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ALLEGAN COUNTY GROUNDWATER STUDY

Phase 1 – Understanding the Big Picture

"Story" of Allegan County's Groundwater

With a Focus on Management Implications

March 22, 2021

Report No.: HSA2021001

Development, Population Growth, and Increased Water Use

Allegan County is undergoing a period of growth and development that started decades ago and has continued in recent years. Increased agricultural activities and above-average population growth (with respect to statewide and nationwide averages - see Figure 1) has resulted in water use increases across the county. To effectively protect and manage the long-term sustainability of the county's water resources, a holistic understanding of the county's "water system" is needed.

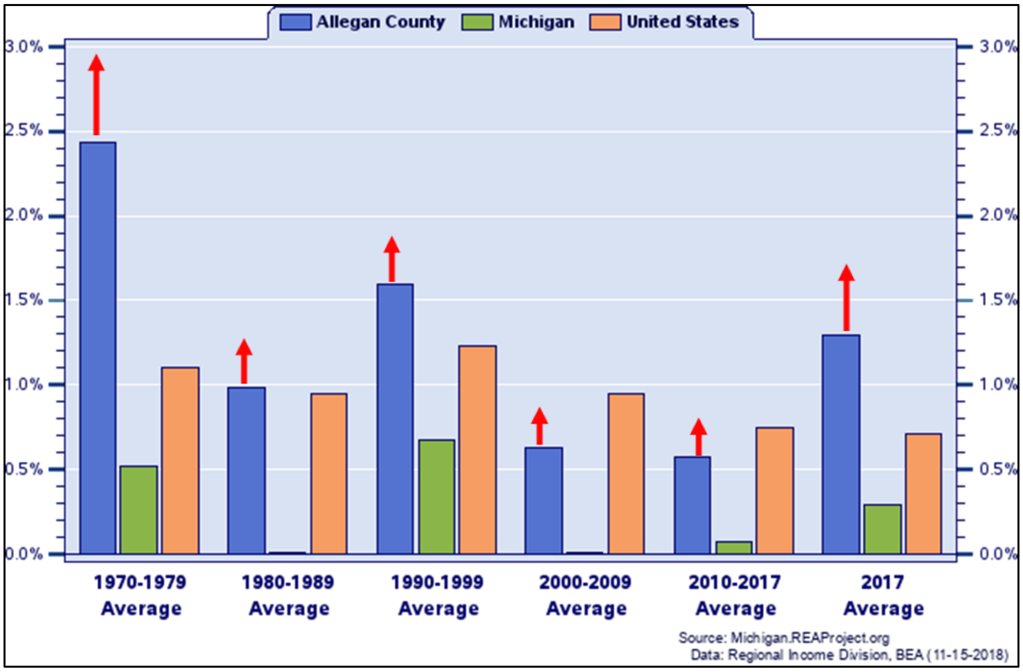

Figure 1: Average population growth by decade in Allegan County, State of Michigan, and the United States. In some decades, the growth rate in Allegan County was significantly higher than the statewide and/or nationwide averages. The above-average population growth in Allegan county, coupled with increased agricultural activities, has increased groundwater use in the county.

Source of Water: Groundwater

Presently (and historically), almost all the water supply in Allegan County is from groundwater, used for: households / private drinking water; year-round public water supply (Type I wells); transient and non-transient community water supply (Type II wells); irrigation, and industry (including power generation). Holistic management of the county's groundwater resources is especially important, considering that the subsurface is 'invisible' (or often deemed mysterious) and actions and events impacting groundwater (quantity and quality) are delayed and cumulative in nature.

Groundwater in Allegan County is pumped from two aquifers: a shallow "glacial" aquifer, and a deep "bedrock" aquifer. The glacial aquifer consists of unconsolidated sediments left behind from multiple episodes of glacial advance and retreat. The glacial aquifer exists throughout the county, ranging in thickness from 25ft to 470ft. The bedrock aquifer consists of the fractured / semi-fractured portions of the Marshall Sandstone Formation occupying the northeastern portion of the county. The rest of the county is underlain by the low permeability Coldwater Shale Formation (see Figure 2). The Marshall

Formation generally pinches out along its western subcrop extent, increasing in thickness in the east-northeast direction. See slides 11-13 in the main report for complete details.

Water wells are found throughout all townships, cities and villages in Allegan County. A vast majority of the water wells in Allegan County are completed in the glacial aquifer: as of August 2020, 88% of the wells in the *Wellogic* water well database were confirmed as "glacial wells" (13354 out of 15114 total wells). Only 1095 (or 7%) of the wells were confirmed as "bedrock wells". The remaining wells lack sufficient information to make a distinction.

Most wells in Allegan county are used for domestic water supply; as of August 2020, 86% of the wells in *Wellogic* were classified as "household wells" (13050 out of 15144 total wells) – see Figure 3. Roughly 6% (896 wells) were classified as public supply wells); 3.4% (521) as irrigation wells; and 0.3% (42) as industrial wells. See slide 60 in the main report for complete details.

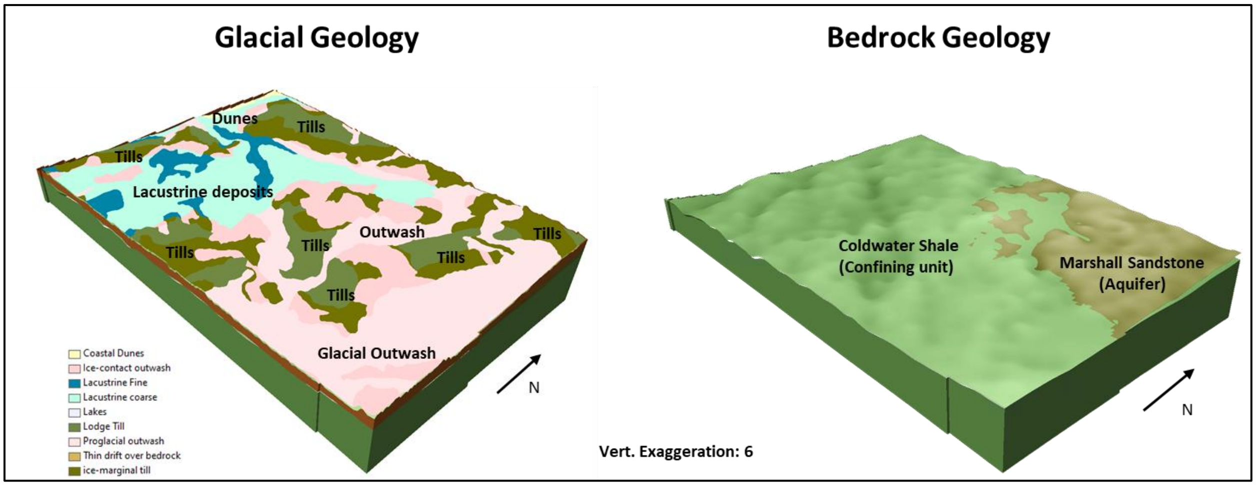

Figure 2: 3D depiction of the large-scale glacial geology (shallow) and bedrock geology (deep). Most water wells in the county are screened in the glacial aquifer, which is extremely heterogeneous, both vertically and horizontally. Wells completed in the bedrock are generally limited to the central and northeast portion of the county where the Marshall Sandstone Formation (aquifer or marginal aquifer) subcrops.

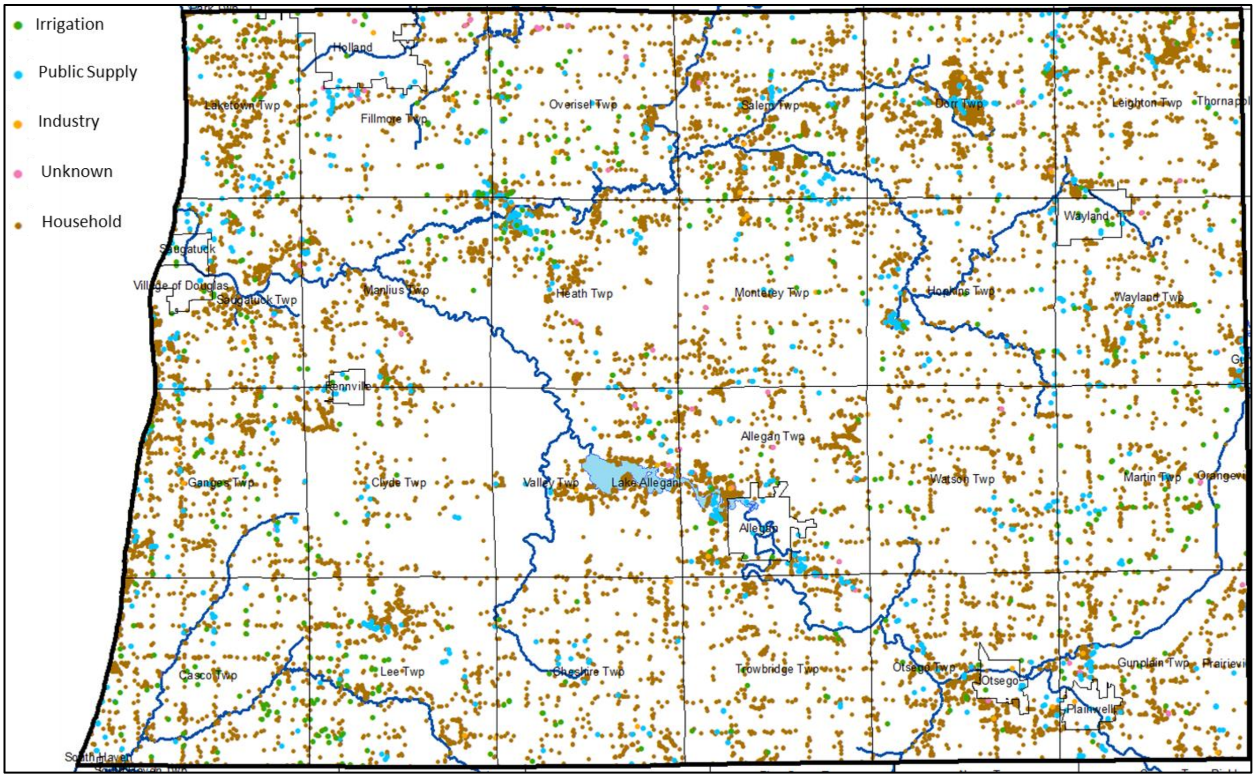

Figure 3: Water wells in Allegan County as of August 2020, by water sector: irrigation, public supply, industry, household, or unknown. Most wells in Allegan County are used for domestic water supply. When many household wells are operating in close proximity, the cumulative impacts of pumping can mirror high-capacity wells used for irrigation, public supply, and/or industry.

Increased Groundwater Use

Spatial and temporal analysis of *Wellogic* well records indicates significant increases in groundwater use in past decades, especially the last two (1999-2009, and 2010-2020). Up to 2000, six hundred and thirty-one wells were reported. By 2020, nearly 9000 more wells were added, and by August 2020, a total of 15144 wells were reported to the Wellogic system (see Figure 4)[1]. See slides 55-56 in the main report.

Groundwater use has increased in virtually all townships of the county, but most significantly in the "outer" townships along the periphery of the county, particularly in Ganges, Casco, Lee, Salem, and Dorr townships (see Figure 5). Not surprisingly, some of these water use "hot-spots" occur in sections inside / near population centers (because many residential 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. See slides 61-65 in the main report for complete details.

[1] 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., drift vs. bedrock wells, or domestic vs. irrigation) is accurate based on our analysis in other parts of the state.

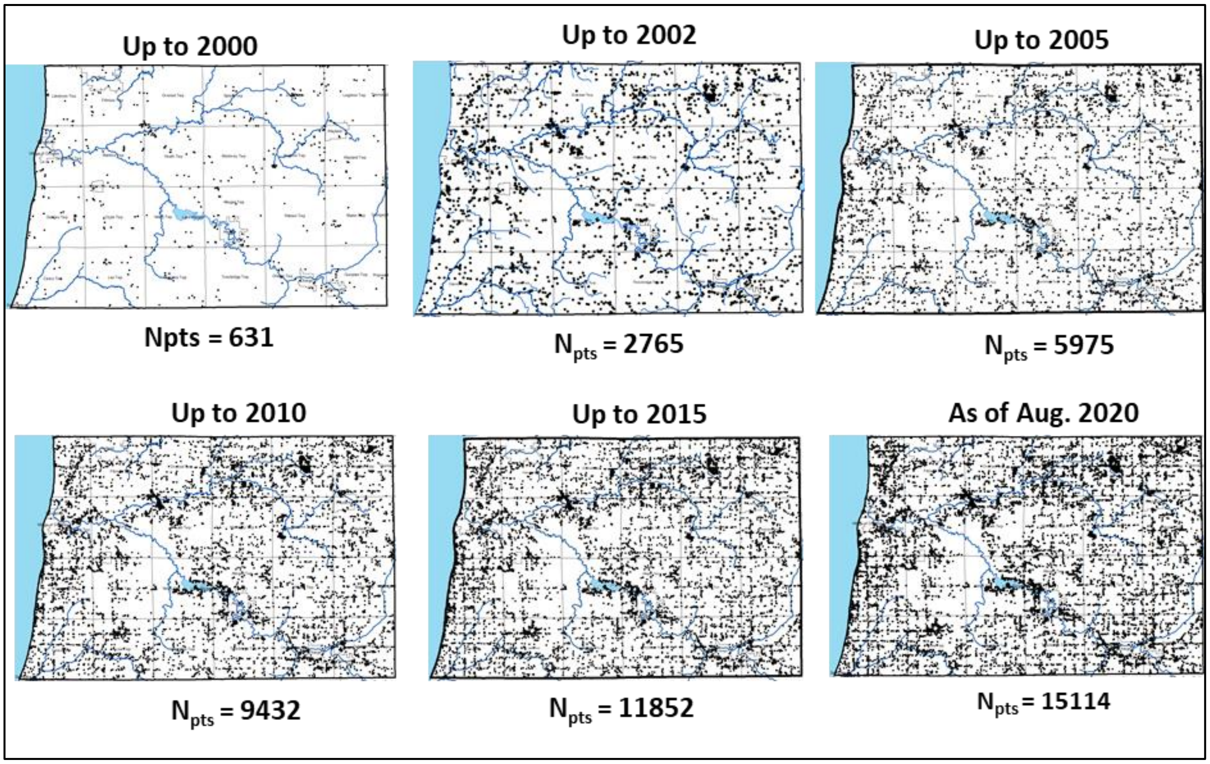

Figure 4: Water well network growth over the past two decades. There has been steady and significant growth in the water well network throughout virtually all parts of the county (west-central Allegan County is a notable exception). This natural, unmanaged growth is beginning to stress the groundwater system, both in terms of water quality, but also water quantity (water levels). Future development will benefit from coordinated management between local and county levels of governance, and from information gathered / visualized / analyzed in this study.

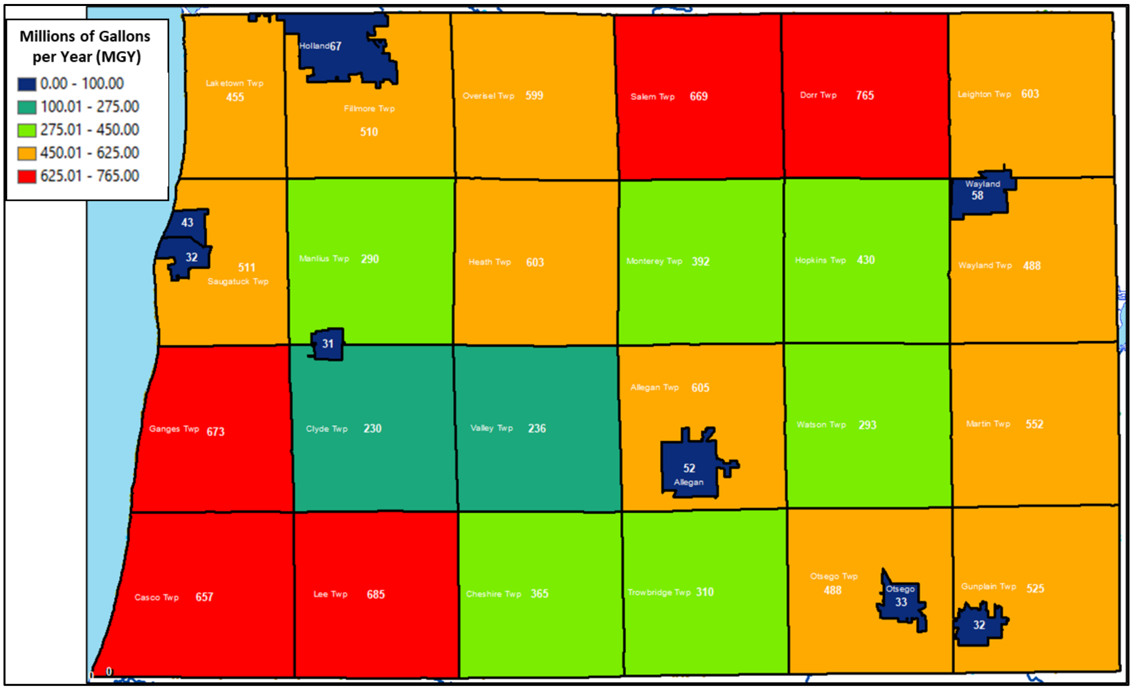

Figure 5: Screening-level estimate of annual groundwater use, by township, for present day (as of August 2020). Each township includes a name label, and the number representing the estimated annual water use in millions of gallons per year (MGY). The townships estimated to be using the most groundwater 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). Note that these values are screening-level or "ballpark" estimates.

3D Heterogeneity of the Subsurface

One major challenge to understand / manage groundwater is the heterogeneity of the subsurface environment in which it occurs. Although the bedrock aquifer (Marshall Sandstone Formation) is relatively homogenous (similar geology across space)[2], the glacial aquifer is extremely heterogeneous, both vertically and horizontally (see Figure 6). Some parts of the glacial aquifer are very permeable (e.g., areas consisting of glacial outwash and coarse-grained lake sediments), while other parts are less permeable (e.g. where glacial tills and fine-grained lake sediments are found). See slide 12 and slides 14-28 in the main report for 3D visualizations and 2D cross-sections of borehole lithologies.

[2] The bedrock aquifer along the Marshall-Coldwater Shale interface is fairly complex, "islands" of the Marshall Sandstone Formation surrounded by confining materials and vice versa shown in Figure 2. The islands are most likely the result of erosion of the Marshall Sandstone Formation along its thin margins.

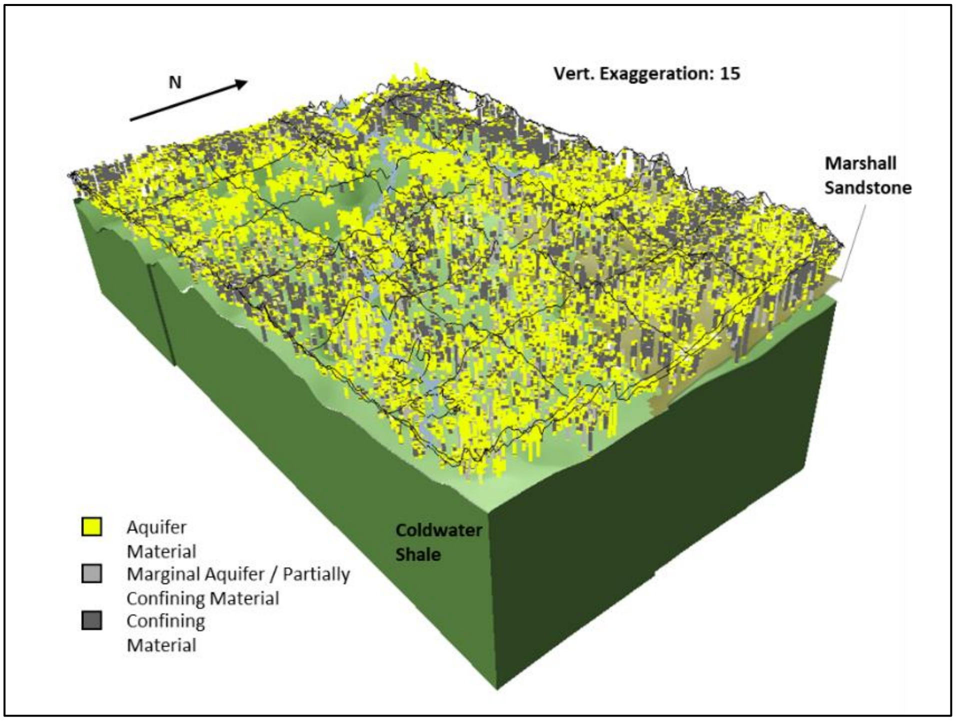

Figure 6: 3D depiction of categorized water well borehole lithologies across the county. These data are extremely valuable – they are free (previously collected) and available "everywhere" with excellent spatial density. Interactive 3D visualizations from different perspectives and 2D cross-sections can be used to estimate aquifer and aquitard extents (both horizontally and vertically) without performing modeling/simulation.

3D Geological Model

A 3D model of the glacial aquifer heterogeneity was created using an advanced geostatistical approach (transition probability) based on more than 10,000 wells in the *Wellogic* dataset. In the resulting 3D model, each cell is assigned as one of the four following material types: aquifer material [AQ], marginal aquifer material [MAQ], partially confining material [PCM], and confining material [CM].

The model shows (see Figure 7): in some areas, there are relatively extensive/continuous shallow fine-grain tills (CM and PCM) underlain by coarser-grained materials (AQ and MAQ), or aquifer "pockets"; in the northeast, many wells pierce through the less permeable clays/silts (CM) to withdraw water from the Marshall Sandstone aquifer (AQ / MAQ); in other areas, more permeable materials (AQ, MAQ) are typically found near the surface; and in the low land areas, extensive, continuous lacustrine deposits are found where it is common to have continuous shallow sand deposits (AQ /MAQ) underlain by clays/silts (CM / PCM). In short, there are no "perfectly stratified" geologic layers as described in many standard text books. See slides 30-34 in the main report for representative cross-sections of the 3D geology model.

The ability to characterize such heterogeneity is extremely useful, in terms of water resources development and well siting (i.e., determining where to drill and at what depth), protection of strongly connected streams and groundwater-dependent ecosystems, and prediction of contaminant transport needed for pollution control. But the complexity / important heterogeneity cannot be exhaustively presented in a written report. Rather, the 3D model is best used in a dynamic Decision-Support System

(DSS) that allows users zoom in anywhere, at any depth, to find out the likely geological materials (graphically, descriptively, and interactively).

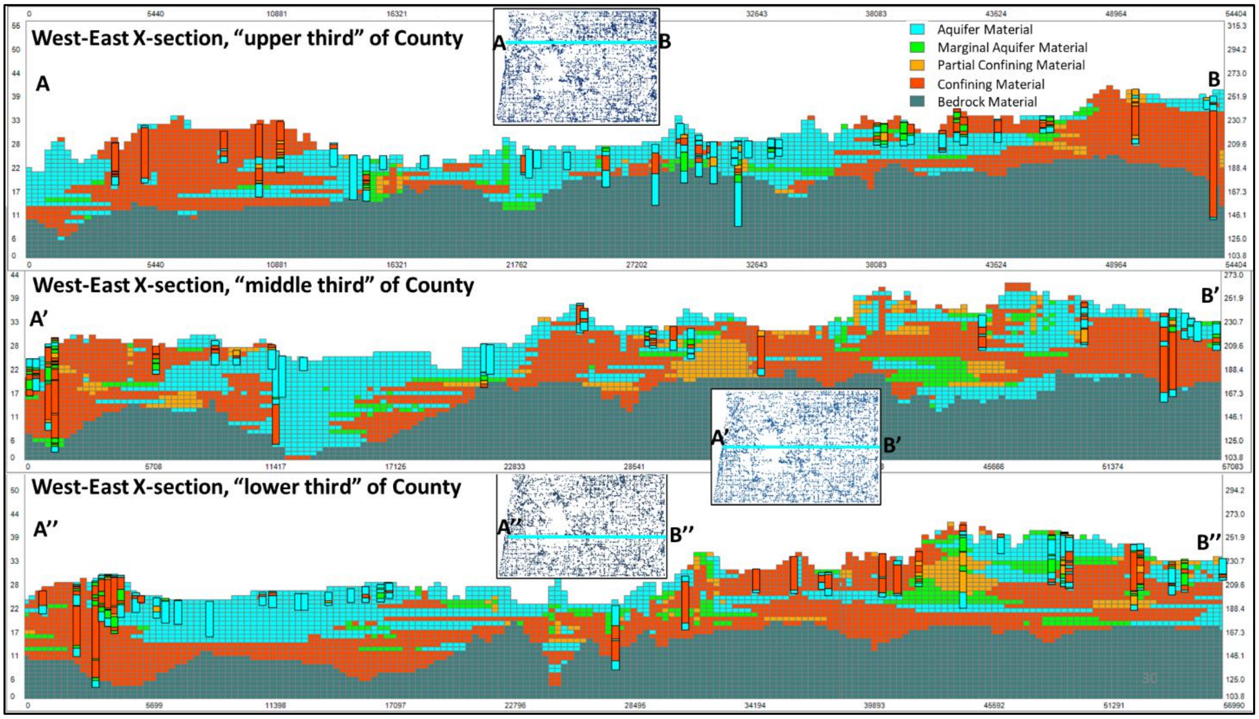

Figure 7: Cross-sections from the 3D geological model, with categorized boreholes. Red cells / borehole intervals represent confining materials; orange is partially confining material; green is marginal aquifer material; and blue is aquifer material. The bedrock is shown as a continuous grey bottom surface. Note that the glacial aquifer is complex and heterogeneous – both aquifer and non-aquifer (confining) material exhibits strong spatial persistence, but there are no “perfect layers”.

Hydraulic Conductivity and Transmissivity

An understanding of the geologic spatial variability can yield insights to spatial changes in hydraulic properties of the subsurface (i.e., how fast water moves, how much water can be pumped, etc.). Hydraulic conductivity (K) quantifies how permeable different sediments are – it is a fundamental property of geologic materials that controls how fast groundwater moves, when combined with knowledge of the water table or head gradients.

In Allegan County, zones of high K in the glacial aquifer 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.) – see Figure 8. Zones of low permeability are found in the southwestern portions (i.e., parts of Casco and Lee Twp., parts of Ganges and Clyde Twps.) and western portions (parts of Saugatuck, Manlius, and Valley Twps.) of the county. See slide 38 in the main report for more details.

The product of K and aquifer thickness, called transmissivity (T), controls aquifer productivity (or how transmissive the aquifer is over the entire aquifer thickness). Transmissivity of the glacial deposits is generally highest in the central and eastern portions of the county where glacial outwash is found.

Transmissivity is lower in areas where fine-grained tills are mixed with coarse-grain sediments (e.g., northwest and west-central Allegan County).

In the bedrock aquifer, T is generally higher in the east-northeastern portions of the county (Wayland, Leighton, and Hopkins Twps.), and in parts of Watson and Martin Twps. (see Figure 9). Transmissivity decreases along a southeast-northwest gradient, with relatively low values found in Salem, Monterey and Overisel Townships. At the regional 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. See slides 39 and 40 in the main report for more details.

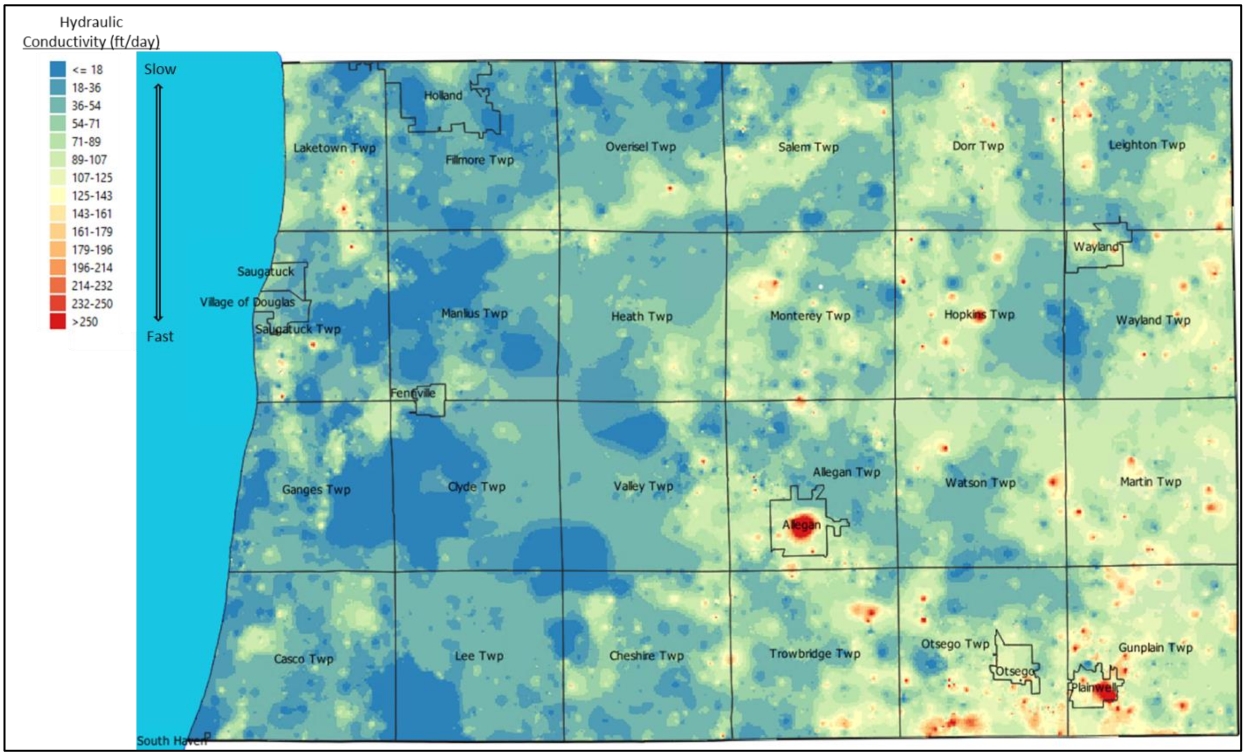

Figure 8: Vertically averaged hydraulic conductivity of the glacial deposits. Zones of high K in the glacial aquifer are found in the north, northeast, east, and southeast. Zones of low permeability are found in the southwestern and western portions of the county.

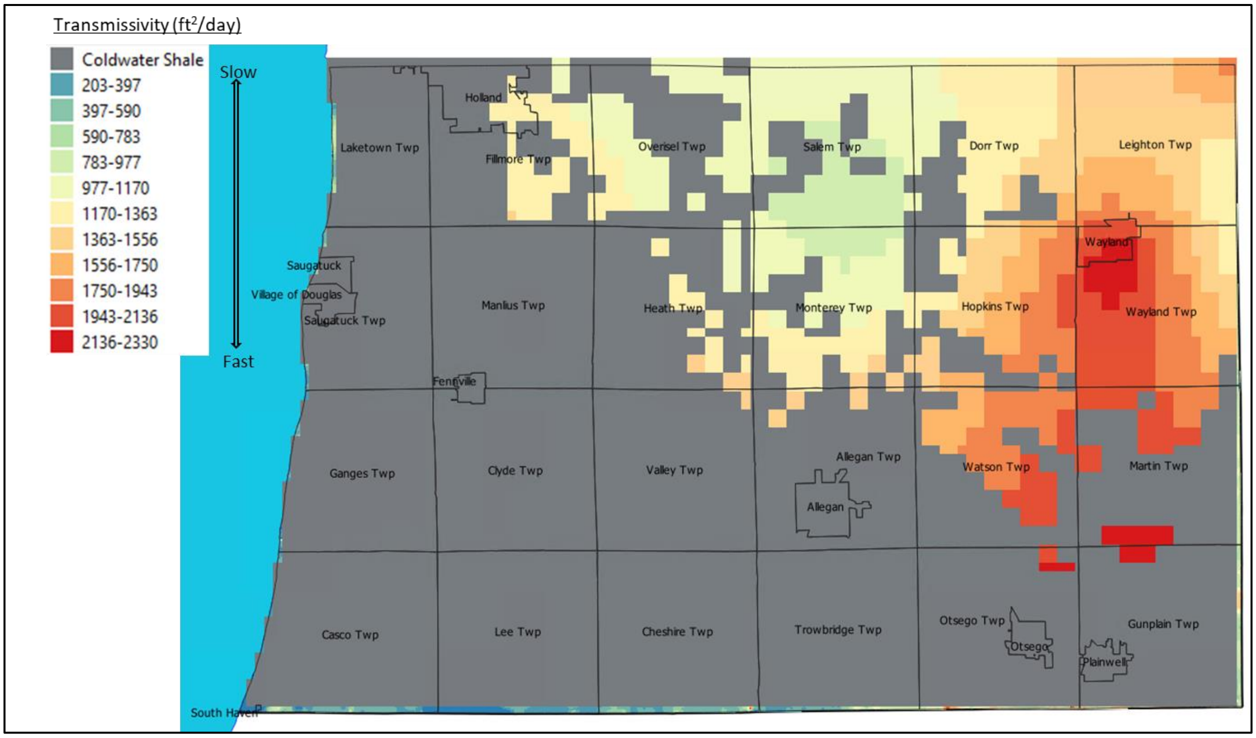

Figure 9: Transmissivity of the Marshall bedrock aquifer. Relative to values seen elsewhere in the state, the Marshall bedrock transmissivity is low because of its small thickness (recall that it generally pinches out along its western subcrop extent) and low permeability. Within the county, bedrock transmissivity is generally higher in the east-northeastern portions of the county and in parts of Watson and Martin Twps. Transmissivity decreases along a southeast-northwest gradient, with relatively low values found in Salem, Monterey an Overisel Townships.

Aquifer Yield

Transmissivity can be directly related to the yield of the aquifer (ability to produce water). For this study, an estimate of aquifer yield was made by calculating the pumping rate that would be required to lower the hydraulic head at the well to 50% of the available drawdown over 3 months, given an estimate of local transmissivity and a known mathematical relationship between drawdown, pumping, and aquifer properties (Jacob-Cooper Approximation).

Under this definition, aquifer yield is small (<70 gallons per minute, or GPM) in the western-central Townships of Manlius, Clyde, and Lee, and also in large portions of Overisel, Heath, Valley, and Ganges Townships (see Figure 10). Yield is expected to be somewhat large (70-500 GPM) along most of the Lake Michigan coastline (Laketown, Saugatuck, Casco Twps.), along parts of the northern border of the county (Salem, Dorr, Leighton Twps.) and the southern border (Cheshire and Trowbridge Twps.), and throughout most of Watson Township. 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 yield is expected to be very large (>1500 GPM) are very small and limited to a few locations. See slides 51-53 in the main report for more details.

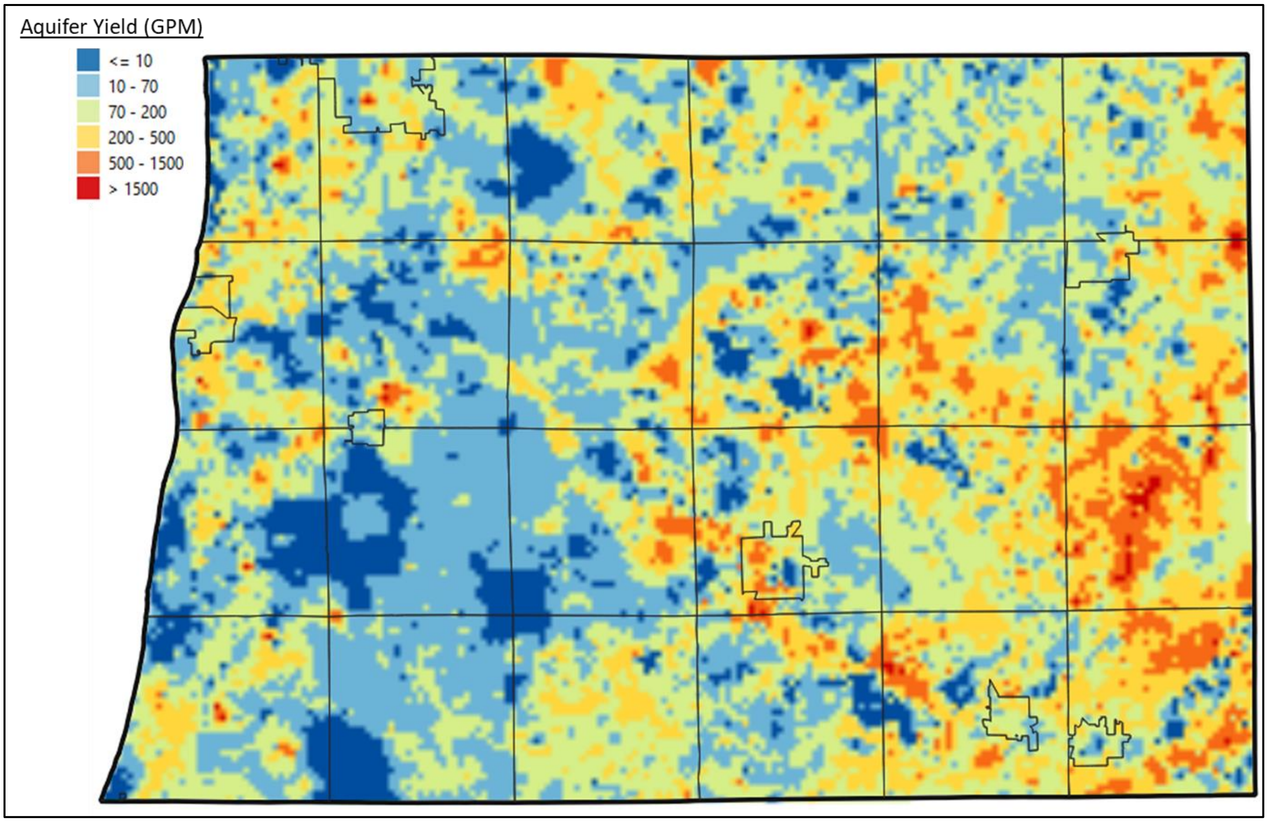

Figure 10: Screening-level estimate of aquifer yield in the glacial aquifer, or the pumping rate that would be required to lower the hydraulic head at the well to 50% of the available drawdown over 3 months, under the given set of assumptions. In this analysis, we assume a well efficiency of 70%. We also assumed purely 2D flow to wells screened across the entire saturated thickness, but in reality, the well is screened across a portion of the saturated thickness, and there is significant vertical flow with associated head loss. Therefore, the *actual* yield encountered in the field is expected to be less than that reported here.

Sustainable Yield and Recharge

The estimated aquifer yield is not the same as the "sustainable yield" or pumping that will preserve groundwater resources over the long-term. Sustainable yield depends on not only aquifer properties and pumping rates, but also well density and the long-term aquifer recharge (net infiltration of precipitation to the water table). It is therefore more meaningful for a defined area and over a sufficiently long-time period. For example, when pumping in an area consistently exceeds recharge (annual pumping exceeds annual recharge), the yield is *not* sustainable, and groundwater levels decline (so-called "groundwater mining").

In Allegan County, several "hot-spots" can be identified in terms of well density: central Dorr Twp.; north-northeast Leighton Twp.; western Allegan Twp. / Allegan City; northwest Leighton Twp.; and portions of Saugatuck, Ganges, Laketown, Salem, Otsego and Gunplain Townships (see slide 58 in the main report).

A map of long-term mean recharge was generated following empirical methods involving observed stream flow hydrographs and information related to land use, soil conditions, and watershed characteristics. 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 (see Figure 11). Recharge is generally low in the upland areas of Fillmore and Overisel Townships and in the portions of Casco and Ganges Townships (and Saugatuck Twp., to lesser degree). See slide 41 in the main report.

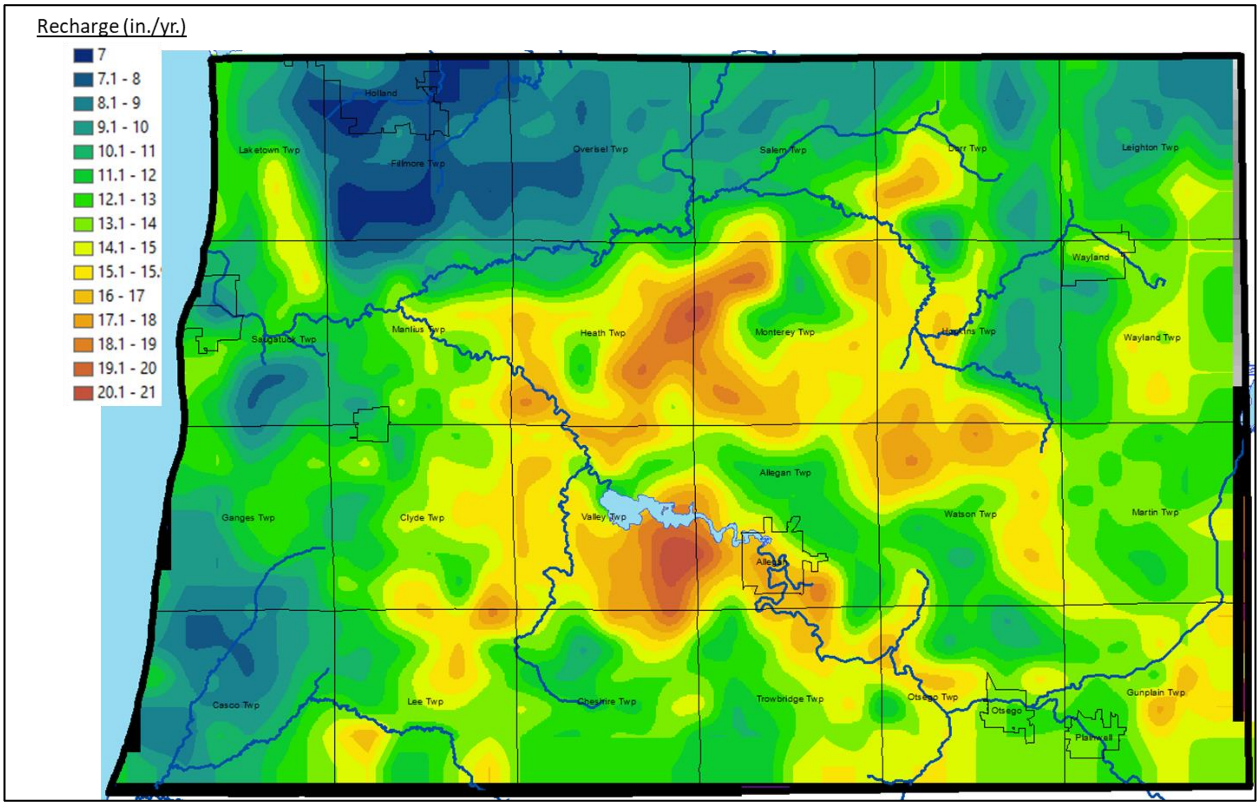

Figure 11: Estimates of long-term mean recharge rate across the county. Recharge is generally largest in the central portions of the county, north and south-southeast of Lake Allegan, and along the upper and middle reaches of the Kalamazoo River. Recharge is generally low in the upland areas of Fillmore and Overisel Townships and in the portions of Casco and Ganges Townships (and Saugatuck Twp., to lesser degree).

Temporal Water Level Trends

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.

Although normally data is collected at a "point" over time at a particular well, 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", a trend can be identified (see Figure 12 for an example). 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.

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 finer 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. See slides 66-82 in the main report.

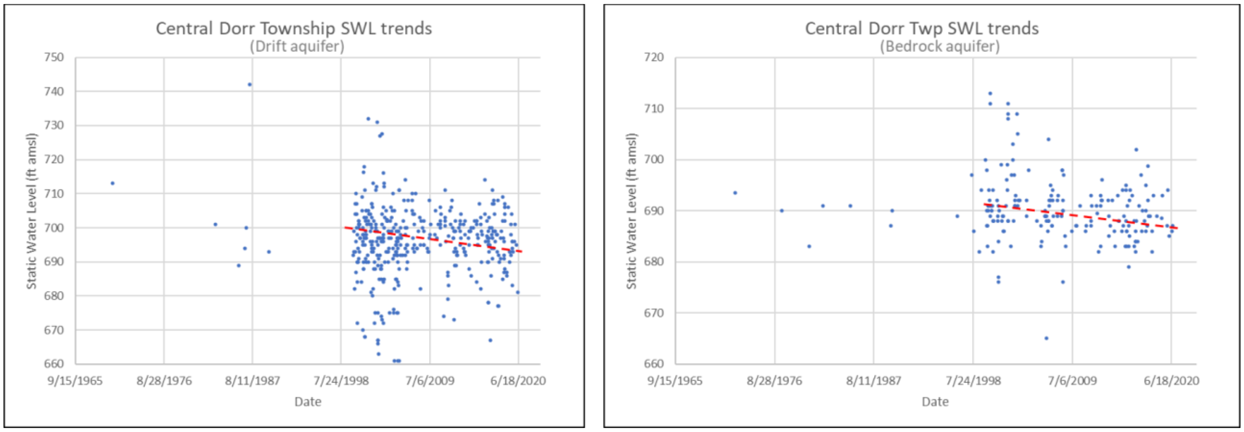

Figure 12: Example of SWL trend analysis that suggests a systematic decline across multiple sections in Dorr Township, for both the glacial aquifer ("drift") and bedrock aquifer. Note the data "gap" prior to 2000. The Wellogic system was initiated around 2000, and although an effort has been made to include wells constructed prior to 2000, there are many older (pre-2000) wells missing from the database. There may also be post-2000 wells missing from the database, albeit a much smaller amount than pre-2000. If more historical data are / become available, the SWL analysis may become more meaningful.

Flow Patterns in the Glacial and Bedrock Aquifers

The water table pattern plays a critical role in groundwater management; it dictates groundwater flow direction (groundwater moves "downhill", from where head is high to where it is low). Combined with hydraulic conductivity, it controls groundwater velocity.

The water table is generally high in the eastern and central portions of the county (especially Monterey Twp.), and low in the western portions and along the Kalamazoo, Rabbit, and Black Rivers (see Figure 13). The water table depression in topographic lowlands where surface water bodies are found is typical of regional discharge areas where groundwater is converging to streams, rivers, wetlands, etc. See slides 42-47 in the main report for more details.

Water levels in the bedrock aquifer are highest in the northeast corner of the county (Leighton Twp.) and along the interface with the Coldwater Shale in Monterey Twp. (see Figure 14). Groundwater in the bedrock aquifer primarily discharges toward the surface (through the glacial aquifer) to the Little Rabbit River and the Rabbit River. Regionally, the bedrock aquifer is recharged to the east in Barry County (see the "mound" in the Figure 14); however, the regional gradient inside Allegan County is small, meaning the bedrock aquifer flow system in the county is localized (i.e. there is relatively little flux of groundwater from the regional recharge mound).

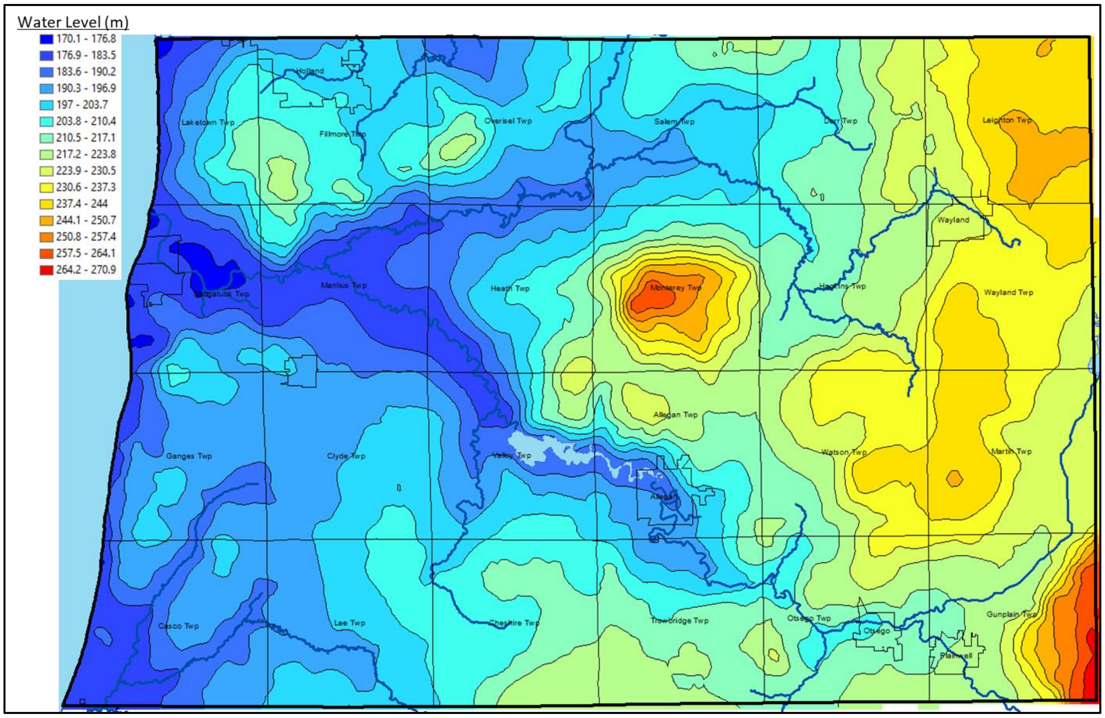

Figure 13: Long-term mean water table pattern in the glacial aquifer. The water table is generally high in the eastern and central portions of the county (especially Monterey Twp.), and low in the western portions and along the Kalamazoo, Rabbit, and Black Rivers.

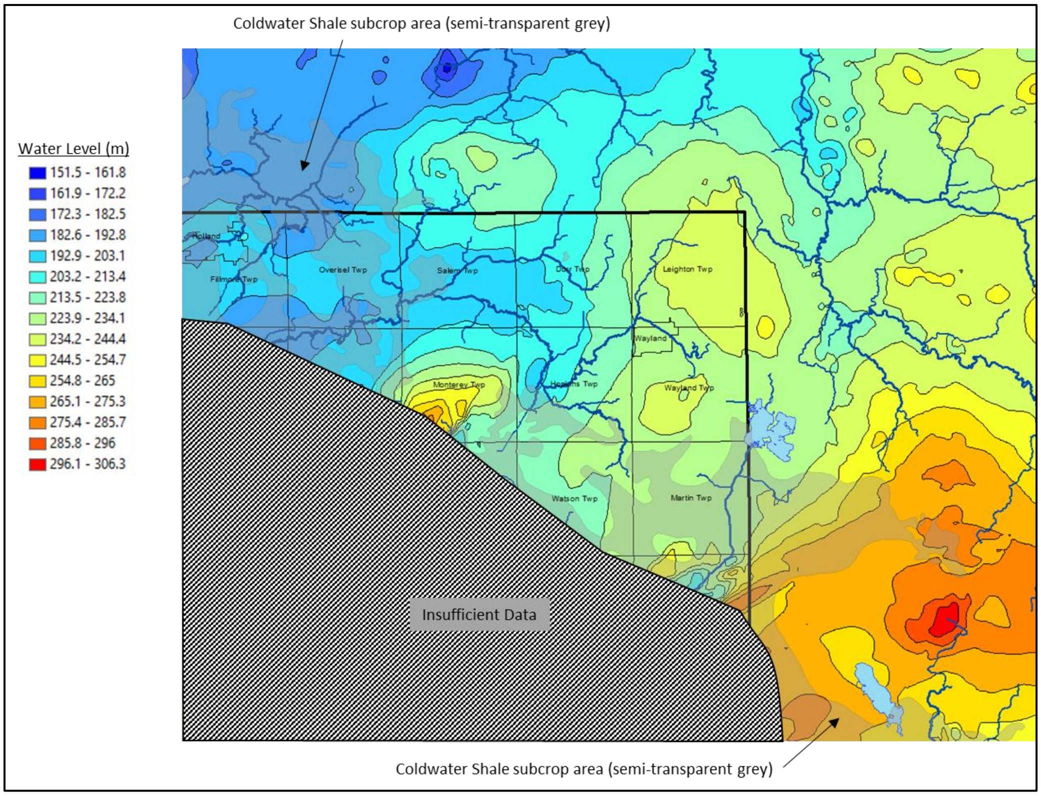

Figure 14: Long-term mean groundwater levels in the bedrock aquifer. Water levels in the bedrock are highest in the northwest corner of the county (Leighton Twp.) and along the interface with the Coldwater Shale in Monterey Twp. (see Figure 14). Groundwater in the bedrock primarily discharges toward the surface (through the glacial aquifer) to the Little Rabbit River and the Rabbit River.

Depth to Water Table

The map of the water table can be combined with high-resolution Digital Elevation Model of the land surface to derive a countywide map of depth to water (DTW). The DTW plays an important role in groundwater management. For example, we need to know DTW when designing a water well, for evaluating of risk of basement flooding, or for assessing aquifer vulnerability.

In Allegan County, the depth to water table is expected to be large (>15m) along the Lake Michigan coastline and in highland areas in central, south-central, and eastern portions of the county (see Figure 15). The depth to water table is small along streams and rivers and in the low-lying, flat areas of western / southwestern Allegan county. See slide 48 in the main report for more details.

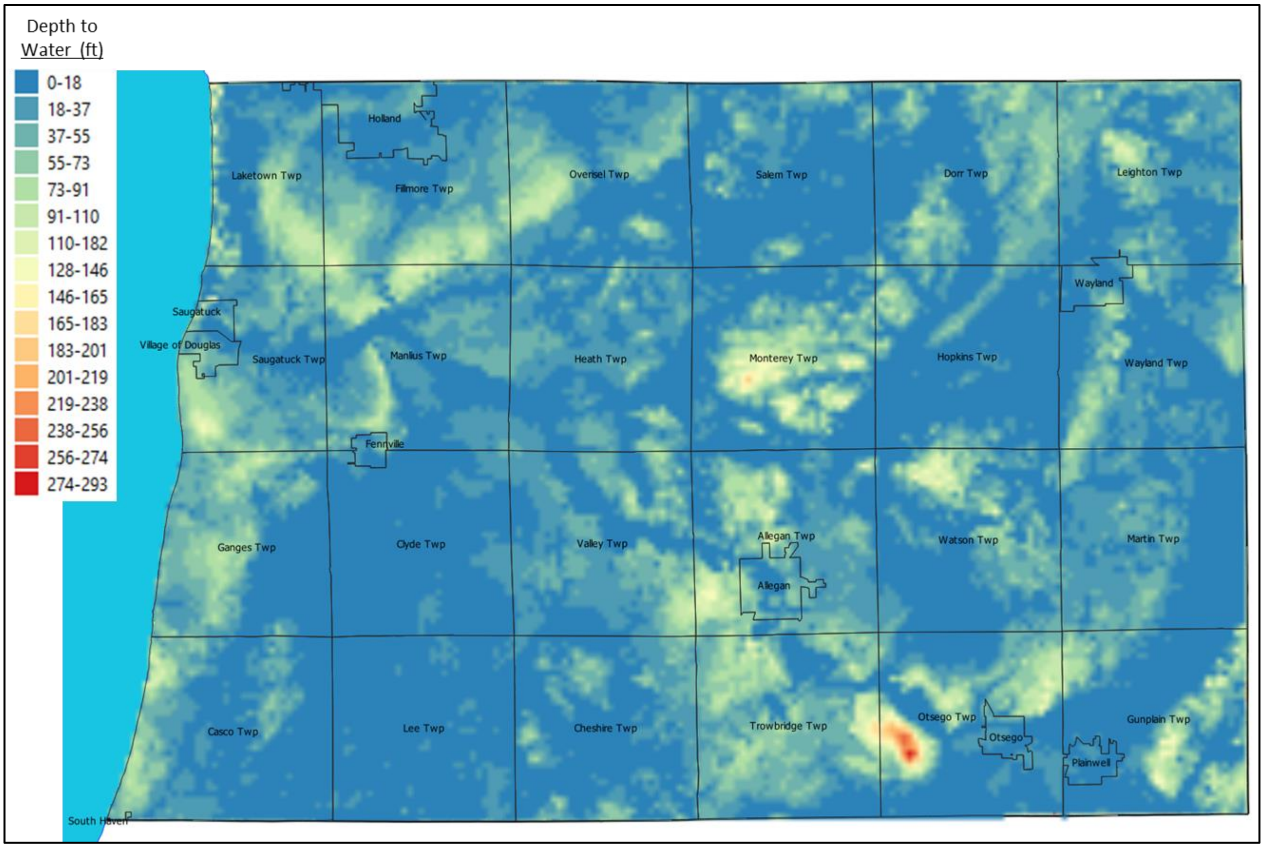

Figure 15: Countywide depth-to-water (DTW) map. The DTW plays an important role in groundwater management. For example, we need to know DTW when designing a water well, for evaluating the risk of basement flooding, or for assessing aquifer vulnerability.

Discharge Areas in the Glacial Aquifer

The water table, along with other data (e.g., hydraulic conductivity), can be used to define aquifer discharge areas and recharge areas that play a critical role in aquifer management.

Although natural recharge into the shallow unconsolidated aquifer occurs in a distributed manner everywhere, not all areas are equally important. In some areas, usually at lower elevations, groundwater moves upwards and discharges to streams, lakes, and wetlands, and rainwater recharge percolating to the water table gets "immediately" discharged. These are called discharge areas. Streams, lakes, and wetlands in discharge areas often have a significant groundwater component and are habitats for groundwater-dependent ecosystems (see Figure 16).

In Allegan County, groundwater discharges primarily to the major surface water bodies (e.g. the Rabbit, Kalamazoo, and Black Rivers) and along their corridors (see Figure 17). Groundwater 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. See slide 50 of the main report.

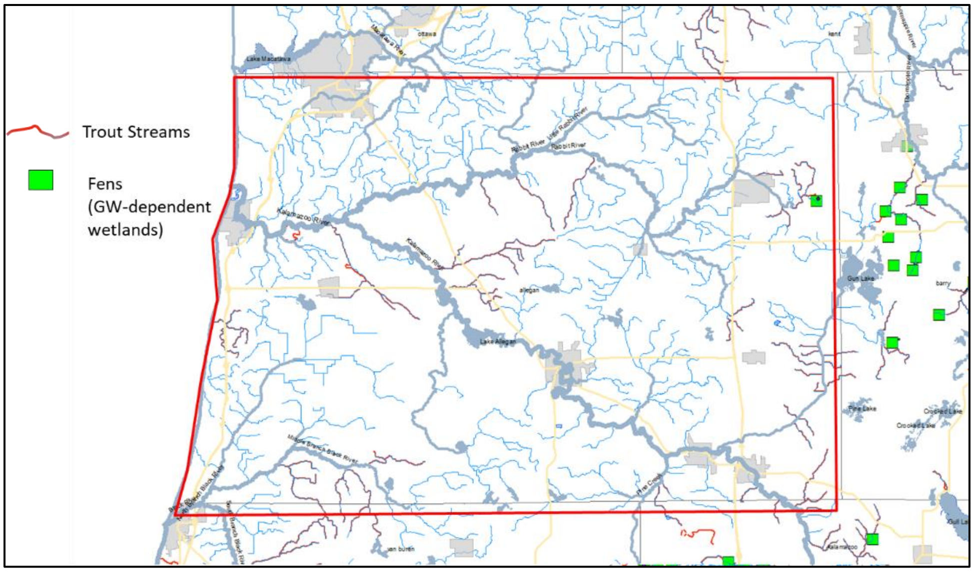

Figure 16: Streams, including known trout streams (red stream segments), and fens in/near Allegan County. Fens are globally rare groundwater-dependent wetlands that harbor a disproportionate amount of biodiversity. The fens just east of the Allegan-Barry County line receive groundwater from recharge areas in both Allegan County and Barry County; therefore, proper management may require coordination between the counties.

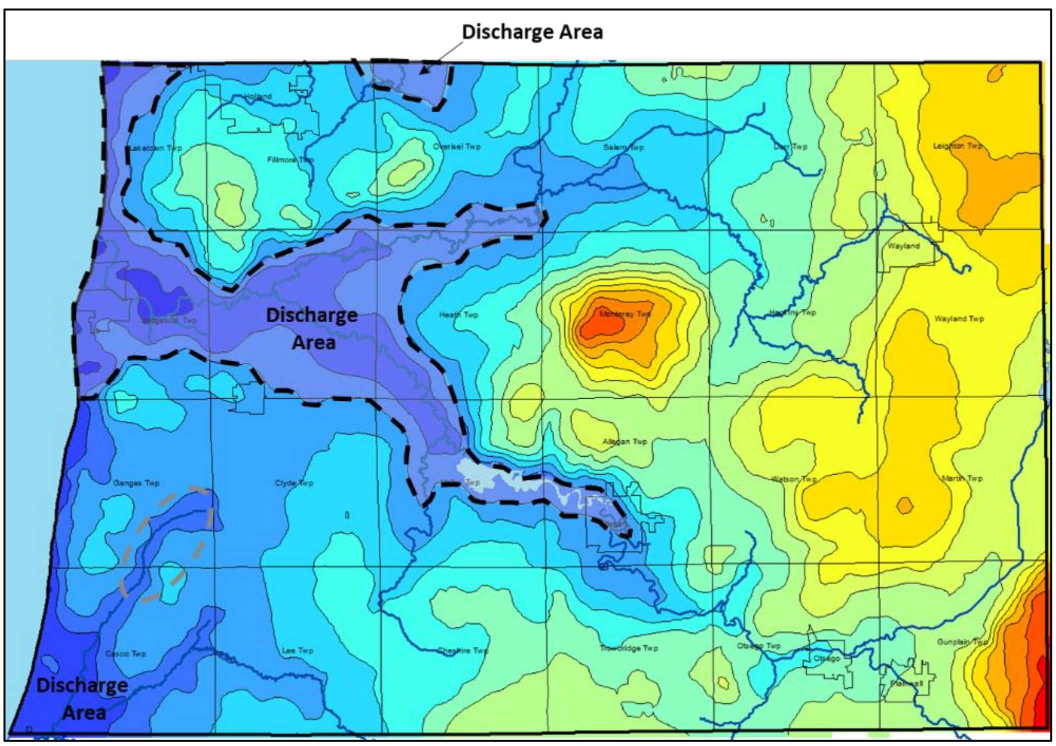

Figure 17: Map of primary groundwater discharge areas in Allegan County. Streams, lakes, and wetlands in discharge areas often have a significant groundwater component and are habitats for groundwater-dependent ecosystems.

Recharge Areas for the Glacial Aquifer

In other areas, the groundwater flow pattern is such that the flow direction points downward (this usually occurs at higher elevations); recharging water moves deep and travels regionally, feeding the entire aquifer or having a more regional impact. These areas are called recharge areas. The location of recharge areas has implications on land use planning (e.g., development in recharge areas disproportionately impacts aquifer sustainability) and on waste disposal activities (e.g., spills in recharge areas have significantly more impact than in discharge areas). Groundwater monitoring in recharge areas is critically important.

At a countywide scale, the major groundwater recharge areas are situated along the eastern townships (Leighton, Wayland, Martin, and Gunplain) and in the central portion of the county (primarily Monterey Twp.) – see Figure 18. The former area may have recharge areas extending into Kalamazoo, Barry, and/or Kent County, which would require trans-county coordination. There are also minor local recharge areas in the northwest (Fillmore Twp., and Overisel Twp. to a lesser degree), and the south-central portion of the county (Cheshire and Trowbridge Townships). See slide 49 in the main report.

Recharge Areas for the Bedrock Aquifer

Recharge areas for the bedrock aquifer can be more difficult to identify. Often, they can be traced out to areas far away the area of interest (e.g., at an outcrop). For Allegan County, the bedrock aquifer is clearly recharged “locally” or directly from above. Local mounding of groundwater levels in the bedrock aquifer are found in the northwest corner of the county (Leighton Twp.) and along the interface with the Coldwater Shale in Monterey Twp. (mimicking the pattern seen in the glacial aquifer). These areas are local recharge areas for the bedrock aquifer. See Slides 54 and 55 in the main report.

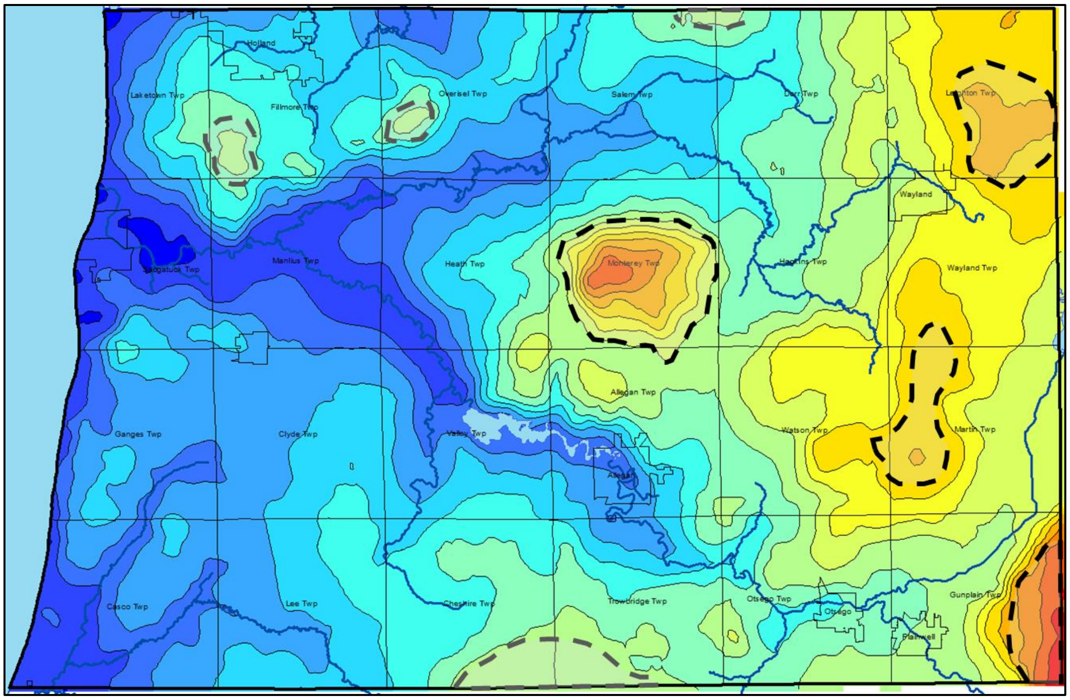

Figure 18: Map of primary groundwater recharge areas of the glacial aquifer. Recharging water moves deep and travels regionally, feeding the entire aquifer. Therefore, the location of recharge areas has implications on land use planning (e.g., development in recharge areas disproportionately impacts aquifer sustainability) and on waste disposal activities (e.g., spills in recharges areas have significantly more impact than in discharge areas). Groundwater monitoring in recharge areas is critically important.

Known & Potential Sites of Contamination

There are a significant number of sites (78) of environmental concern where environmental damage is suspected, possible, or confirmed based on available information (see Figure 19). See slide 120 in the main report for more details.

There are two known PFAS (Perfluoroalkyl and polyfluoroalkyl substances) sites in Allegan County: the 636 40th Street East site in Holland, and the Watson Township Dump in Watson Township. PFAS 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.

There are 168 confirmed leaky underground storage tanks (LUSTs), 61 which are "open" (a release has occurred from and corrective actions have not been completed to meet the appropriate land use criteria). There are an additional 165 locations with at least one underground storage tanks (USTs) that is not closed in place or removed. See slides 121 and 122 in the main report.

Also of significance are 38 historical landfills and 3 waste handler facilities (which may pose a risk to groundwater contamination from leachate of waste products stored on site), as well as 94 oil / gas wells (which may provide a vertical conduit for flow of deeper, highly mineralized groundwater to the near-surface environment). See slides 123-124 in the main report.

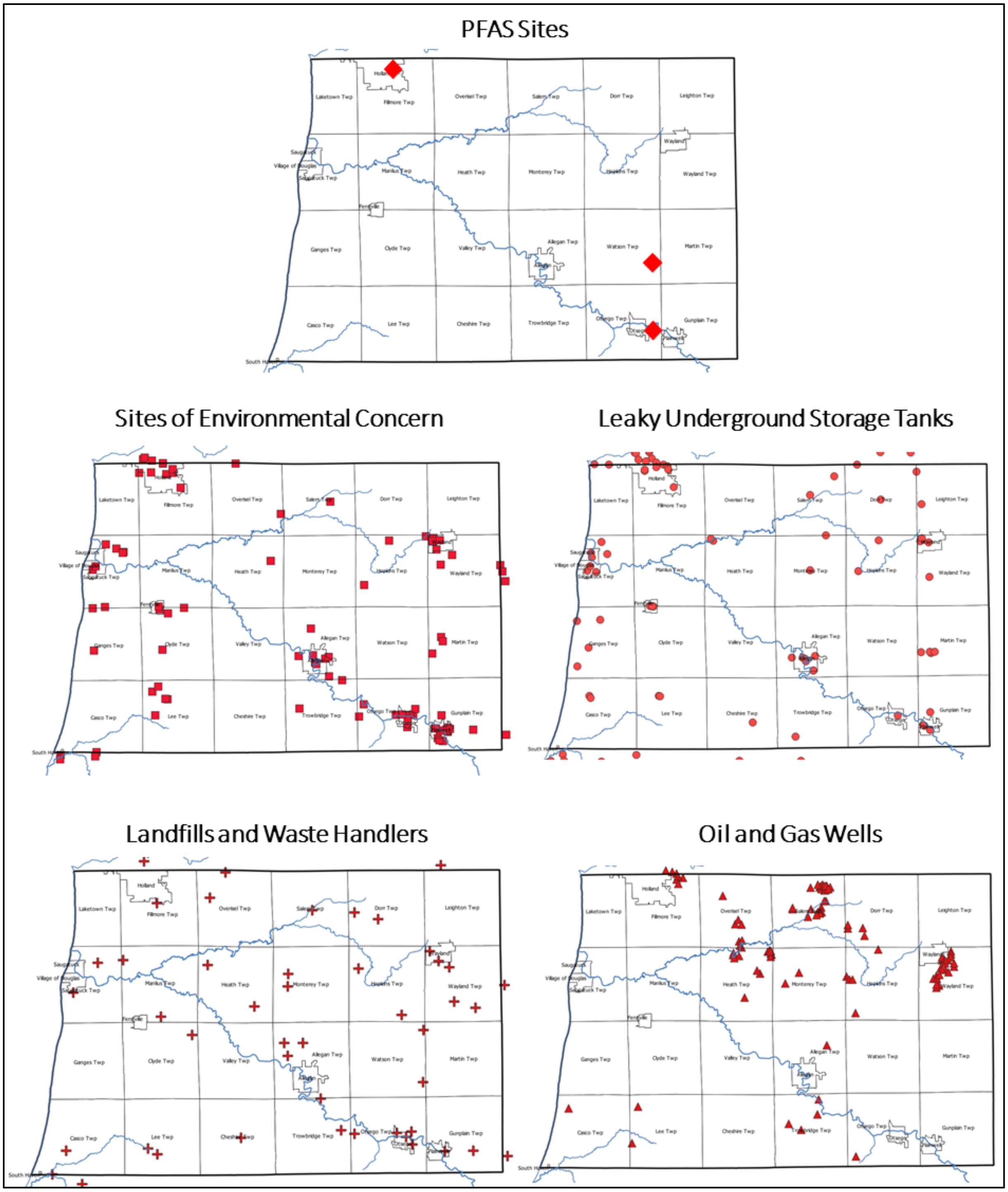

Figure 19: Maps of potential or known sources of groundwater contamination, including confirmed PFAS sites. Monitoring the large number of sites in Allegan County is very expensive, so prioritization is critical. It becomes very important to understand where the contamination goes if there is a spill, and if there are any potentially vulnerable groundwater receptors in its path. On the other hand, if contamination is detected at a monitoring well (or domestic drinking water well), we need to know where the contamination is coming from, and which potential site of concern was most likely responsible.

Contaminant Particle Tracking

The hydraulic conductivity and water table maps created for this study can be combined to map groundwater speed and directions. The information obtained can then be used to track the movement of groundwater "particles" forward and backward along the water table surface. Forward tracking is best used to answer: if a spill occurs, where does it go (see Figure 20), and how long will it take? Backward tracking is best used to determine: if a contaminant is found in a monitoring well, where did it come from (Figure 21), and how long ago was it released?

This technique is best utilized in an interactive DSS so that it can be applied dynamically in an unknown future scenario at a local site in the county.

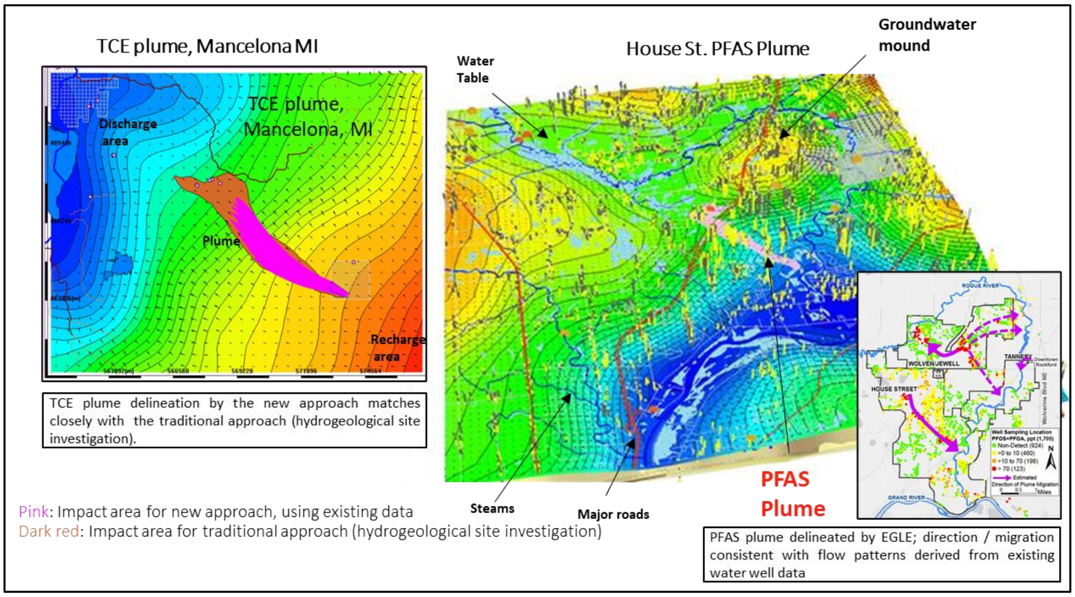

Figure 20: Examples of forward contaminant particle tracking: (left) comparison of the TCE plume in Mancelona, MI, where the red polygon is the plume delineated from traditional hydrogeological field investigation, and the pink is the envelope of simulated particle path lines; (right) House St. PFAS plume (pink polygon) and the simulated water table. Forward tracking is best used to answer: if a spill occurs, where does it go, and how long will it take?

Wellhead Protection Area

Backward particle tracking can also be used to delineate capture zones of groundwater receptors, e.g., a water well. Understanding the capture zone for a well is critically important for protecting the water supply. The area that is providing water to a pumping well is called the wellhead protection area (WHPA). See Figure 21 for an example.

Given the large number of wells and the fact that new wells are constantly added, the backward particle tracking technique for delineating a WHPA is best utilized in a DSS so that the county can dynamically delineate the capture zones for any wells, including new wells.

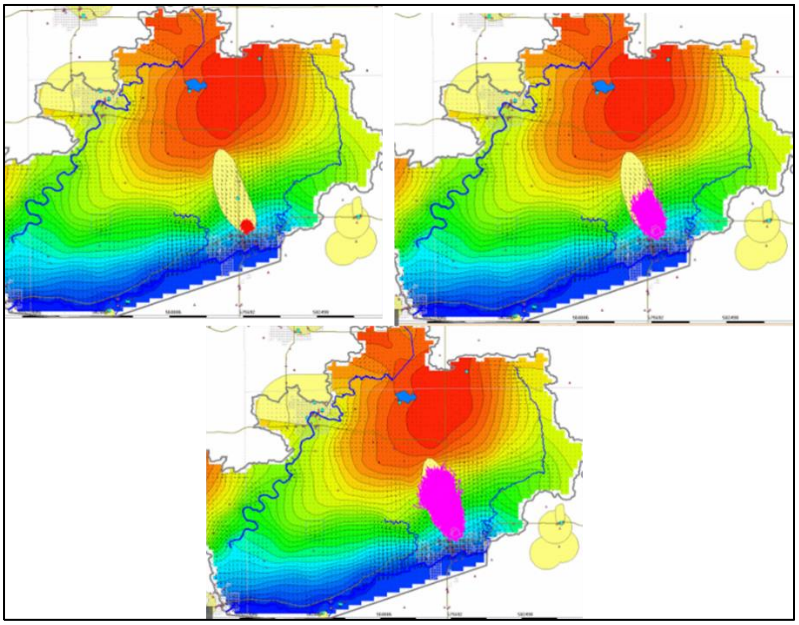

Figure 21: Example of reverse particle tracking in for wellhead protection area (WHPA) delineation. The different graphics show the pathlines at different elapsed times (starting at time≈0 in the top-left). The simulated pathlines match well with the wellhead protection area delineated with traditional hydrogeological field investigations. Backward tracking is best used to determine: if a contaminant is found in a monitoring well, where does it come from (Figure 21), and how long ago was it released?

Nonpoint Source pollution – Nitrate

Groundwater contamination in the county is not limited to point sources. Nonpoint sources of pollution are significant in Allegan.

Nitrate contamination is a significant issue in the shallow aquifer predominantly due to agricultural activities (runoff from fertilizer), but also possibly from leaking septic tanks/sewage. Approximately 4% of the groundwater quality samples from the *WaterChem* database (or 524 of 14383 total samples) are above the Maximum Contaminant Level (MCL) of 10 mg/L – a legally enforceable standard 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) – see Figure 22. Almost 10% of the samples are above 5 mg/L, which can be considered more than twice the expected "natural" nitrate concentration in groundwater (about 2 mg/L or less). See slides 86-91 in the main report.

Nitrate concentrations in drinking water above the MCL is known to cause adverse impacts on human health, specifically the risk of methemoglobinemia – a condition in which blood lacks the ability to carry sufficient oxygen to body cells. Infants below the age of one have the highest risk of developing methemoglobinemia. And although the MCL was set at 10 mg/L based on acute (short-term) health effects, research into possible chronic health effects of consuming water with nitrates at elevated concentrations is on-going.

Elevated nitrate concentrations in groundwater that discharges to surface water bodies can also lead to eutrophication, or the growth of algae that feed on nutrients, resulting in unsightly scum on the water surface, thereby decreasing the recreational value of the water body.

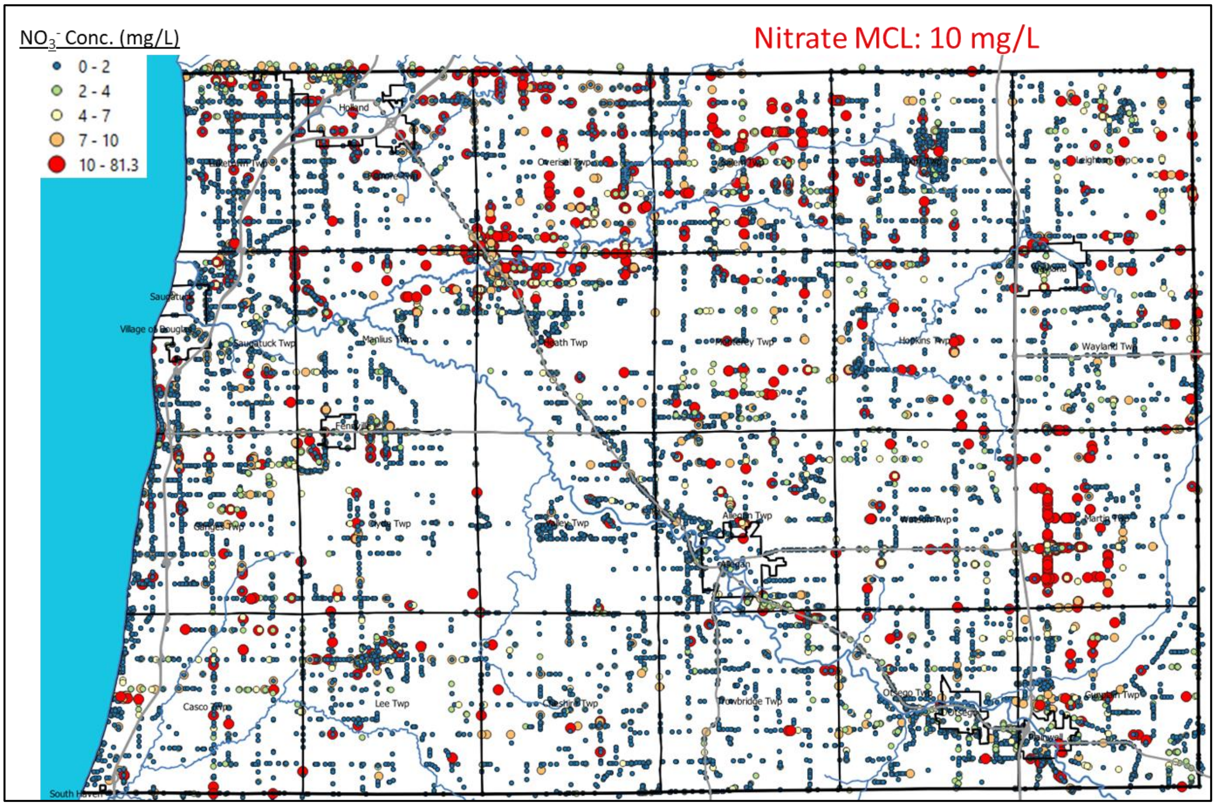

Figure 22: Point nitrate concentration data across the county; from the *WaterChem* database. Approximately 4% of the groundwater quality samples from the *WaterChem* database (or 524 of 14383 total samples) are above the Maximum Contaminant Level (MCL) of 10 mg/L. Nitrate concentrations in drinking water above the MCL is known to cause adverse impacts on human health, specifically the risk of methemoglobinemia.

Nonpoint Source Pollution – Salinity

Nitrate contamination tends to impact the shallow glacial aquifers, since the primary source (agricultural fertilizers) is at the land surface. Another significant nonpoint source contamination is a natural process from below. Michigan's fresh groundwater sits on a pool of brine, slowly inching toward the surface to significantly impact groundwater quality in discharge areas where groundwater is predominantly moving upwards. This phenomenon was well documented in neighboring Ottawa County and is suspected to be impacting Allegan County's groundwater resources (albeit to a lesser degree).

Typically, most shallow aquifers in this part of the country have natural chloride concentrations of less than 15 mg/L. In Allegan County, 4242 of the 22741 chloride samples (8%) from the *WaterChem* database are clearly elevated (>100 mg/L). Approximately 2% of the samples are significantly elevated above the Secondary Maximum Contaminant Level (SMCL) of 250 mg/L set by the US Environmental Protection Agency (EPA). Samples with concentrations above the SMCL are found throughout the county, although most townships have significantly fewer elevated samples relative to samples with low/natural concentrations. Fillmore Twp., Overisel Twp. – and to a lesser degree, Laketown, Salem, Lee Townships –

have notable visual “clusters” of samples above the SMCL (see Figure 23). Most elevated or significantly elevated samples occur next to or close to a stream or river (where groundwater is discharging to the surface). See slides 92-96 in the main report.

SMCLs are non-mandatory guidelines to assist public water systems in managing 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. But there are risks to applying groundwater with elevated chloride concentrations (>100 mg/L) as irrigation water to agricultural crops. It is well documented that crops can be damaged or destroyed by chloride-laden water applied to them.

Note that the “signal” from the natural brine upwelling process is likely mixed with the signals from other possible sources of chloride, including: application of halite (“road salt”) for roadway deicing; septic tank effluent; and livestock excretion or fertilizer application (but expected concentrations are typically below 30 mg/L).

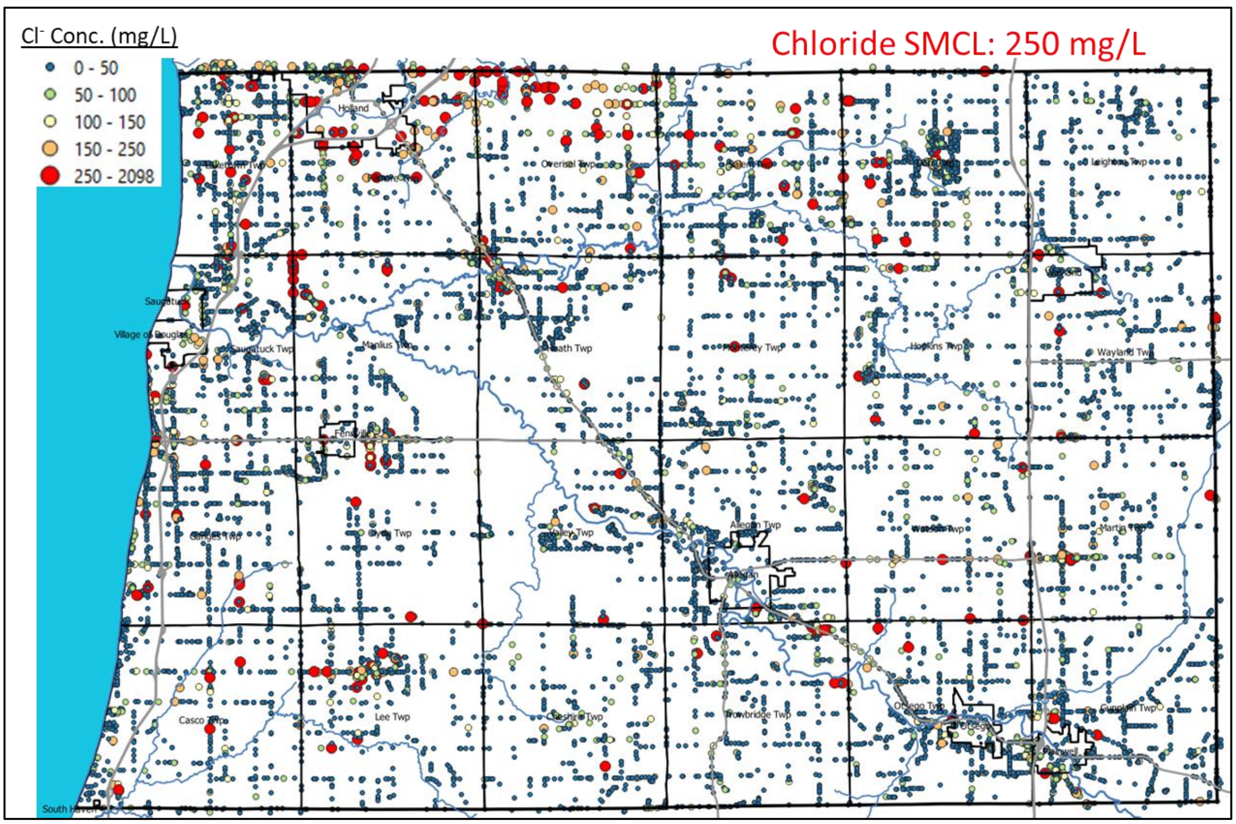

Figure 23: Point chloride concentration data across the county; from the *WaterChem* database. Chloride concentrations at or above the Secondary MCL are not considered to present a risk to human health. However, there are risks to applying groundwater with elevated chloride concentrations (>100 mg/L) as irrigation water to agricultural crops.

Nonpoint Source Pollution – Other Chemicals

Concentration data for a few other water quality parameters were available from the *WaterChem* database, namely: sodium; iron; manganese, lead, and arsenic.

There were relatively few data points for sodium and there is no established SMCL, but the relationship between aesthetic quality ("saltiness") of sodium is similar to that of chloride. Most of the samples that are available have low concentrations (<150mg/L). Approximately 1.4% of the sodium data are above 250mg/L. See slides 97-99 in the main report.

Iron and manganese are considered secondary standards and have SMCLs of 0.3 mg/L and 0.05 mg/L, respectively. Both are commonly found in rock-forming minerals and have concentrations in groundwater controlled by the distribution of compounds and minerals and the environmental geochemistry. The SMCL is a guideline for the minimum level for color and/or staining and metallic taste. It is not uncommon for these SMCLs to be exceeded, especially in deeper aquifers. In Allegan County, this is indeed the case. Approximately 36% and 34% of the samples for iron and manganese, respectively, exceed the SMCL. Iron concentration varies dramatically over very short distances (see Figure 24). There is insufficient data for manganese to capture local-scale variability. See slides 100-103 and 114-115 in the main report.

Both lead and arsenic are primary (legally enforceable) standards based on known impacts to human health. Lead has a MCL of zero; if concentrations exceed the action level of 0.015 mg/L in 10% of samples (e.g., from customer taps sampled), the water supply system must undertake a number of additional actions to reduce concentrations. Approximately 1.1% of the lead samples from *WaterChem* are above the lead action level. Arsenic has a MCL of 0.010 mg/L. Samples with concentrations above the MCL (about 6.7% of the total number of samples) are found in a few isolated across the county. Townships with at least one sample above the arsenic MCL include: Fillmore, Overisel, Dorr, Saugatuck, Clyde, Allegan, Martin, Casco, Lee, and Cheshire. See slides 104-108 and 109-113 in the main report.

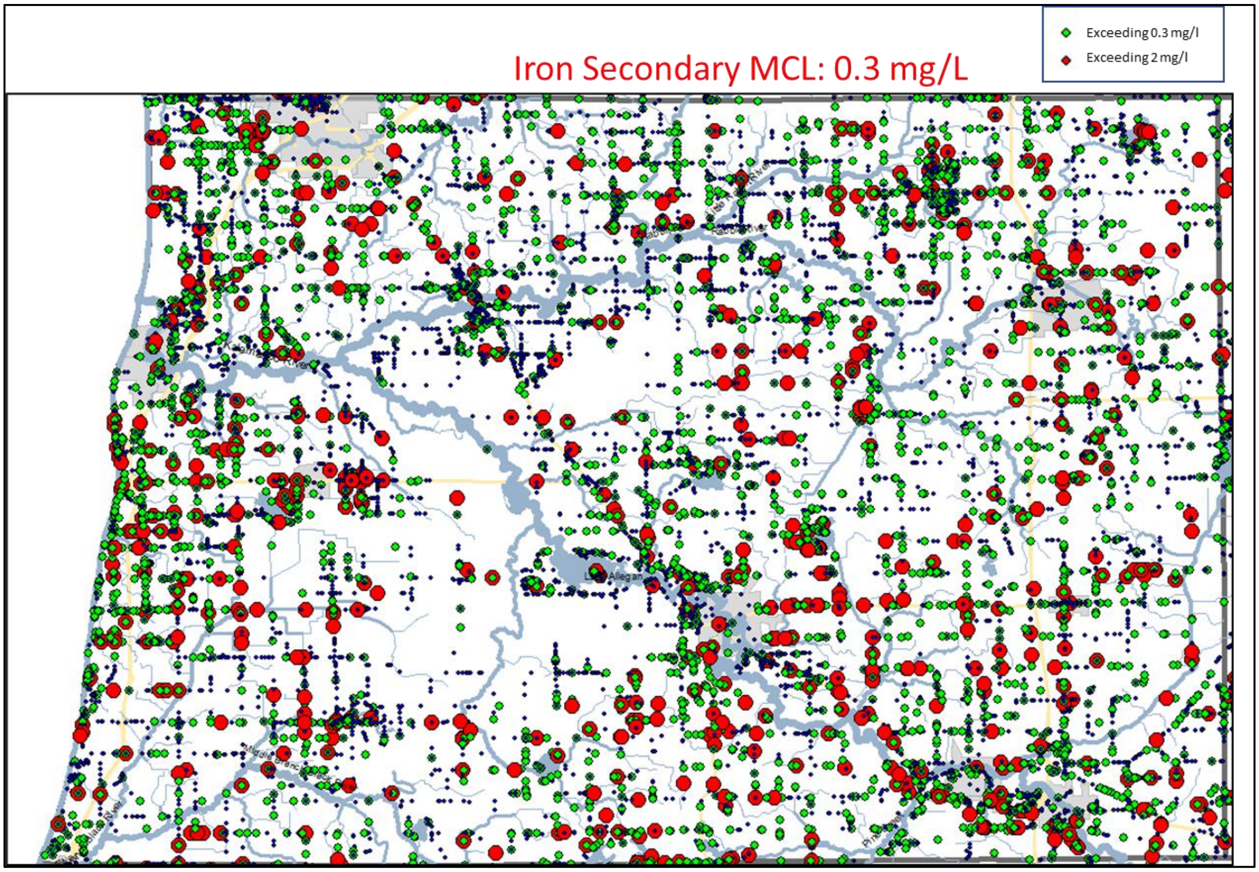

Figure 24: Point iron concentration data across the county; from the *WaterChem* database. Iron is commonly found in rock-forming mineral. The iron secondary MCL is a guideline for the minimum level for color and/or staining and metallic taste. It is not uncommon for iron SMCLs to be exceeded, especially in deeper aquifers. Concentrations exceeding the iron SMCL are common in Allegan County.

Recommendation for Future Work – An Interactive Decision Support System

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. As we have touched on throughout this summary, the best way to use the data, maps, and visualizations presented in this study is to develop a unified groundwater information system for Allegan County.

An 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.

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 tools 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.