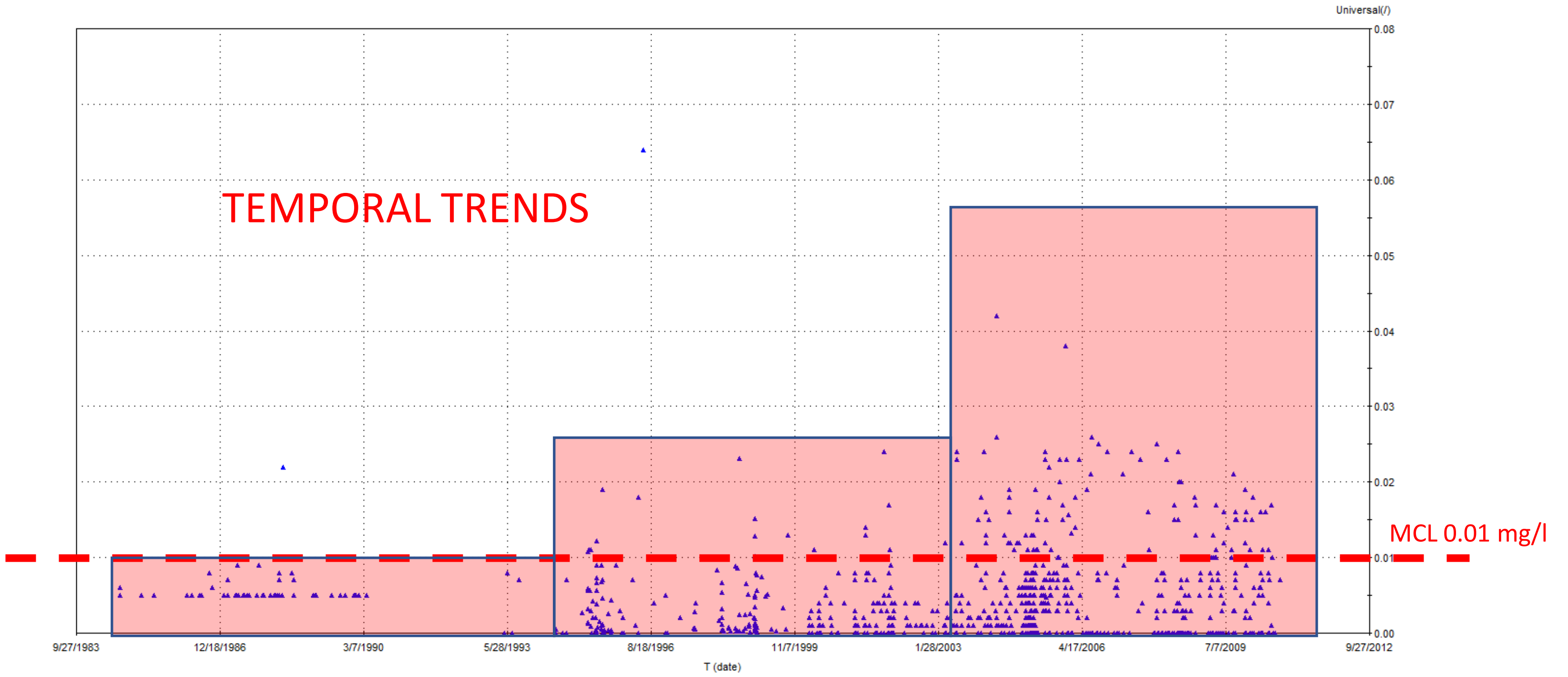
Arsenic Concentrations (As)

Temporal Trend Analysis

Note the significant numbers of data points above the drinking water standard in Allegan County.

The number of exceedances seems to be increasing with time. Note that the other chemicals analyzed (nitrate, chloride, sodium, iron, lead, and manganese) did not exhibit an obvious temporal trend.

This slide presents arsenic data over time from 1983 to 2010.



Arsenic MCL: 0.010 mg/L

Arsenic Concentrations (As)

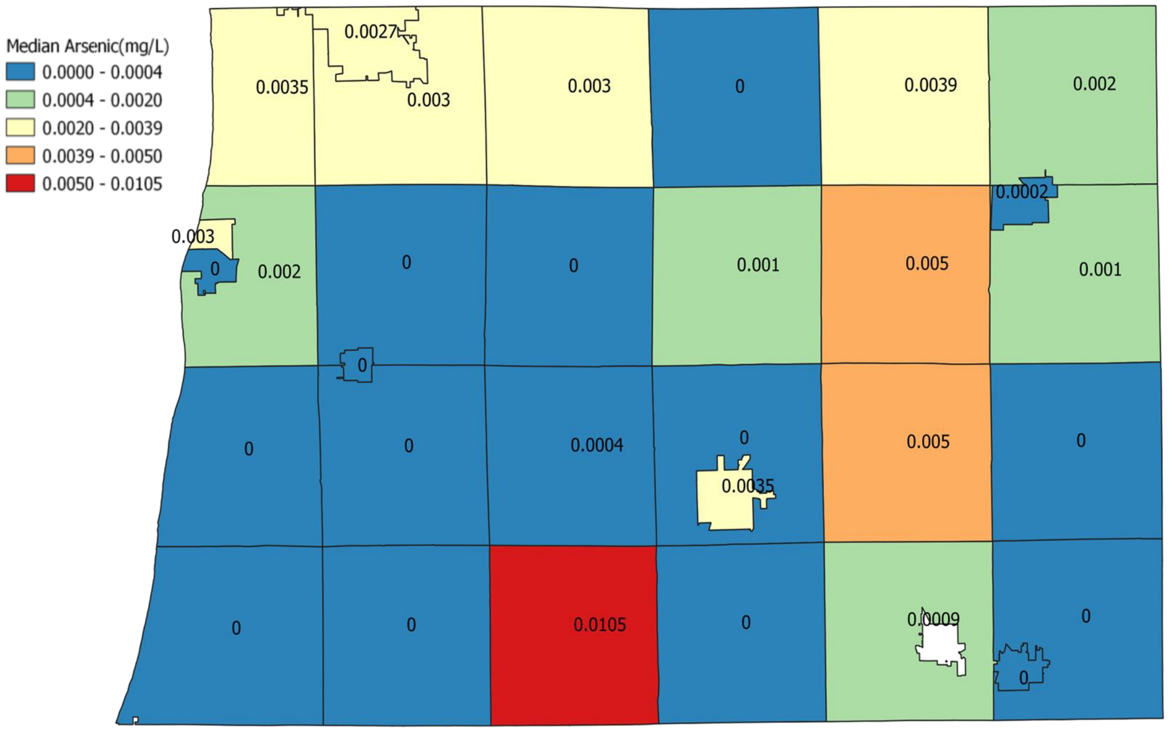
Aggregated Spatial Analysis

Township-by-township

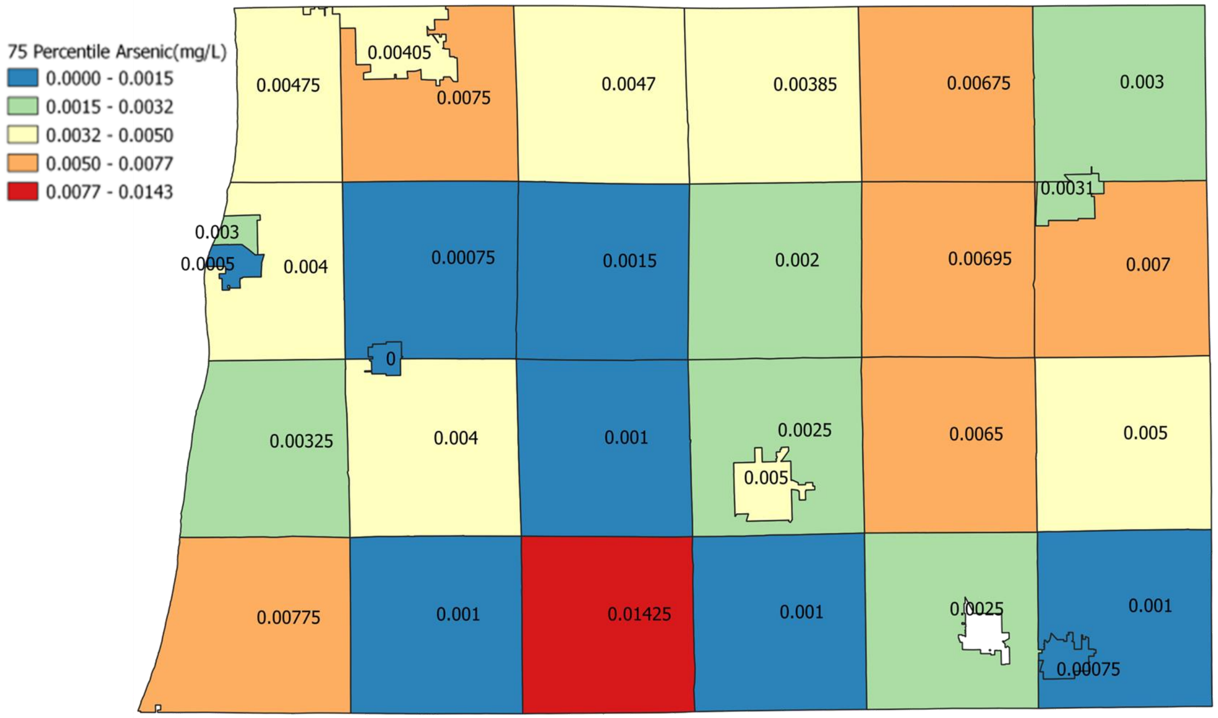
Median (50th *Percentile)* and *75th Percentiles* Concentrations

This slide presents the results for 50th and 75th percentile concentrations for arsenic. For the 50th percentile, the areas with the highest concentrations are Cheshire Twp. (0.0105mg/L), Hopkins Twp., and Watson Twp. (0.005mg/L each). The areas with the highest 75th percentile concentrations are Cheshire Twp. (0.01425mg/L), Fillmore and Casco Twps. (0.00775mg/L each), Wayland Twp. (0.007mg/L), Hopkins Twp. (0.00695mg/L), Dorr Twp. (0.00675mg/L), and Watson Twp. (0.0065).

Median Arsenic



75 Percentile Arsenic



Arsenic MCL: 0.010 mg/L

Arsenic Concentrations (As)

Water Quality Indices

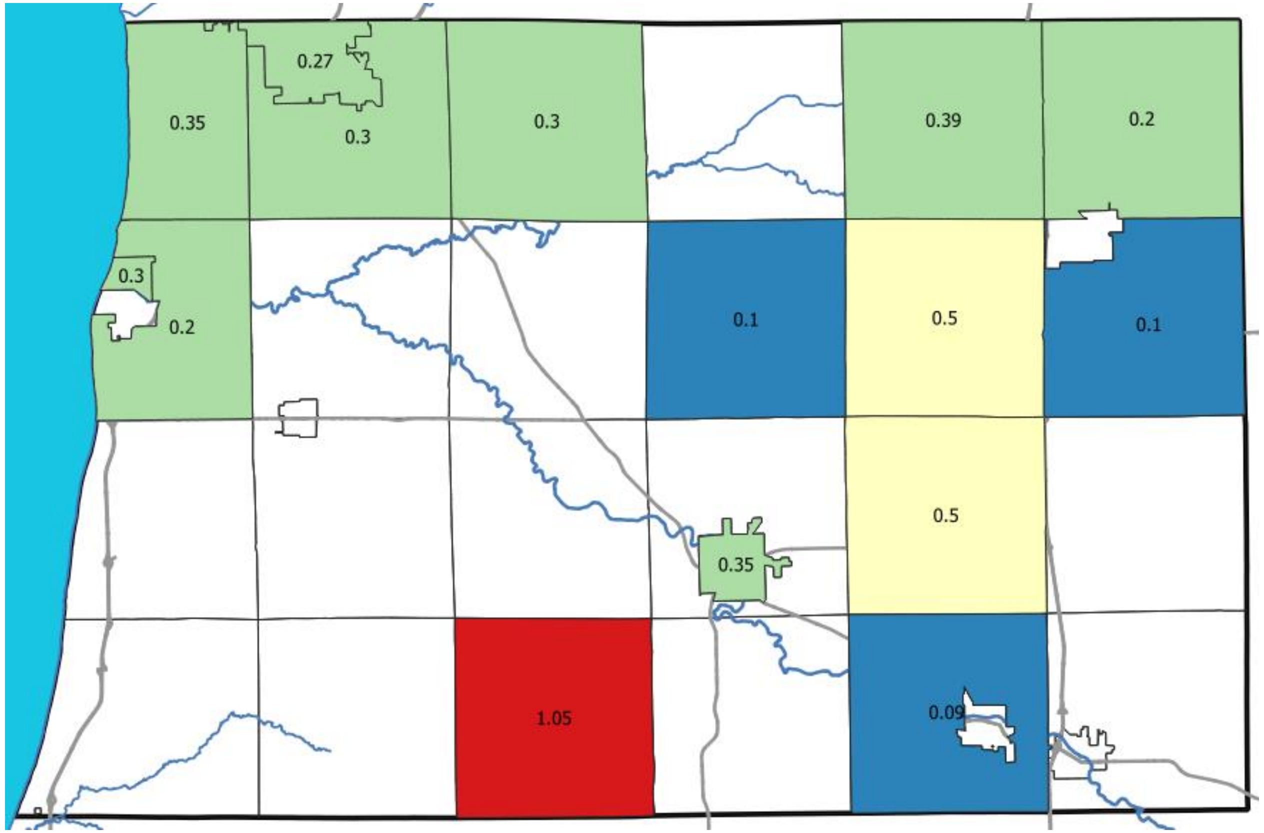
Township-by-township

WQ Index

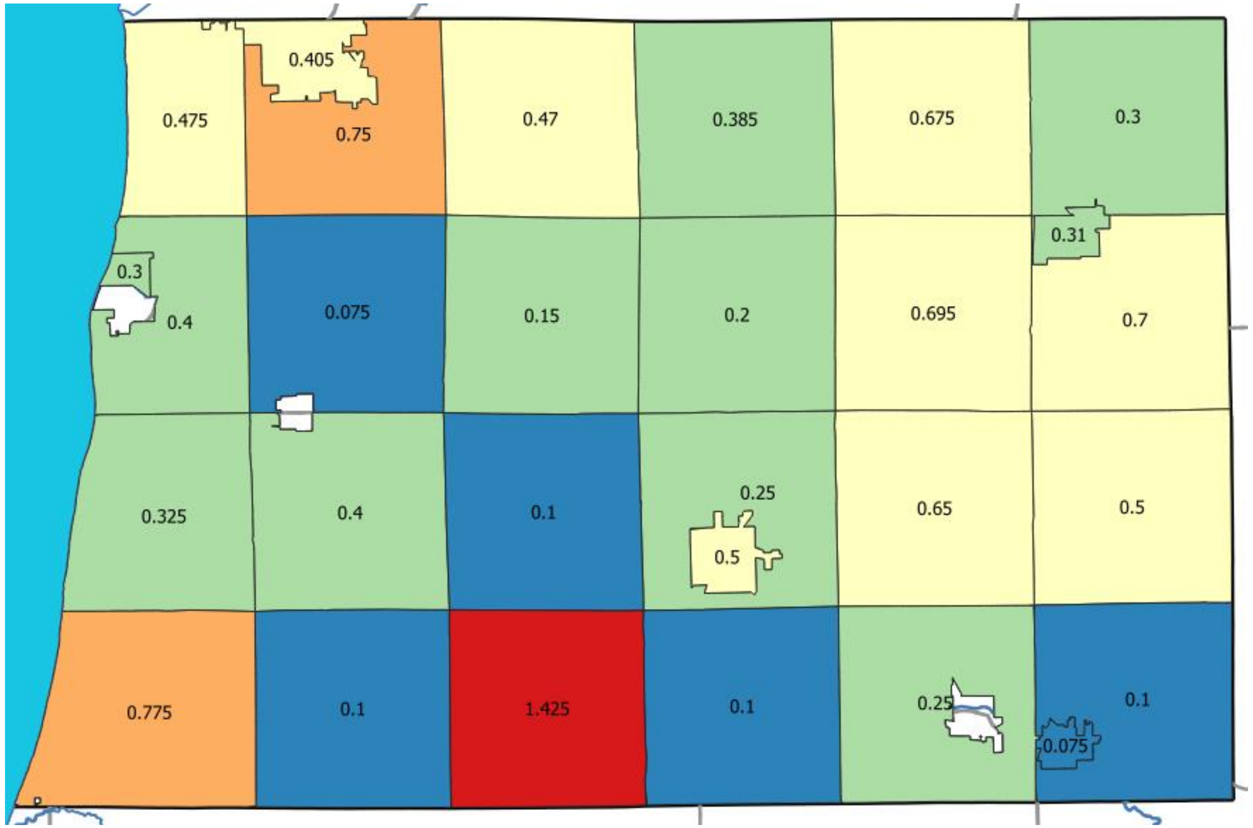
- <0.1
- 0.1 - 0.4
- 0.4 - 0.7
- 0.7 - 1
- >1

The median and 75 percentile concentrations for each township were normalized by the arsenic Maximum Contaminant Level (MCL) of 0.010 mg/L to create an "arsenic water quality index". The results are shown here. (Townships with median and/or 75th percentile concentrations of zero also have an arsenic water quality index of zero.)

50th Percentile



75th Percentile



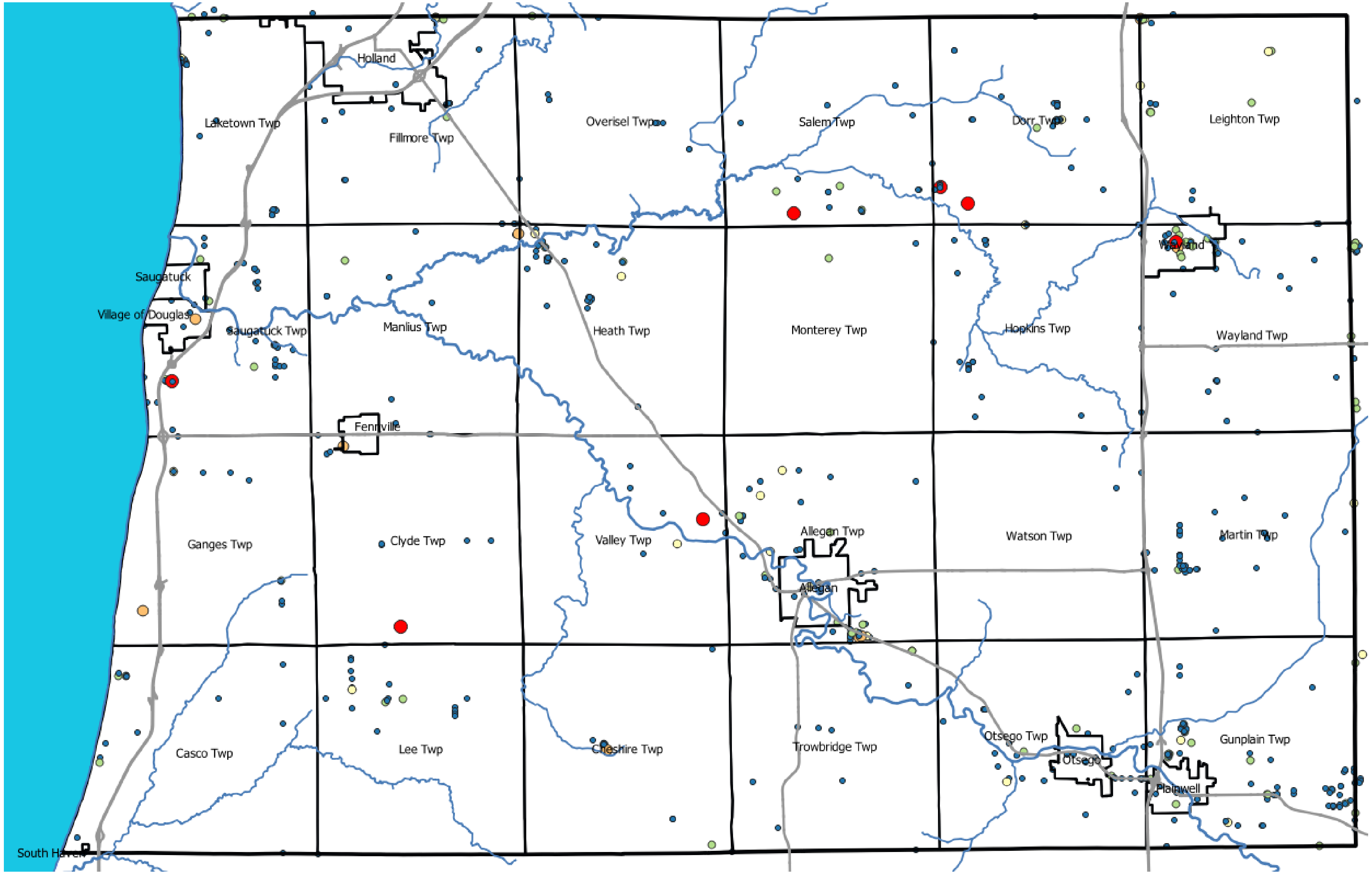
Arsenic MCL: 0.010 mg/L

Lead Concentrations (Pb)

This slide shows the distribution of lead point concentration data in Allegan County. Note that the large red circles indicate samples with concentrations above the lead Action Level of 0.015 mg/L. The Maximum Contaminant Level Goal (MCLG) is zero; if concentrations exceed the action level of 10% of samples (e.g., from customer taps sampled), the water supply system must undertake a number of additional actions to reduce concentrations.

Samples with concentrations above the MCL are found in a few isolated places across the county. Townships / cities with at least one sample above the Action Level include: Salem Twp., Dorr Twp., City of Wayland, Saugatuck Twp., Clyde Twp., and Valley Twp.

Approximately 1.1% of the data shown here are above the lead action level. The next slides provides a full set of statistics for the lead point concentration data.



Pb Conc. (mg/L)

- 0 - 0.001
- 0.001 - 0.005
- 0.005 - 0.01
- 0.01 - 0.015
- 0.015 - 0.103

Lead Action Level: 0.015 mg/L

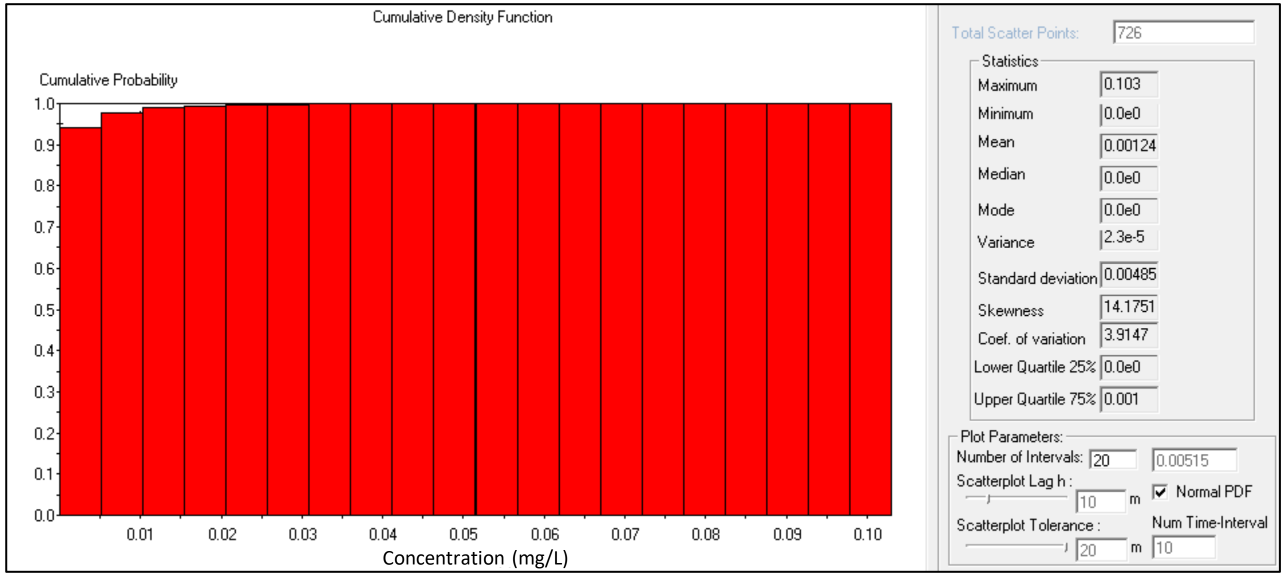
Lead Concentrations (Pb)

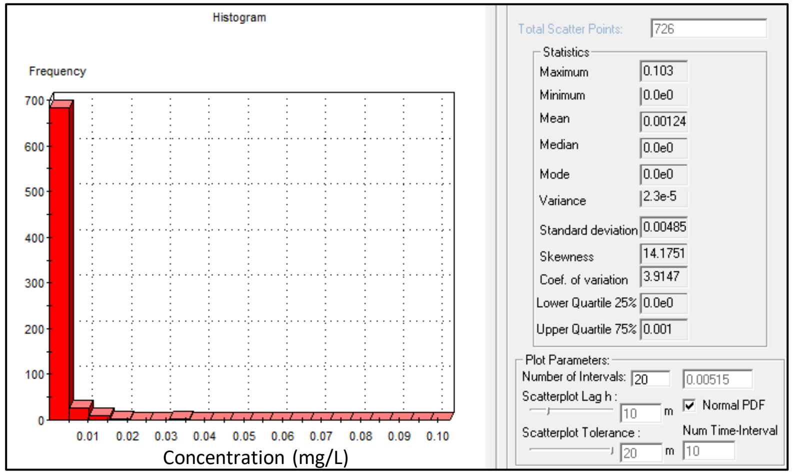
Aggregated Statistical Analysis

Countywide CDF and Histograms

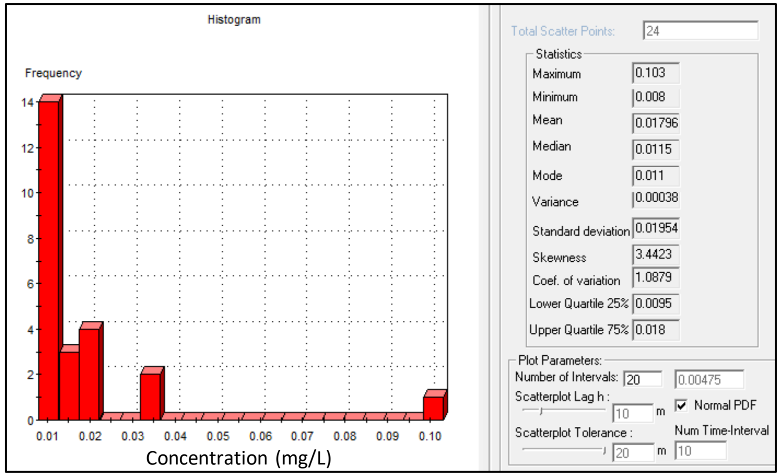
COUNTYWIDE STATISTICS, LEAD CONCENTRATIONS:

- Number of points: 726
- Min: 0
- Max: 0.103 mg/L
- Mode: 0 (no detection)
- Mean: 0.00124 mg/L
- Median: 0 (no detection)
- Standard Deviation: 0.00485 mg/L

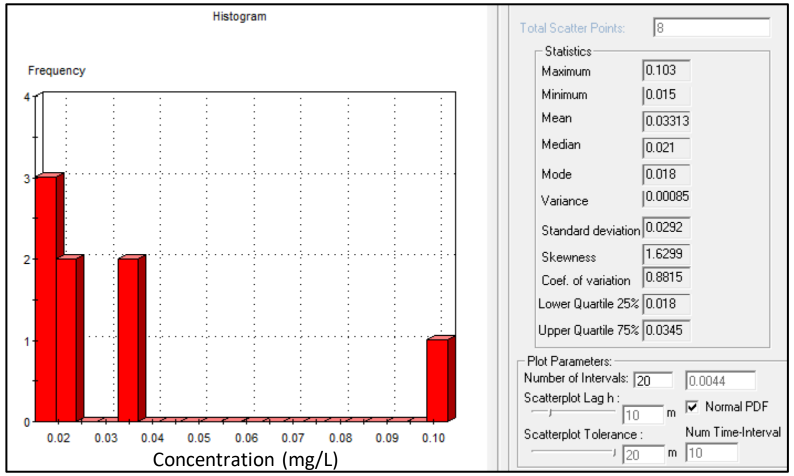




All Wells



Wells with Lead > 0.0075 mg/L



Wells with Lead > 0.015 mg/L

Lead Action Level: 0.015 mg/L

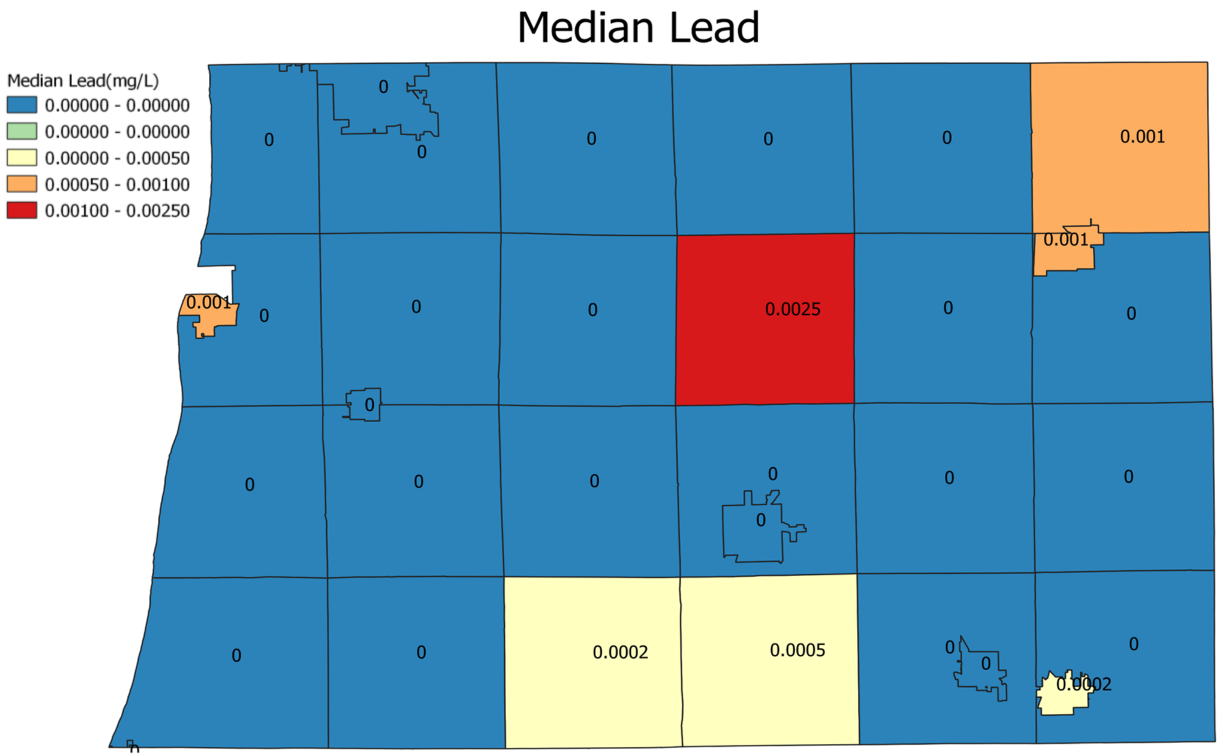
Lead Concentrations (Pb)

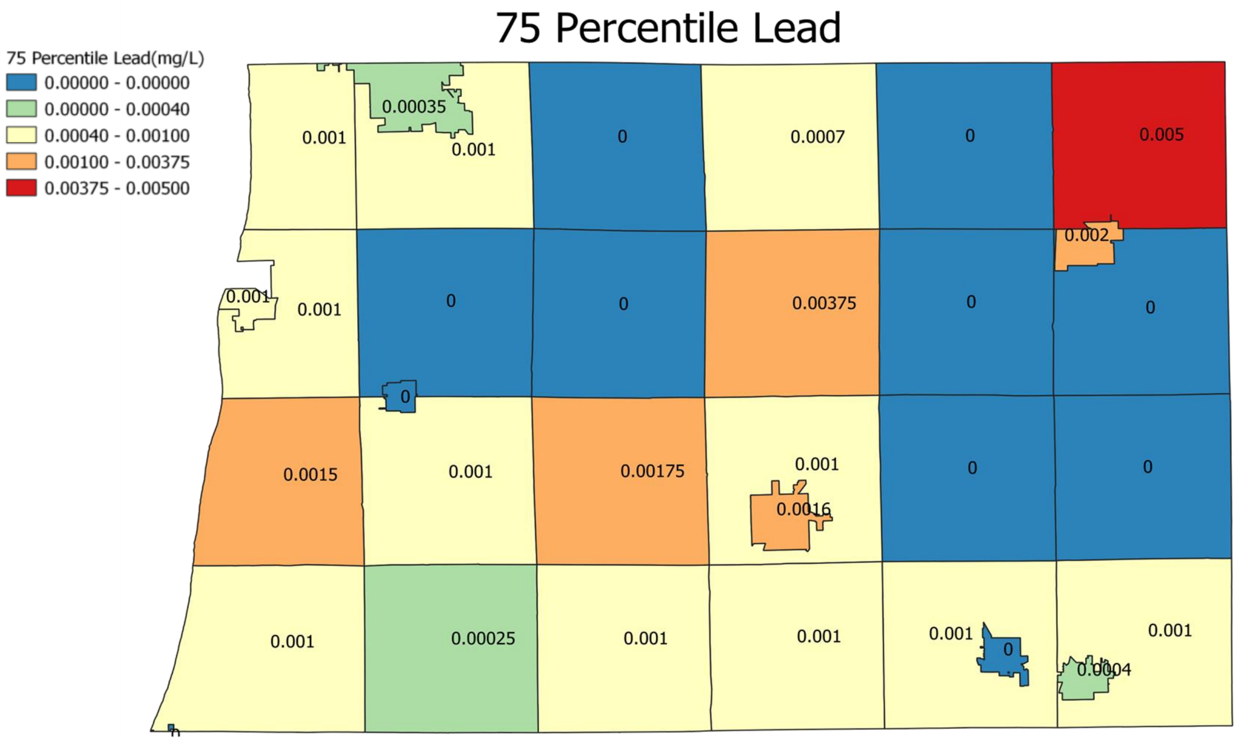
Aggregated Spatial Analysis

Township-by-township

Median (50th *Percentile)* and *75th Percentiles* Concentrations

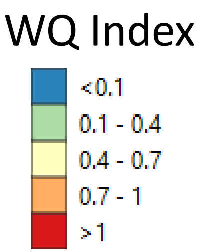
This slide presents the results for 50th and 75th percentile concentrations for lead. For the 50th percentile, most of the townships / cities have a concentration of 0 mg/L (i.e., at least half of the samples were "no detect"). Those with non-zero 50th percentile concentrations for lead include Monterey Twp. (0.0025 mg/L), Leighton Twp. and the cities of Douglas and Wayland (0.001mg/L each), Trowbridge Twp. (0.0005 mg/L), and Cheshire Twp. (0.0002 mg/L). Leighton Twp. has the highest 75th percentile concentration (0.005 mg/L), followed by Monterey Twp. (0.00375mg/L), Valley Twp. (0.00175mg/L), City of Allegan (0.0016 mg/L), and Ganges Twp. (0.0015mg/L).





Lead Action Level: 0.015 mg/L

Lead Concentrations (Pb)

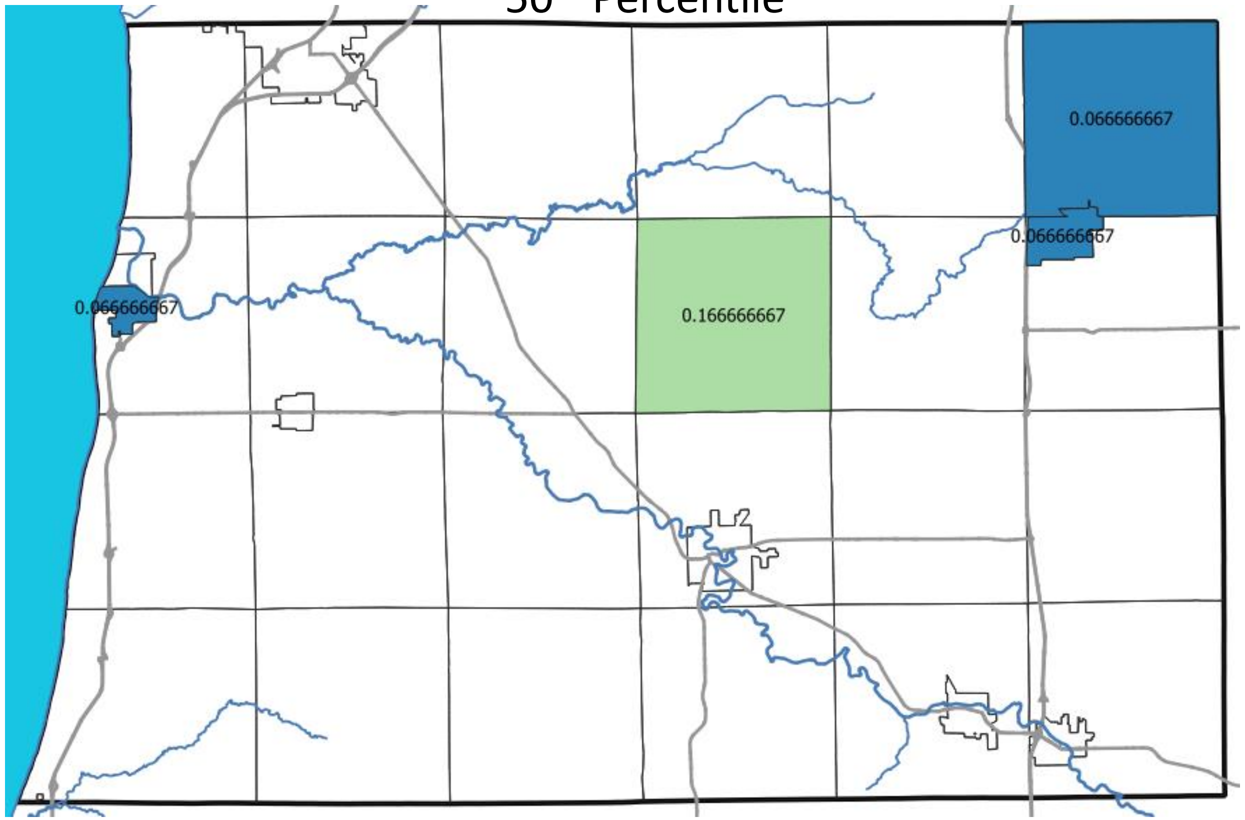


Water Quality Indices

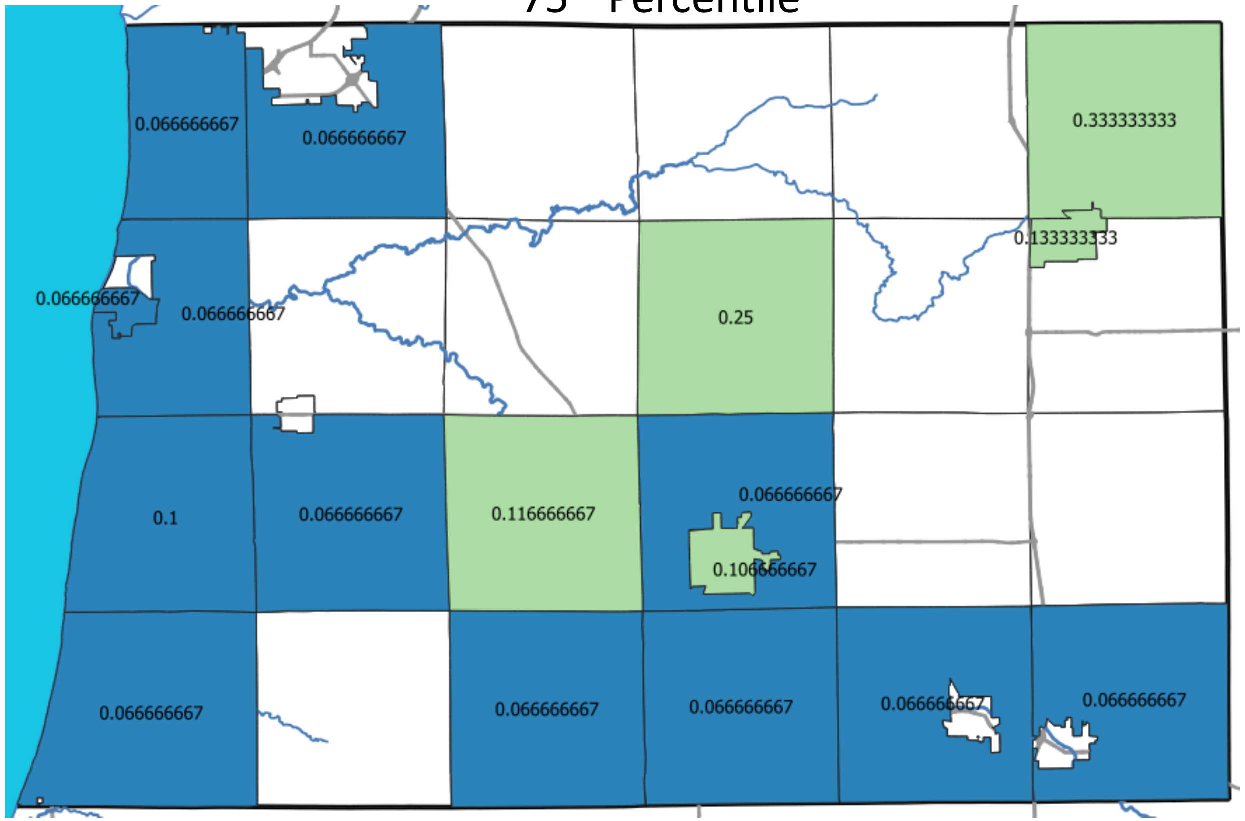
Township-by-township

The median and 75 percentile concentrations for each township were normalized by the lead Action Level of 0.015 mg/L to create a “lead water quality index”. The results are shown here. (Townships with median and/or 75th percentile concentrations of zero also have a lead water quality index of zero.)

50th Percentile



75th Percentile



Lead Action Level: 0.015 mg/L

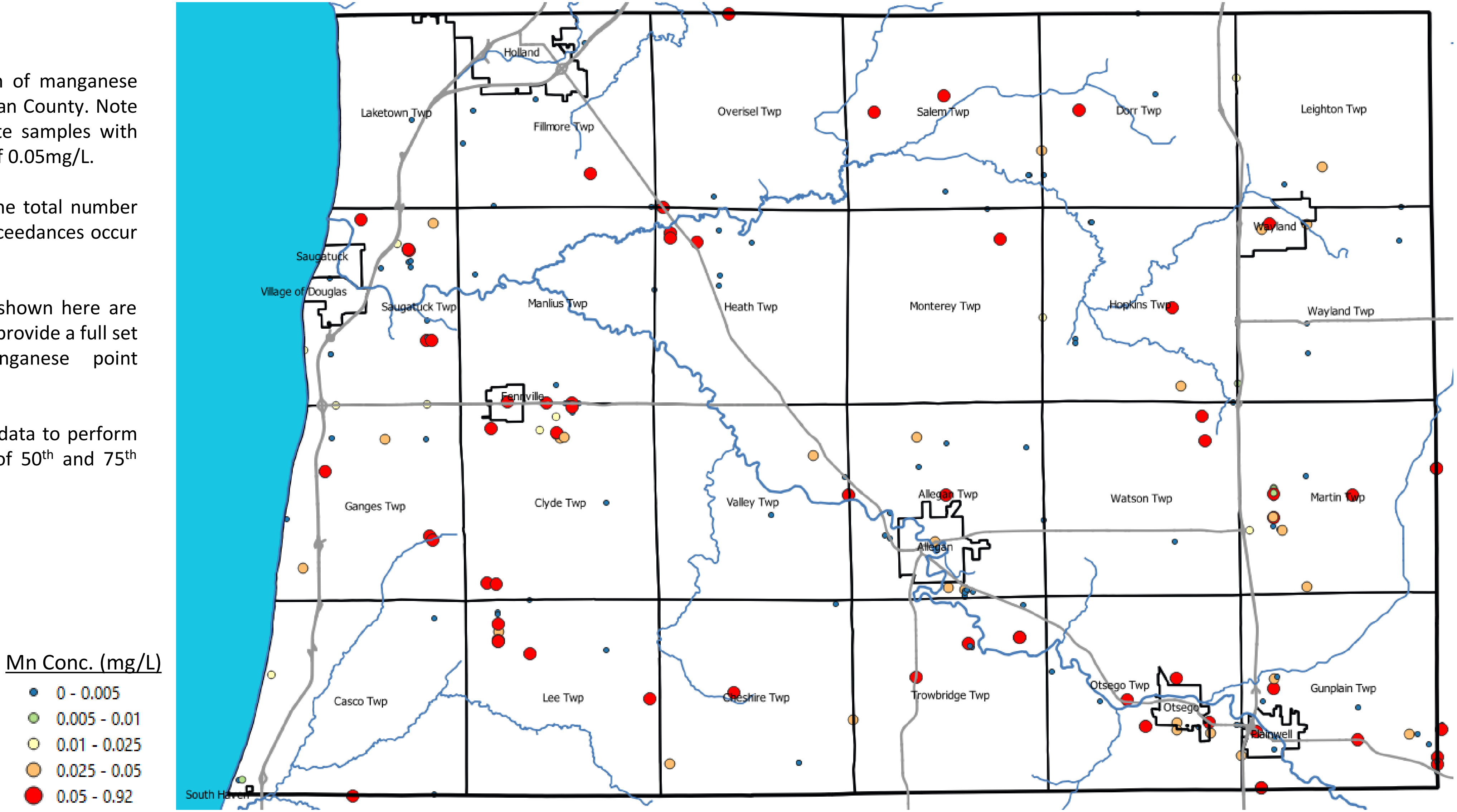
Manganese Concentrations (Mn)

This slide shows the distribution of manganese point concentration data in Allegan County. Note that the large red circles indicate samples with concentrations above the SMCL of 0.05mg/L.

The map shows that, although the total number of samples is low, manganese exceedances occur throughout Allegan County.

Approximately 34% of the data shown here are above the SMCL. The next slides provide a full set of statistics for the manganese point concentration data.

Note that there was insufficient data to perform township-by-township mapping of 50th and 75th percentile concentrations.



Manganese Secondary MCL: 0.05 mg/L

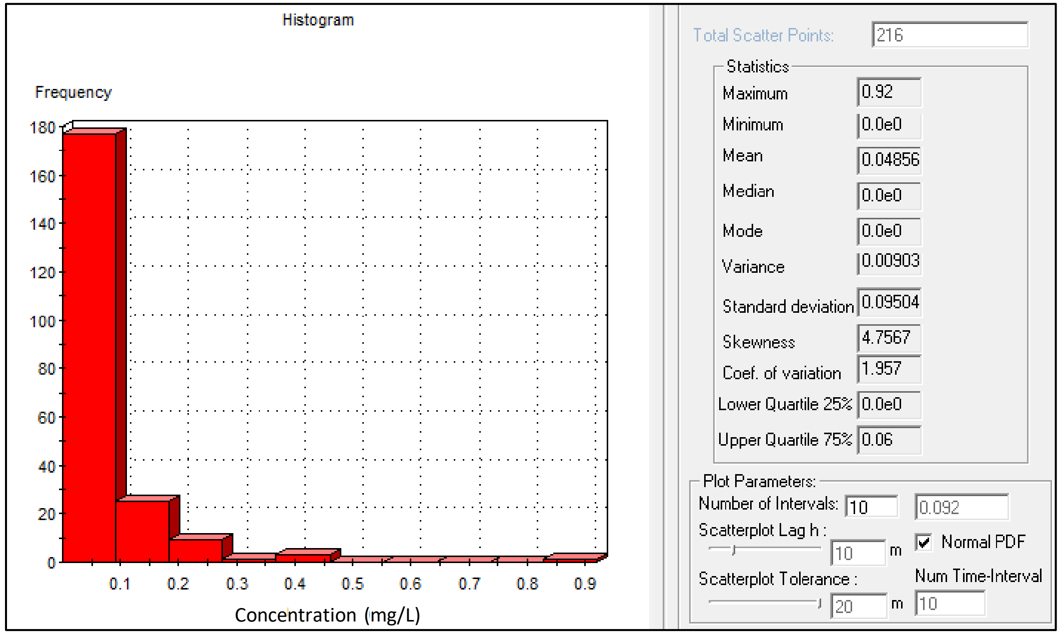
Manganese Concentrations (Mn)

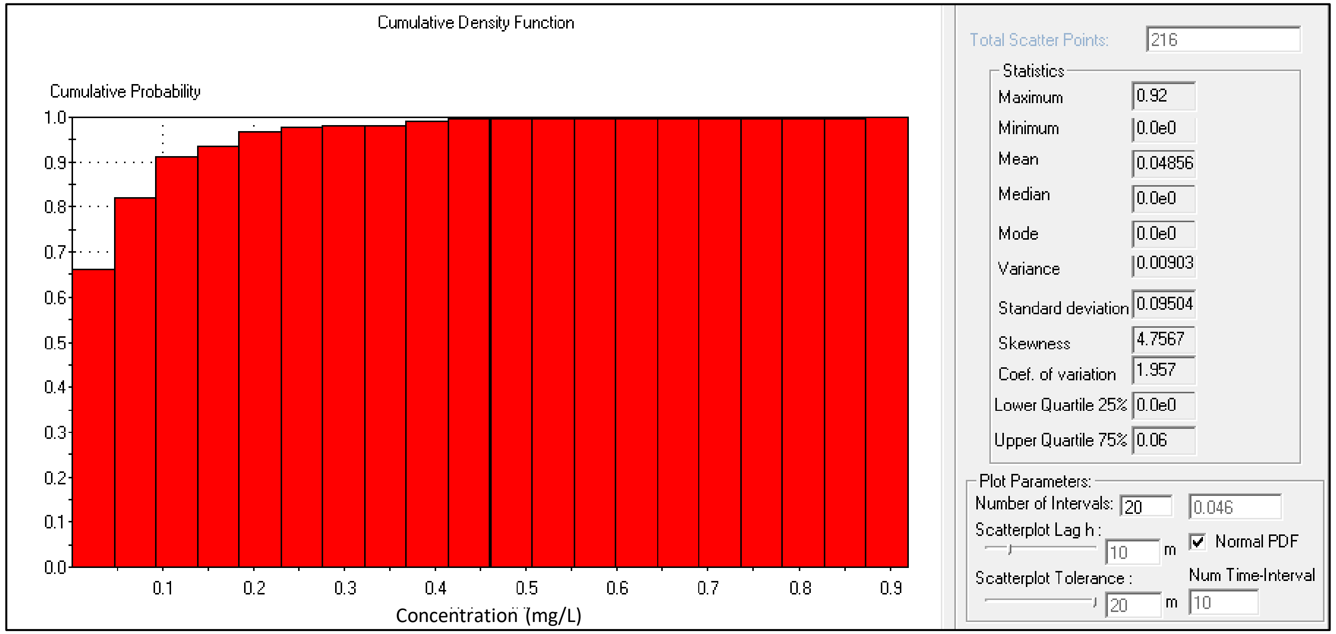
Aggregated Statistical Analysis

Countywide CDF and Histograms

COUNTYWIDE STATISTICS, MANGANESE CONCENTRATIONS:

- Number of points: 216
- Min: 0
- Max: 0.92 mg/L
- Mode: 0 (no detection)
- Mean: 0.04856 mg/L
- Median: 0 (no detection)
- Standard Deviation: 0.095 mg/L





Manganese Secondary MCL: 0.05 mg/L

Water Quality Severity Rankings

A water quality "severity index" was generated for all chemical parameters for which a water quality index (WQI) was computed, namely, nitrate, chloride, iron, lead, and arsenic (recall that water quality index was calculated as the 50th or 75th percentile concentrations normalized by the MCL or Secondary MCL of the chemical).

A "primary" severity index was calculated by summing the WQI for the contaminants known to adversely impact human health: nitrate, lead, and arsenic (i.e., those with a MCL or Action Level). A similar "secondary" severity index was computed for chemicals with non-mandatory water quality standards: chloride and iron (recall that there was note enough data to create a water quality index for sodium and manganese).

Primary and secondary severity indexes for all townships and cities/villages and were then ranked from largest severity index to smallest. The results are presented in the tables to the right.

Cheshire Township ranks highest in terms of primary water quality severity index - due to the high arsenic concentrations found in a limited number of samples – followed by Overisel, Martin, and Holland City (primarily because high nitrate concentrations). The townships of Hopkins, Watson, Fillmore, and Dorr also have high-ranking primary water quality severity indexes.

Ganges Townships ranks highest in terms of secondary water quality severity index – due to high iron concentrations – followed by Holland City (relatively high iron and chloride concentrations), Clyde Township, and Otsego Township (high iron concentrations). The townships of Valley, Gunplain, Saugatuck, and Martine also have high-ranking secondary water quality severity indexes.

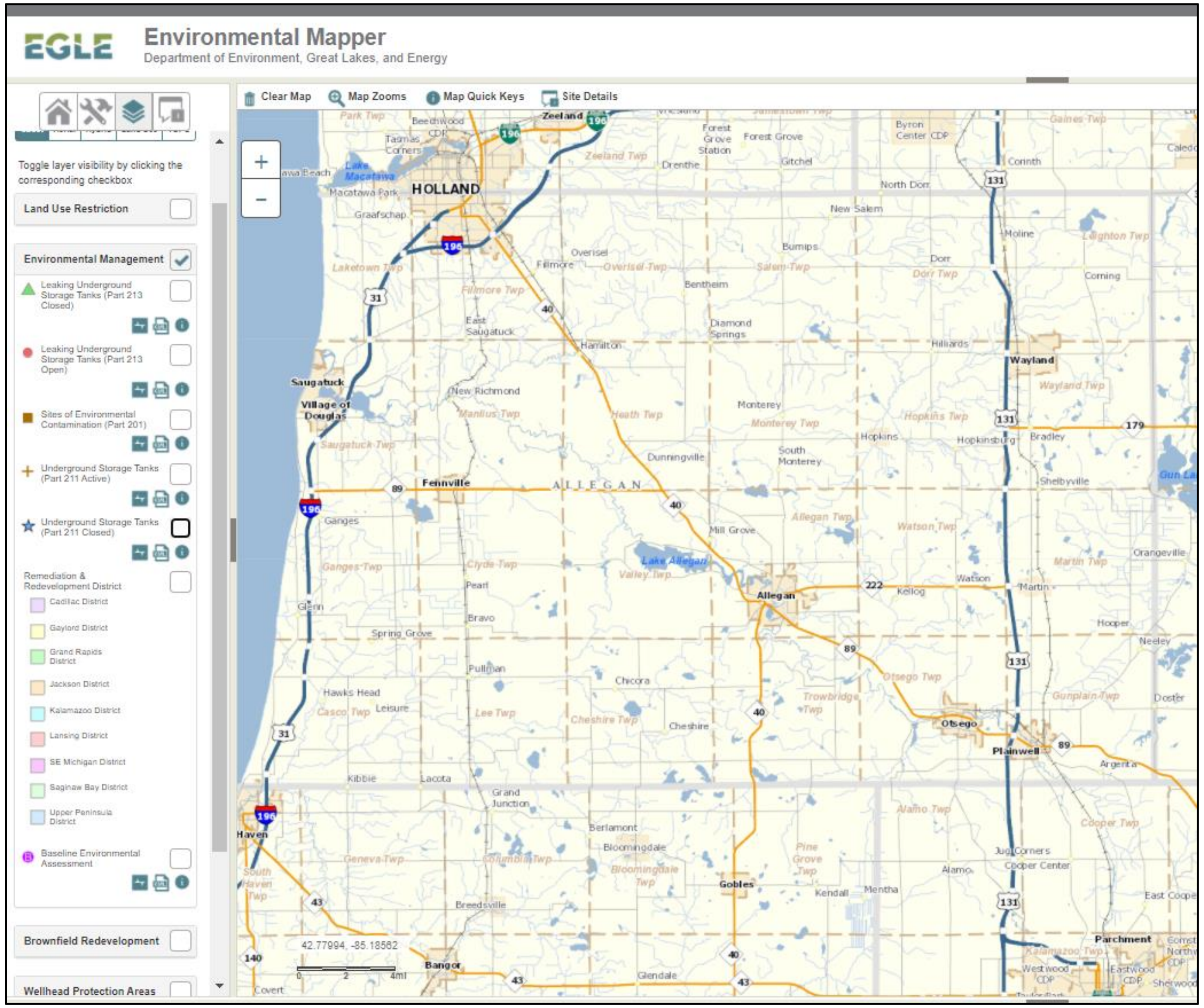
Township/Village	PRIMARY Water Quality Severity Index
Cheshire	**2.54**
Overisel	**1.29**
Martin	**1.25**
Holland City	**1.23**
Hopkins	**1.20**
Watson	**1.15**
Fillmore	**1.12**
Dorr	**1.07**
Leigthon	1.04
Allegan City	0.96
Casco	0.91
Laketown	0.89
Monterey	0.83
Wayland City	0.81
Wayland Twp	0.80
Saugatuck	0.67
Saugatuck City	0.60
Salem	0.55
Clyde Twp.	0.54
Heath	0.50
Otsego	0.50
Ganges	0.43
Allegan	0.41
Gunplain	0.35
Plainwell City	0.23
Valley	0.22
Manlius	0.20
Lee	0.18
Trowbridge	0.17
Douglas City	0.13
Fenvillle City	0.13
Otsego City	0.09

Township/Village	SECONDARY Water Quality Severity Index
Ganges	**6.44**
Holland City	**6.09**
Clyde	**5.83**
Otsego	**5.18**
Valley	**4.73**
Gunplain	**4.73**
Saugatuck	**4.25**
Martin	**4.04**
Hopkins	3.61
Wayland City	3.54
Leigthon	3.31
Fenvillle City	3.31
Casco	2.68
Fillmore	2.52
Dorr	2.29
Wayland Twp	2.06
Cheshire	2.03
Monterey	1.89
Lee	1.89
Salem	1.79
Manlius	1.52
Allegan	1.45
Trowbridge	1.43
Watson	1.41
Allegan City	1.28
Heath	1.16
Laketown	1.15
Otsego City	1.13
Overisel	1.04
Douglas City	0.58
Saugatuck City	0.47
Plainwell City	0.29

Known & Potential Sites of Contamination

Data layers including the locations and attributes of known and potential sites of groundwater contamination in Allegan were downloaded from the Environmental Mapper Tool created and maintained by the Department of Environment, Great Lakes, and Energy (EGLE): [Environmental Mapper (state.mi.us)](). The specific layers used in analysis include: sites of environmental concern; leaky underground storage tanks (LUSTs); underground storage tanks; and historic landfills and waste handlers.

The analysis also includes mapping of PFAS (Perfluoroalkyl and polyfluoroalkyl substances) sites and oil and gas wells (from GWIM database) in Allegan County.



PFAS Sites

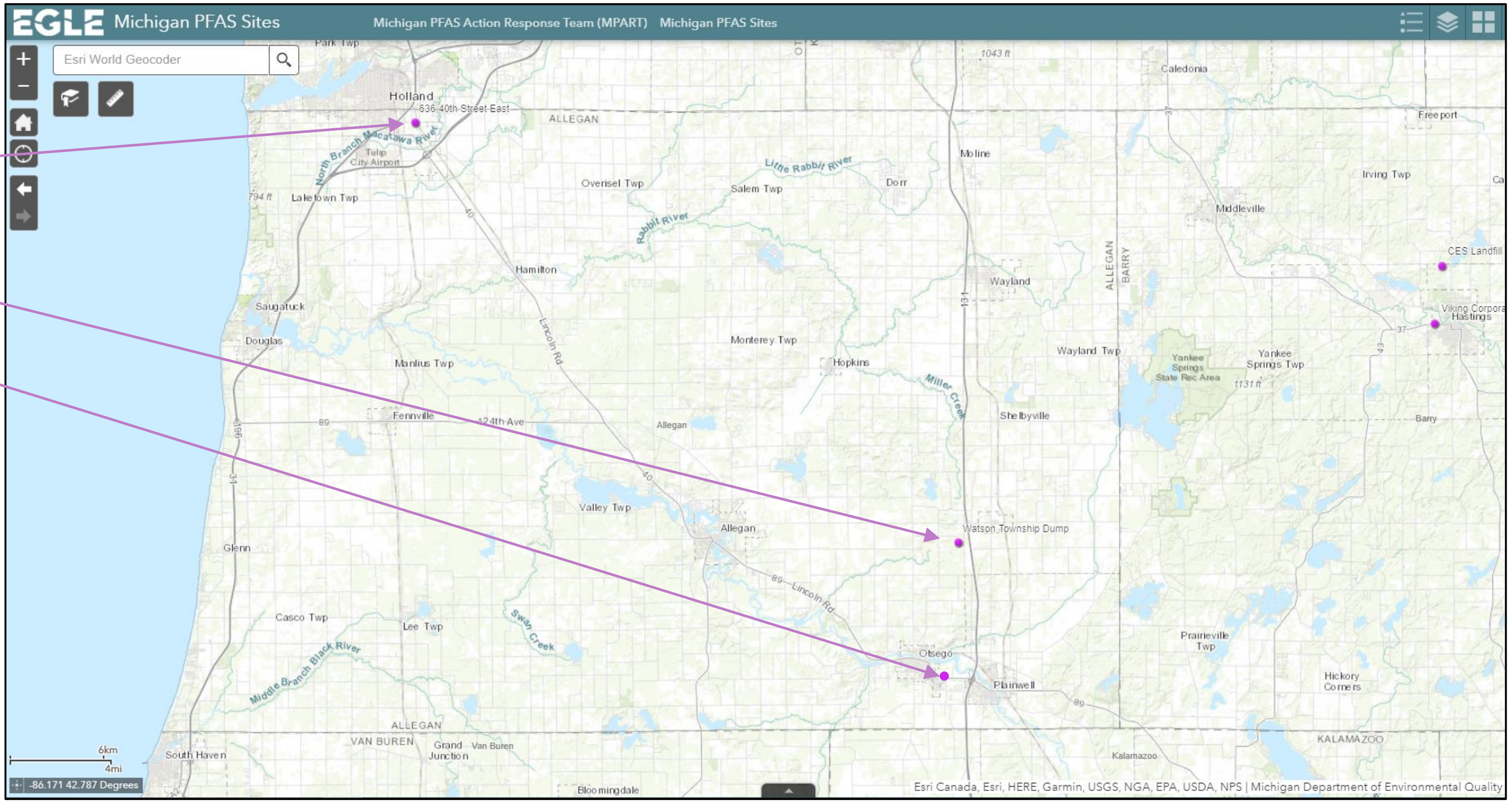
We extracted information on two known PFAS sites in Allegan County from the Michigan EGLE PFAS Sites Web Map:

1 - 636 40th Street East site in Holland

2 – Watson Township Dump in Watson Township.

3 – Greater Otsego area (Hazelwood Subdivision)

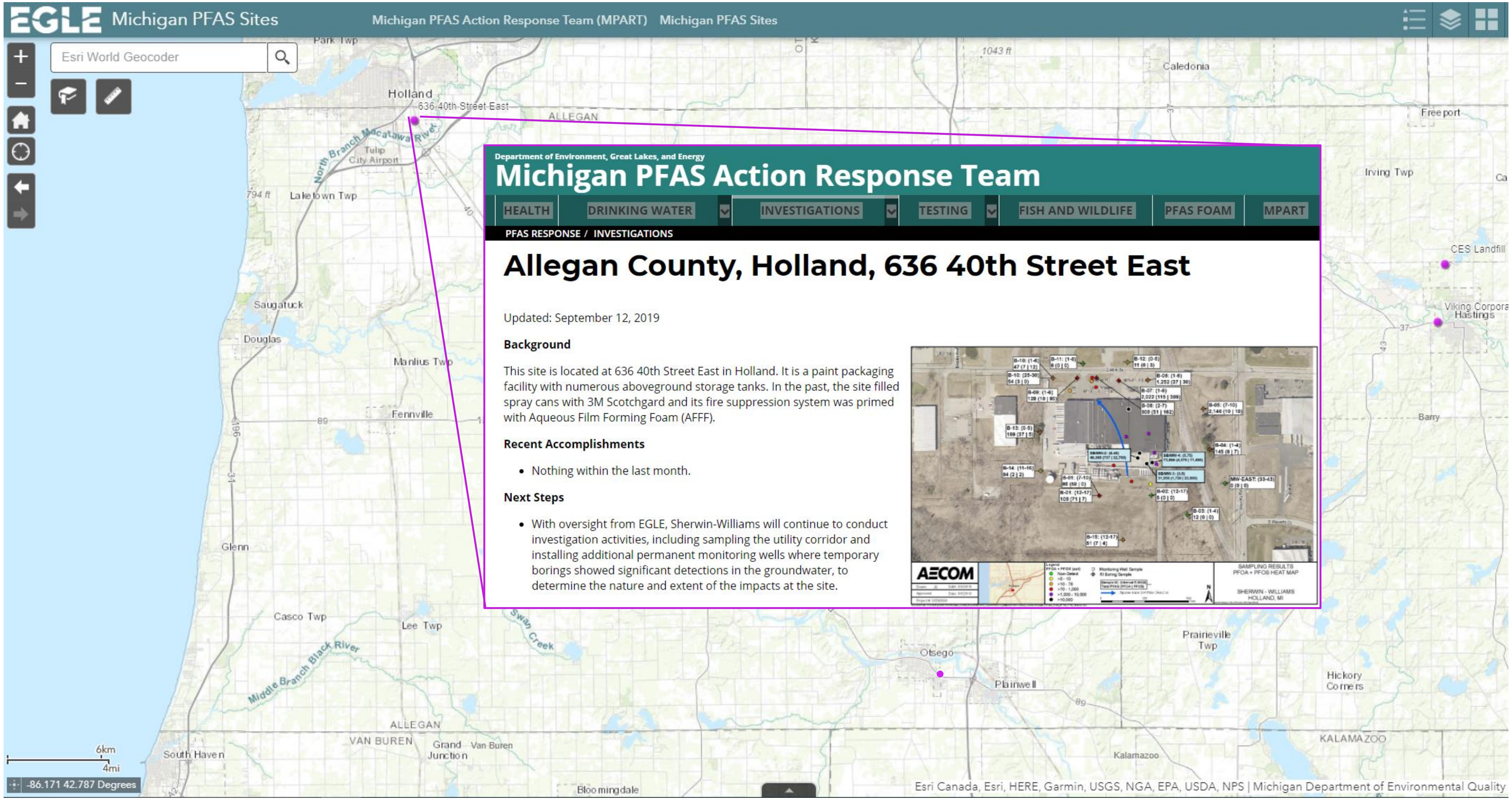
PFAS sites are of particular concern because of their durability in the environment (they are sometimes referred to as "forever chemicals") and the relatively low concentrations in water supply required to have adverse impacts on human health.



PFAS Sites – 636 40th Street East

Full information regarding the 636 40th Street East site can be found at the following link:

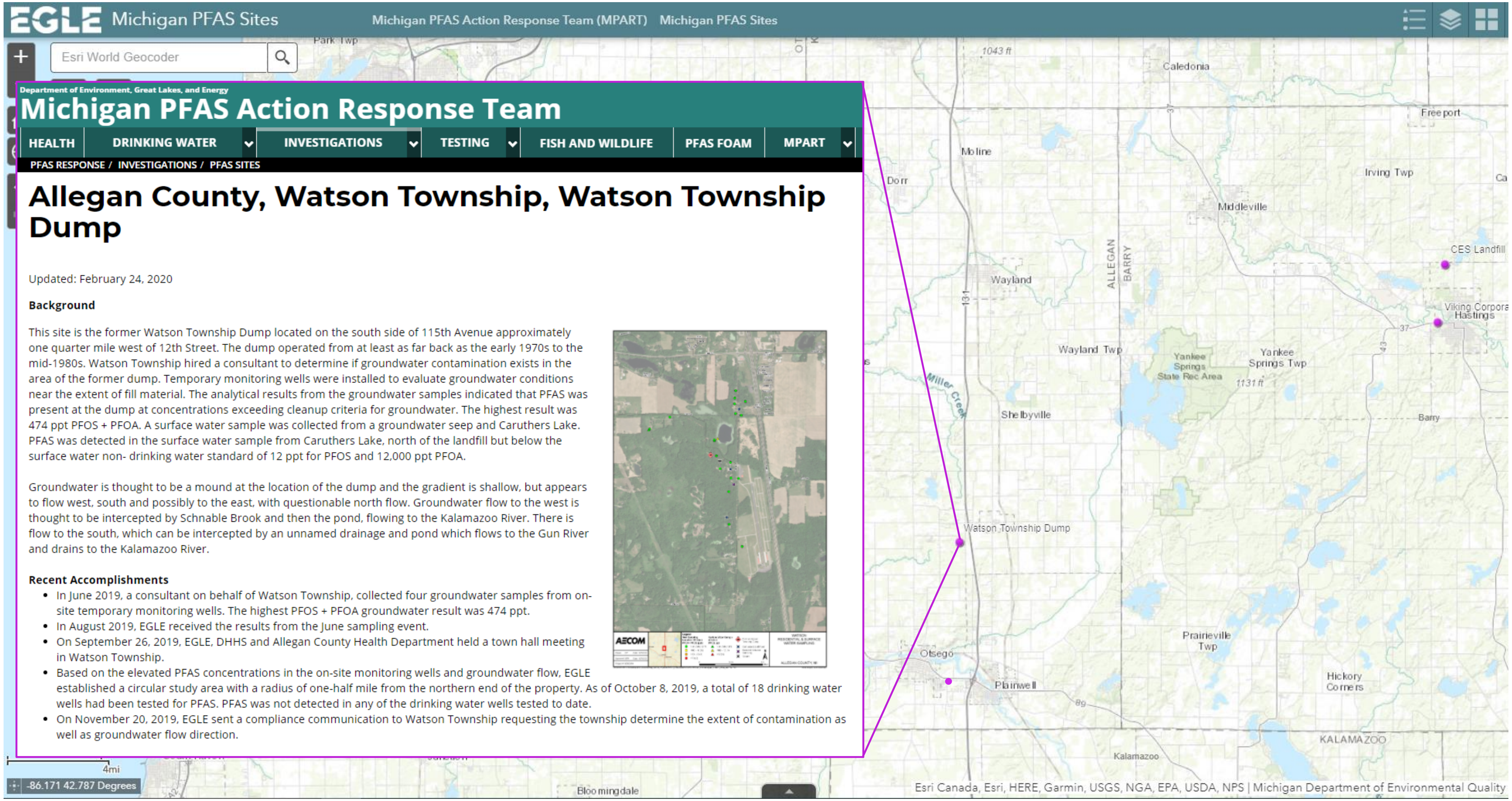
Hyperlink



PFAS Sites – Watson Township Street East

Full information regarding the Watson Township Dump site can be found at the following link:

Hyperlink



Department of Environment, Great Lakes, and Energy

Michigan PFAS Action Response Team

HEALTH | DRINKING WATER | INVESTIGATIONS | TESTING | FISH AND WILDLIFE | PFAS FOAM | MPART

PFAS RESPONSE / INVESTIGATIONS / PFAS SITES

Allegan County, Watson Township, Watson Township Dump

Updated: February 24, 2020

Background

This site is the former Watson Township Dump located on the south side of 115th Avenue approximately one quarter mile west of 12th Street. The dump operated from at least as far back as the early 1970s to the mid-1980s. Watson Township hired a consultant to determine if groundwater contamination exists in the area of the former dump. Temporary monitoring wells were installed to evaluate groundwater conditions near the extent of fill material. The analytical results from the groundwater samples indicated that PFAS was present at the dump at concentrations exceeding cleanup criteria for groundwater. The highest result was 474 ppt PFOS + PFOA. A surface water sample was collected from a groundwater seep and Caruthers Lake. PFAS was detected in the surface water sample from Caruthers Lake, north of the landfill but below the surface water non- drinking water standard of 12 ppt for PFOS and 12,000 ppt PFOA.

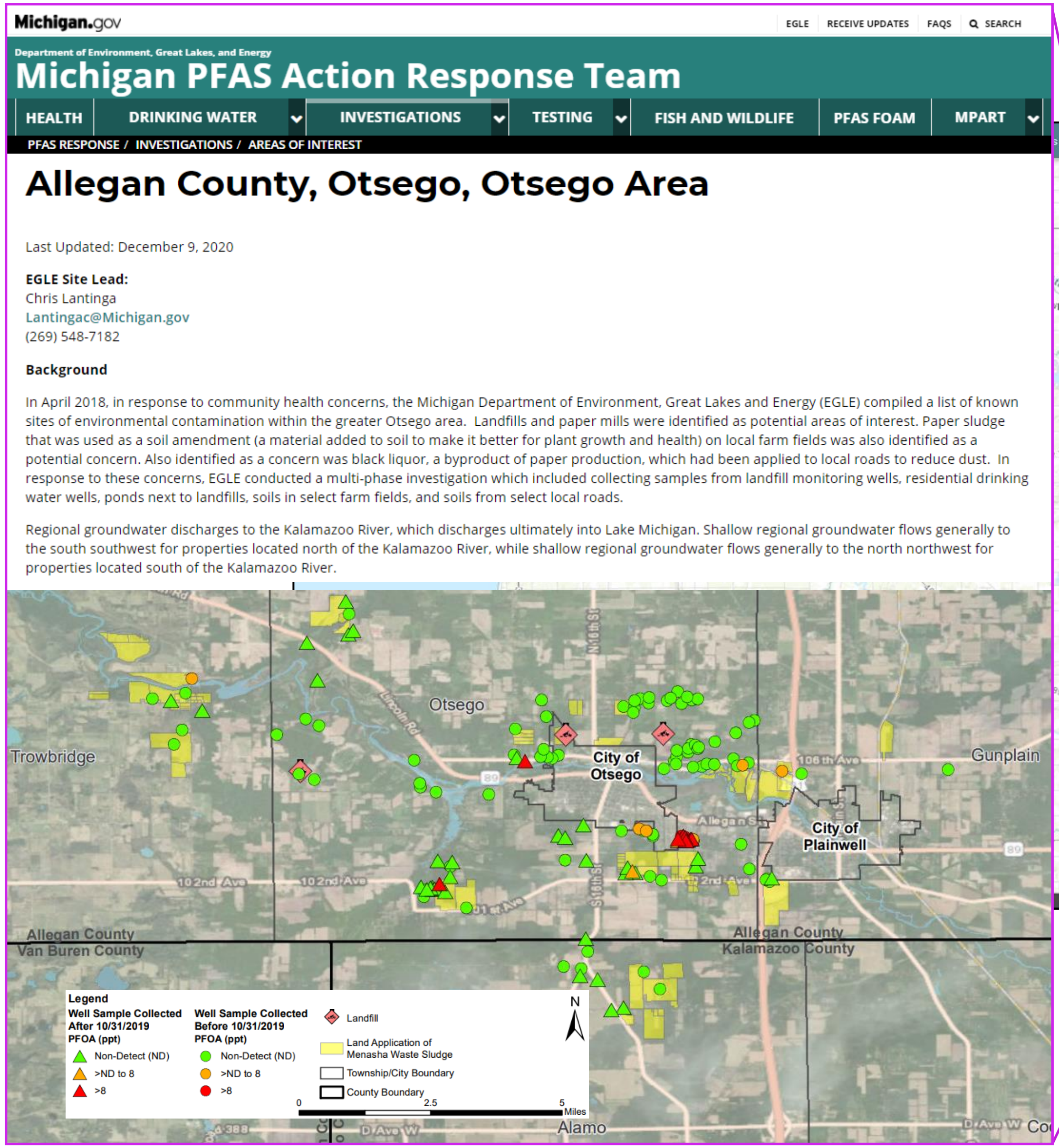
Groundwater is thought to be a mound at the location of the dump and the gradient is shallow, but appears to flow west, south and possibly to the east, with questionable north flow. Groundwater flow to the west is thought to be intercepted by Schnable Brook and then the pond, flowing to the Kalamazoo River. There is flow to the south, which can be intercepted by an unnamed drainage and pond which flows to the Gun River and drains to the Kalamazoo River.

Recent Accomplishments

- In June 2019, a consultant on behalf of Watson Township, collected four groundwater samples from on-site temporary monitoring wells. The highest PFOS + PFOA groundwater result was 474 ppt.
- In August 2019, EGLE received the results from the June sampling event.
- On September 26, 2019, EGLE, DHHS and Allegan County Health Department held a town hall meeting in Watson Township.
- Based on the elevated PFAS concentrations in the on-site monitoring wells and groundwater flow, EGLE established a circular study area with a radius of one-half mile from the northern end of the property. As of October 8, 2019, a total of 18 drinking water wells had been tested for PFAS. PFAS was not detected in any of the drinking water wells tested to date.
- On November 20, 2019, EGLE sent a compliance communication to Watson Township requesting the township determine the extent of contamination as well as groundwater flow direction.

PFAS Sites – Greater Otsego Area

Hyperlink


Michigan.gov
EGLE RECEIVE UPDATES FAQS SEARCH

Department of Environment, Great Lakes, and Energy

Michigan PFAS Action Response Team

HEALTH DRINKING WATER INVESTIGATIONS TESTING FISH AND WILDLIFE PFAS FOAM MPART

PFAS RESPONSE / INVESTIGATIONS / AREAS OF INTEREST

Allegan County, Otsego, Otsego Area

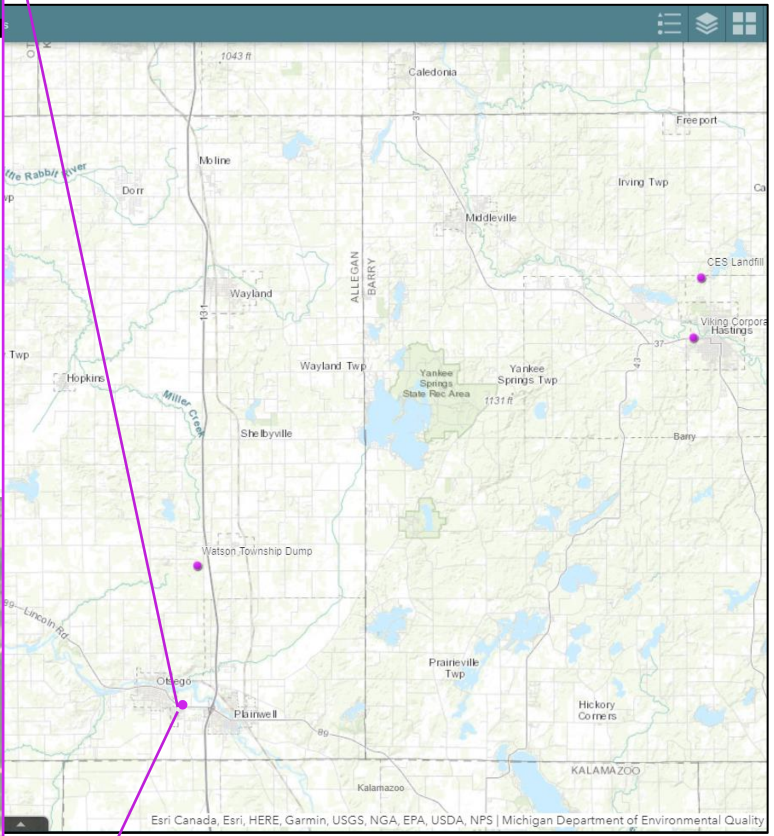
Last Updated: December 9, 2020

EGLE Site Lead:
Chris Lantinga
Lantingac@Michigan.gov
(269) 548-7182

Background

In April 2018, in response to community health concerns, the Michigan Department of Environment, Great Lakes and Energy (EGLE) compiled a list of known sites of environmental contamination within the greater Otsego area. Landfills and paper mills were identified as potential areas of interest. Paper sludge that was used as a soil amendment (a material added to soil to make it better for plant growth and health) on local farm fields was also identified as a potential concern. Also identified as a concern was black liquor, a byproduct of paper production, which had been applied to local roads to reduce dust. In response to these concerns, EGLE conducted a multi-phase investigation which included collecting samples from landfill monitoring wells, residential drinking water wells, ponds next to landfills, soils in select farm fields, and soils from select local roads.

Regional groundwater discharges to the Kalamazoo River, which discharges ultimately into Lake Michigan. Shallow regional groundwater flows generally to the south southwest for properties located north of the Kalamazoo River, while shallow regional groundwater flows generally to the north northwest for properties located south of the Kalamazoo River.



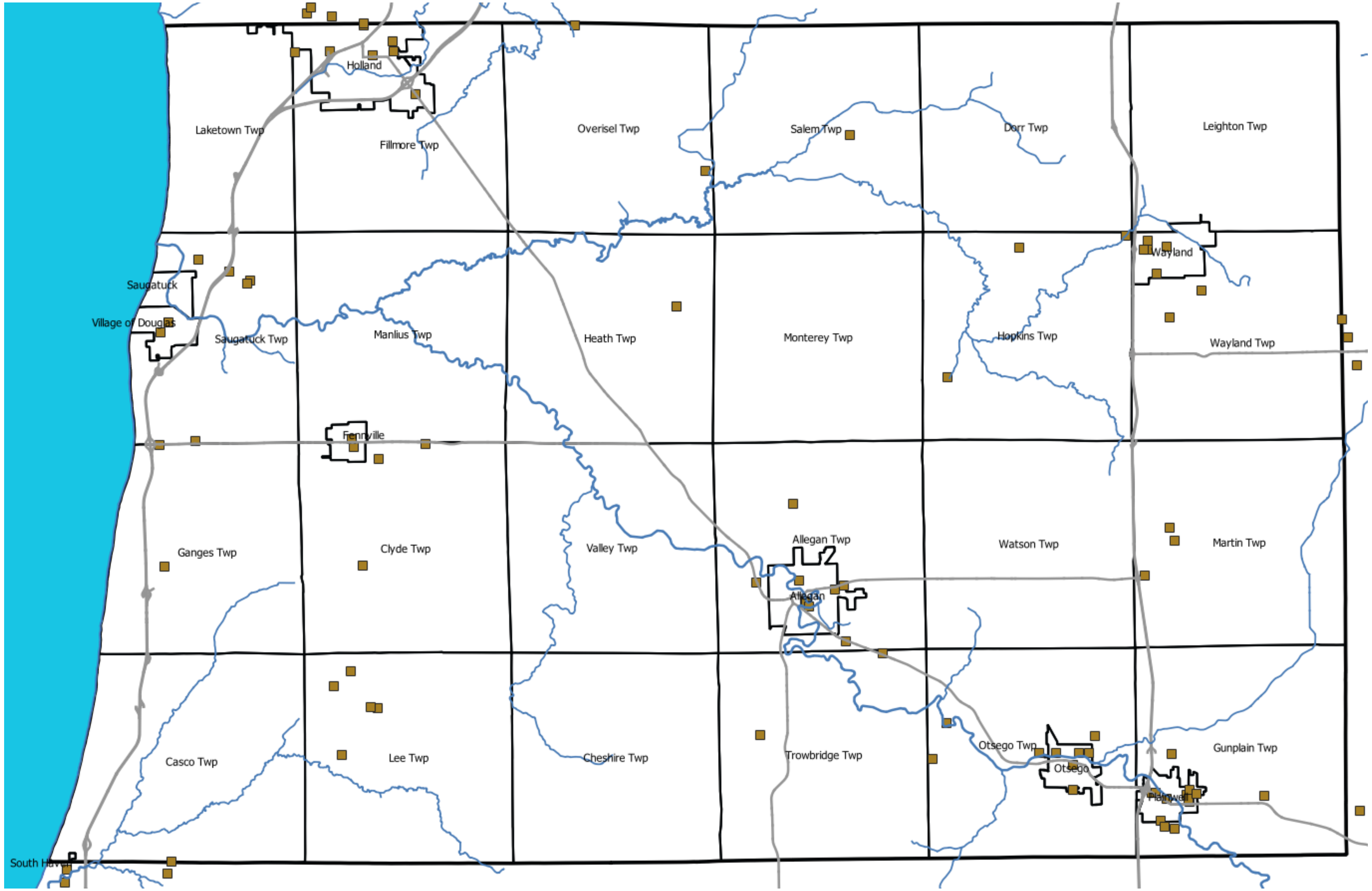
From graphic prepared by the Department of Environment, Great Lakes, and Energy Michigan PFAS Action Response Team

Sites of Environmental Concern

These are sites where environmental damage is suspected or possible based on available information. There are 78 such sites in Allegan County (as of September 2020, when the data were downloaded), primarily located in/near the cities and villages of Allegan County (e.g., Holland City, Allegan City, Otsego City).

Note that the sites are at different stages of management. For example, there status might be “evaluation conducted”, “interim response in progress”, or “risk not determined”.

Additional note from EGLE: “Facilities identified though a Baseline Environmental Assessment are not included and is highly recommended that persons using this information contact the appropriate Remediation and Redevelopment Division District Office for current information regarding known environmental conditions at any property or location.”



Leaky Underground Storages Tanks (LUSTs)

These are sites where leaky underground storage tanks (LUSTs) are known to exist, included "closed" and "open" LUSTs (see below).

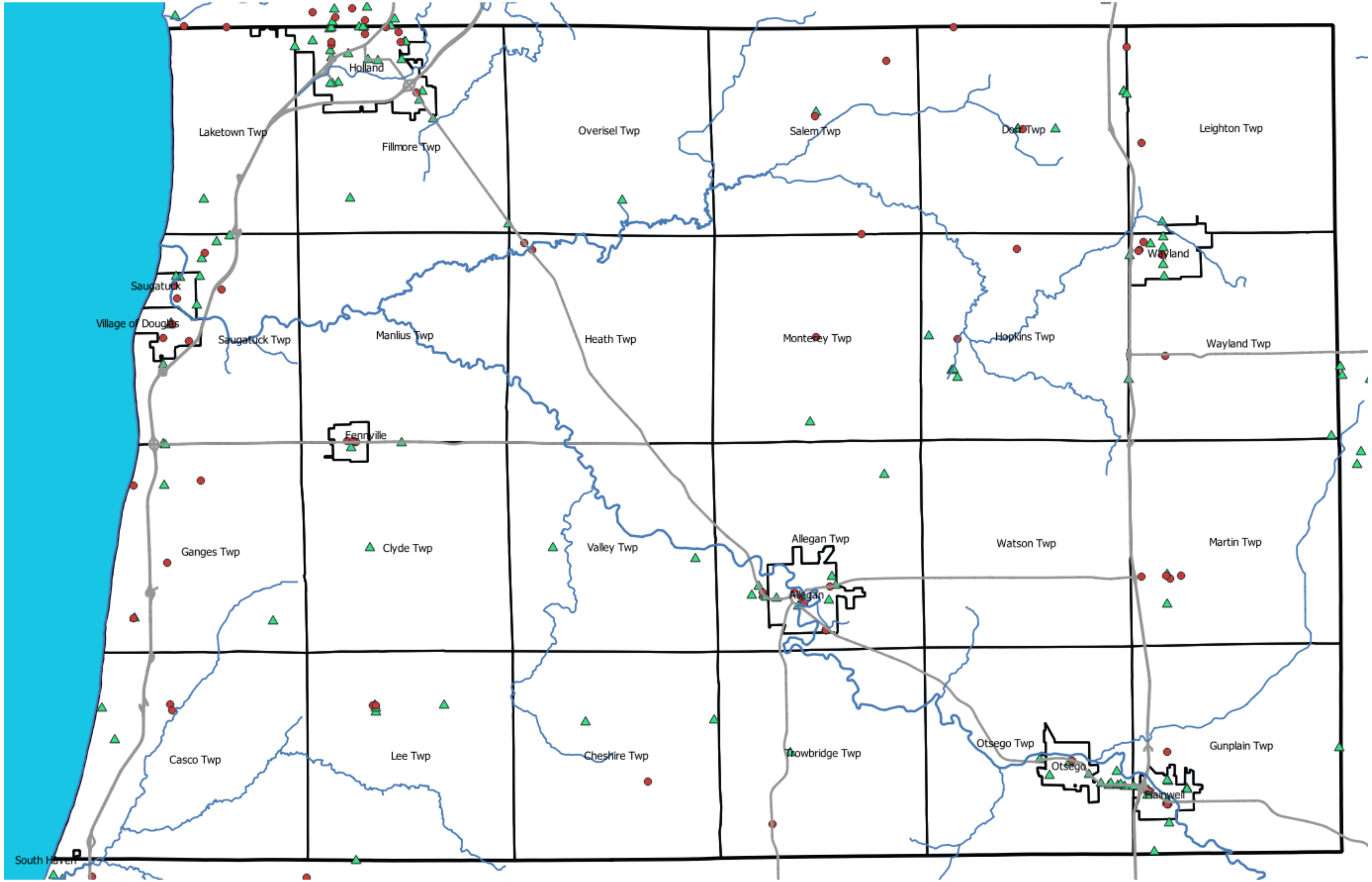
There are a combined 168 LUSTs (61 open and 107 closed) identified in Allegan County at this time.

Closed LUST

"…a location where a release has occurred from an underground storage tank system, and where corrective actions have been completed to meet the appropriate land use criteria. The MDEQ may or may not have reviewed and concurred with the conclusion that the corrective actions described in a closure report meet criteria."

Open LUST

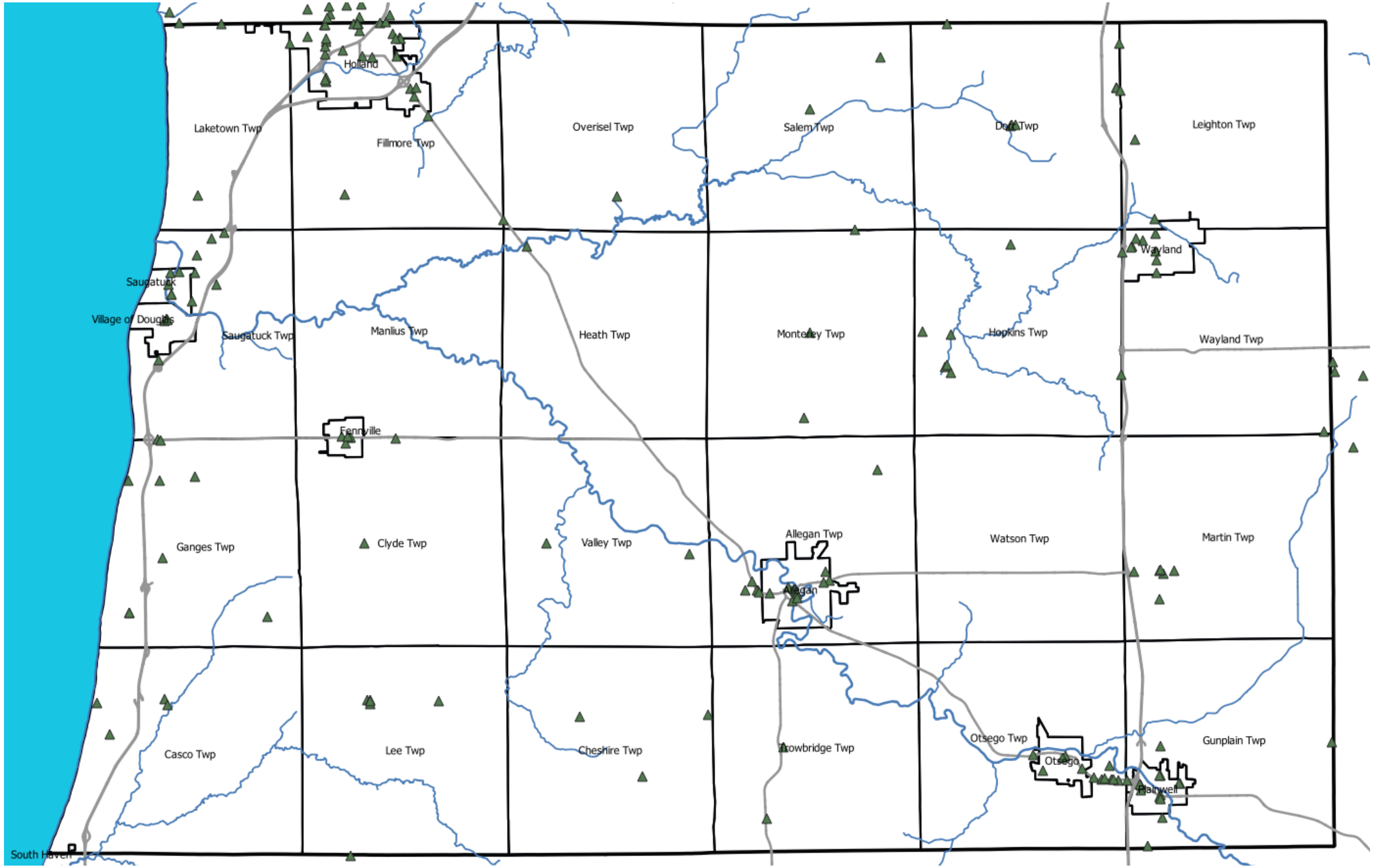
"…a location where a release has occurred from an underground storage tank system regulated under Part 213, and where corrective actions have not been completed to meet the appropriate land use criteria. An OPEN LUST site may have more than one confirmed release."



Underground Storages Tanks (USTs)

These are sites where there is at least one tank at the facility that is not closed in place or removed. There may be closed tanks or active non-regulated tanks (such as heating oil tanks) present at these sites.

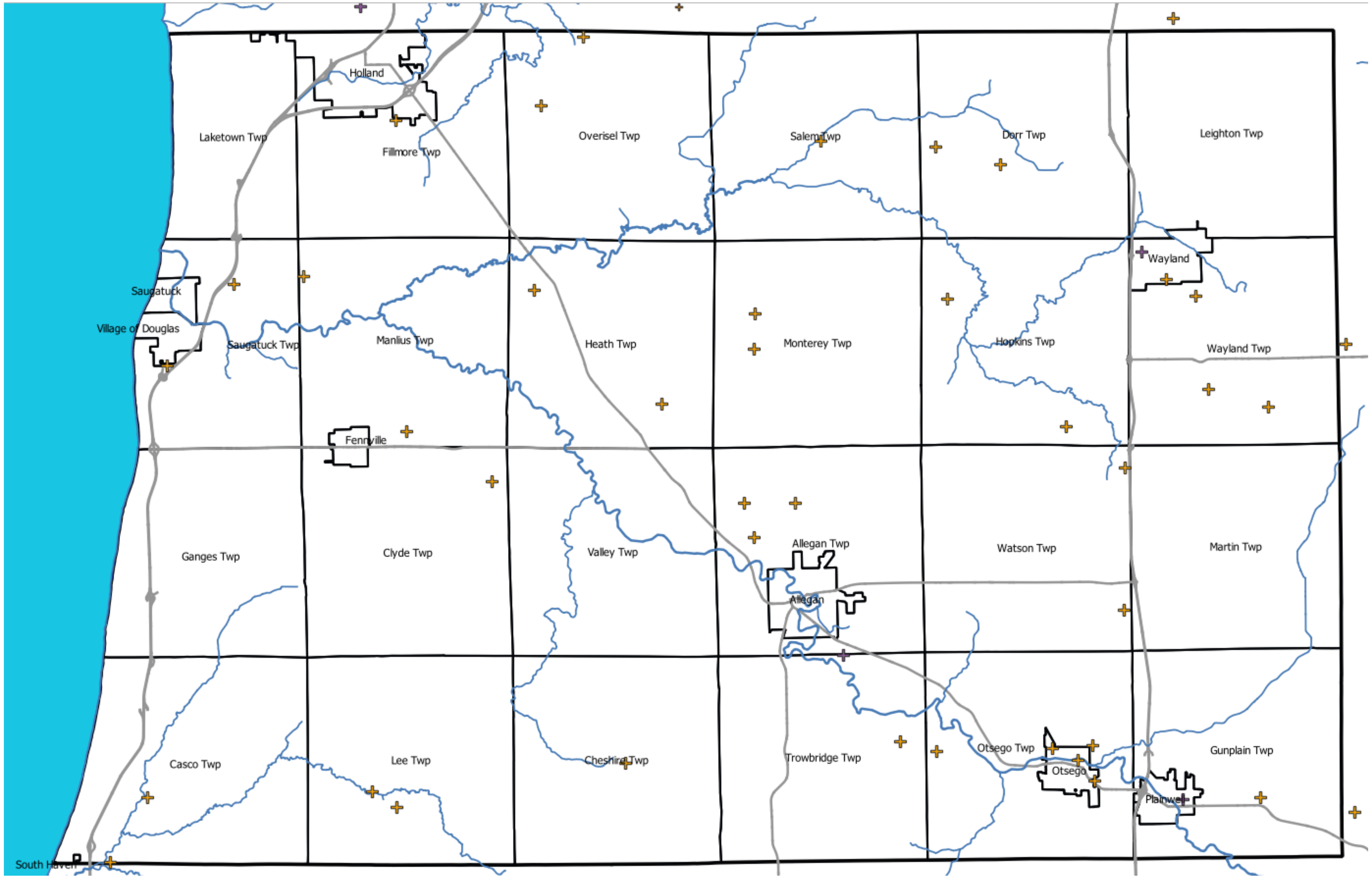
There are 165 USTs identified in Allegan County at this time.



Historical Landfills and Waste Handlers

These are the locations of historic landfills and waste handlers in Allegan County that are included in the statewide dataset. These facilities may pose a risk to groundwater contamination from leachate of waste products stored on site depending on the pollution prevention and control protocols being used.

Thirty-eight historical landfills and three waste handler facilities were identified in Allegan County at this time.



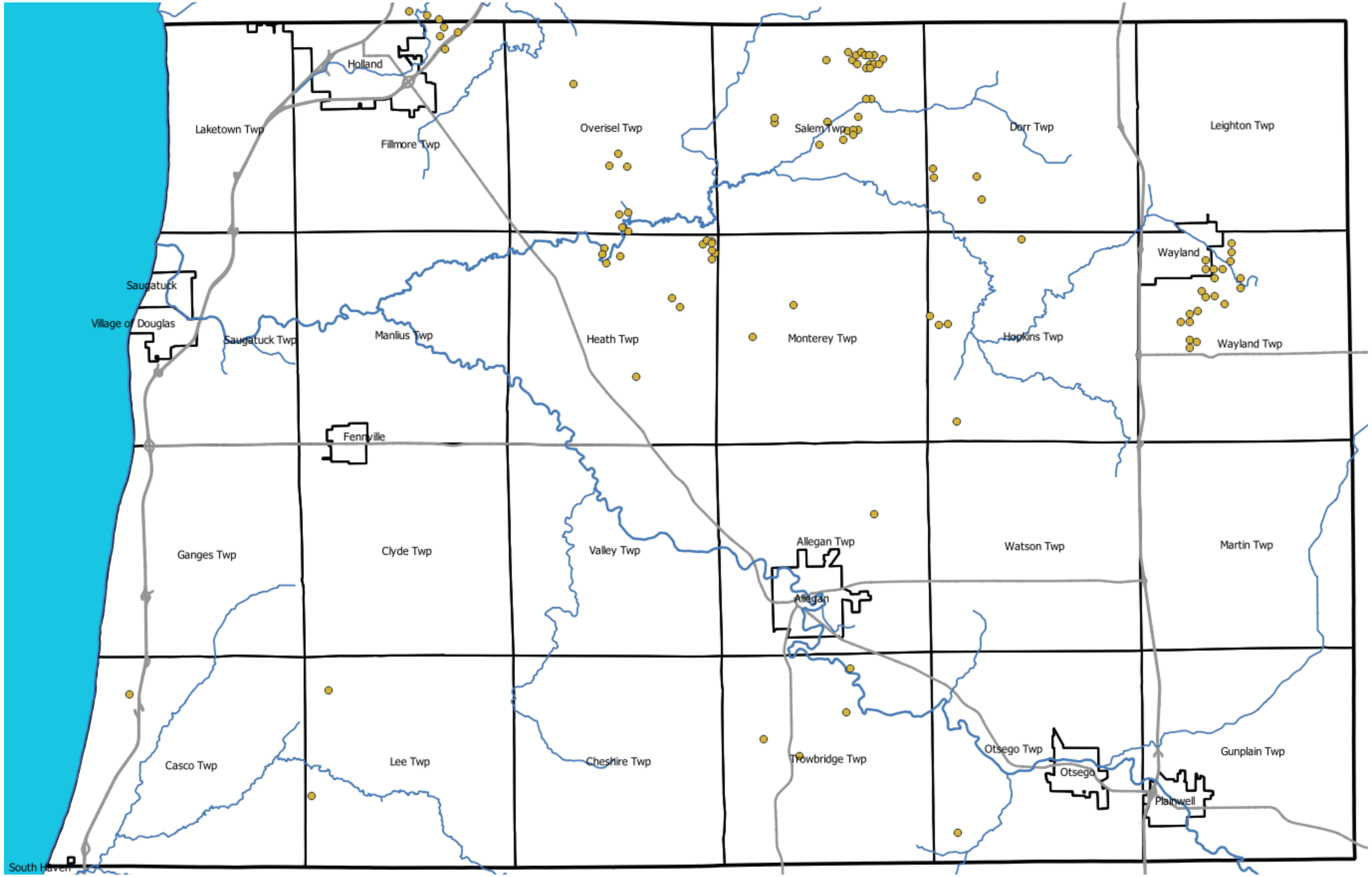
Landfill

Waste Handler

Oil and Gas Wells

These are the locations of oil and gas wells in Allegan County. Leaky / fractured wells or poor well closure practices associated with early oil and gas wells may provide a vertical conduit for flow of deeper, highly mineralized groundwater to the near-surface environment.

Ninety-four oil/gas wells were identified in Allegan County at this time.



Recommendation for Future Work

A traditional report can only go this far; no matter how many graphics are included in this summary and in the main report, we cannot exhaust all possibilities. The best, most cost-effective way to use the data, maps, and visualizations presented in this study is to develop a unified groundwater information system for Allegan County.

This interactive, web-based decision support system can be used to guide water resources planning and permitting processes within agencies of Allegan County, the Townships, and others. This final product is unique in the sense that it empowers the county for years to come, making it possible for the county itself to evaluate scenarios and weigh different management options.

This decision support system (DSS) will enable resource managers and planners to zoom into any location in the county to:

- Visualize the complex 3D geology of the subsurface, including the borehole lithologies and the results from the 3D transition probability geology model;
- Map groundwater level distributions, flow directions and patterns in both the shallow glacial aquifer and, where applicable, the deeper bedrock aquifer;
- Map the cone of depression (water level decline due to pumping) for existing or new wells under different scenarios, and evaluate the impacts on surrounding land parcels;
- Assess vulnerability of a proposed development to insufficient water supply by mapping / analyzing sustainable yield;
- Map environmental receptors and their contributing source water areas / capture zones / "groundwater-sheds" for pumping wells and groundwater-fed streams and wetlands, which is critical for holistic management of aquifer protection, wellhead protection and ecosystem protection;
- Map land use, nonpoint source contamination, and contamination sites, and interactively and dynamically access site information / attributes like address, chemical type (for a contamination site);
- Delineate potential impact areas of emerging contaminants (e.g., PFAS), or trace back from known sites of contamination to identify potential sources;
- Map aquifer recharge areas and discharge areas to assess aquifer vulnerability (or sensitivity) to surface contamination or saline upwelling, respectively;
- Design long-term monitoring well networks for sampling water quantity (levels, fluxes) and water quality, especially in stressed areas identified in this Phase 1 study; and
- Create 2D and 3D integrated overlays of raw, derived, and simulated data layers.

Recommendation for Future Work (Cont’d)

The integrated system will enable the informed participation of citizens and improve interactions between local government, their constituents, researchers, and consultants, bringing the following benefits to the stakeholders:

- Resource managers and planners will be able to evaluate the effectiveness and impact of their management plans to improve policy-making decisions. They can visually evaluate the impact of potential threats, land use, contamination, and withdrawals. They can become more effective in identifying/prioritizing areas for monitoring, development, conservation, or protection. They can also be more effective in engaging the general public and informing high-level decision makers about the implications of a proposed development and the transport of contamination on sensitive receptors (e.g., drinking water wells, residential areas, groundwater dependent ecosystems).
- Communities and stakeholders will be able to visualize the invisible subsurface and better understand the impact of proposed management measures in a vivid and interactive way. They can also visualize the potential impact of their own activities on the groundwater environment. Thus, they are motivated and empowered to engage in the intricate process of community-based ecosystem and water/land use management, planning, and protection.
- Consultants will be able to design more focused, cost effective analysis and monitoring networks to protect county’s water resources and environment (ecosystems, recharge areas, etc.). They also will have an effective mechanism to communicate a solution, a design, or strategy to their clients.
- Policymakers can make more informed decisions with regard to setting and enforcing laws and regulations for water resources management and to use interactive tool to improve public relations and to evaluate future land use management plans related to zoning and new developments.

A DSS allows the county to use the results “dynamically”. The seamless integration of modeling results, data from disparate sources, management analyses, and interactive visual communication will make it possible for resource managers and planners to focus on high level issues and to quickly and iteratively refine management strategies and policies

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