IWR GROUNDWATER REPORT

MICHIGAN GROUNDWATER

OPPORTUNITIES FOR IMPROVED MANAGEMENT

Institute of Water Research
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EXECUTIVE SUMMARY

In 2018, IWR and its advisory board initiated an exploratory series of meetings to examine the emerging threats to groundwater and the opportunities available to improve groundwater management for Michigan. Experts were invited to speak with the staff and board members about stream ecology, climatology, modeling, corporate water neutrality, water withdrawals, recharge/infiltration, contamination risk, and source water protection as they relate to groundwater. The goal of these conversations was to better understand the state of groundwater and identify strategies (ideas, tools, and technologies) that could inform and guide state agencies, local officials, policymakers, water resource managers, and conservation groups on issues critical to sustaining Michigan's groundwater resources into the future.

Groundwater is a critical resource and fuels much of Michigan's economy and the health and well-being of its residents. In agriculture, water is used for crop irrigation, food processing, and livestock watering and is the critical driver for the food and agriculture industries' $104.7 billion annual contribution to Michigan's economy (MDARD, 2019).

The industrial/manufacturing sector is the third largest user of groundwater in Michigan's economy, withdrawing 31.3 billion gallons (15.9% of the total non-self-supplied residential groundwater withdrawals) in 2019 (EGLE, 2019). From a natural resources standpoint, the baseflow that groundwater provides to streams plays a critical role in regulating stream flows, water temperatures, and aquatic habitat. For most of Michigan's streams, groundwater accounts for at least 60% of their annual flow, putting Michigan among the highest baseflow-dominant states in the U.S. (Santhi et al., 2008). Additionally, Michigan and the Great Lakes region boast 21% of the world's surface freshwater; this abundance of water can create a tendency to undervalue the resource and manage it as a somewhat limitless supply. These characteristics, coupled with emerging threats, present unique challenges in Michigan and should be considered and addressed through a statewide groundwater management plan.

The health and sustainability of Michigan's groundwater is currently affected by pollutants such as per- and polyfluoroalkyl substances (PFAS, PFOS, PFOA), agricultural fertilizers and pesticides, failing septic systems, and salinations of shallow aquifers. Furthermore, emerging topics of concern for groundwater in Michigan are focused on a combination of compounding factors that have the potential to further reduce sustainable use of the resource over time. These factors include climate variability (leading to changes in storm timing and intensity), altered hydrology from impervious surfaces, increasing groundwater use and withdrawal, reduced groundwater recharge, water availability for use, undervaluation of groundwater, and overuse of institutional controls. These risks should be monitored and addressed in a strategic plan for groundwater management through a combination of education and outreach programs, tools and technologies, and local or state policies where appropriate.

Much research is needed to better understand how to address emerging threats and their impact on Michigan's groundwater resources, and although datasets are available to help monitor these threats and track groundwater resources, many of them are not sufficiently developed or well integrated with existing tools. This report details seven data, model, and research priorities to address these limitations (Table 1). They include (1) studies on economic and ecological value of infiltration in the region; (2) studies of groundwater and changing precipitation patterns; (3) research on land cover changes, infiltration, and baseflow; (4) development of smart water storage and active management technologies; (5) studies on long-term costs of management strategies on groundwater; (6) mapping and inventory of subsurface drain locations and outlets; and (7) expansion of groundwater monitoring wells.

EMERGING TRENDS OF CONCERN FOR GROUNDWATER IN MICHIGAN ARE FOCUSED ON A COMBINATION OF COMPOUNDING FACTORS THAT HAVE THE POTENTIAL TO FURTHER REDUCE SUSTAINABLE USE OF THE RESOURCE OVER TIME.

Additional opportunities are available to support data collection and improve management of groundwater data. Low-cost monitoring networks using remotely sensed data, including networks of devices with sensors and Arduino-based technologies, can be coupled with crowdsourced data to extend data collection geography and network densities at reduced costs. Decision support systems (DSSs) and online tools described in this report can utilize existing and new data sources to better inform management decisions. They also allow water resources managers to perform what-if scenarios to compare effects of various management strategies. Groundwater-focused education modules should be developed to help inform local officials about basic concepts, existing concerns, and tools available to them. This type of information and training will help raise groundwater awareness and can assist local officials in making more informed decisions regarding how they manage their groundwater resources.

Companies including Coca-Cola, Method Company, Kellogg's, and General Mills are focusing on water-neutral operations, sustainable sourcing of products, and regenerative agriculture as part of their sustainability goals. These companies have invested with partnering organizations to help achieve these goals by offsetting water use, improving soil health, and sourcing from responsibly grown grains. Several of these types of projects are implemented in Michigan, paying landowners to implement farming practices that increase infiltration and enhance aquifer recharge. These types of private partnership projects should be modeled and expanded as part of broader efforts to help improve groundwater recharge and management.

Considering the importance of groundwater to Michigan and the Great Lakes region and the significant threats that are emerging, Michigan should invest further in the discussion and implementation of a statewide groundwater management plan. Data, modeling, and research priorities outlined in the report along with novel approaches discussed can help address these emerging threats. A thoroughly developed strategic groundwater plan can improve Michigan's sustainable use of groundwater and increase its groundwater security for future generations.

PURPOSE OF REPORT

The purpose of this report is to highlight the values of groundwater within Michigan and the Great Lakes region, explore emerging threats to groundwater conditions, and identify opportunities to improve groundwater management in the region. Given the high environmental, economic, and social values of groundwater resources coupled with growing demand, scientifically sound research frameworks and data-driven models to help guide sustainable management strategies are critical needs.

In 2018, IWR and its advisory board initiated an exploratory series of discussions and meetings, inviting experts to speak about stream ecology, climatology, groundwater modeling, corporate water use and water neutrality, contamination, and source water protection as each relates to groundwater. The goal of those discussions was to investigate the current knowledge of groundwater, tools for managing it, and emerging threats that could then be used to guide strategies for its improved management. The advisory board, made up of a diverse set of individuals representing state agencies, Michigan State University and the University of Michigan, conservation groups, and private foundations, acknowledges that sustainable groundwater (directly or indirectly) is tied closely to each of their organizations and members and that improvements in understanding and long-term management will benefit Michigan and the Great Lakes region.

THE PURPOSE OF THIS REPORT IS TO HIGHLIGHT THE VALUES OF GROUNDWATER WITHIN MICHIGAN AND THE GREAT LAKES REGION, EXPLORE EMERGING THREATS TO GROUNDWATER CONDITIONS, AND IDENTIFY OPPORTUNITIES TO IMPROVE GROUNDWATER MANAGEMENT IN THE REGION.

This report is intended to assist state agencies, local governments, and conservation organizations with identifying emerging threats posed to groundwater and to provide ideas, technologies, and tools that can improve groundwater management. The report provides seven recommendations for research, data, and modeling needs and five novel approaches that can be used to support existing or newly developed groundwater management plans. It also includes multiple examples of online tools that can be integrated into programs or projects that support groundwater resources.

IMPORTANCE OF GROUNDWATER

Groundwater plays a critical role in shaping the health of Michigan's rivers and streams, its economy, and its residents' well-being (which includes social, cultural, and financial health and wellness). Groundwater exists as a dynamic landscape feature, shaped as a subdued reflection of the land surface, sloped and generally moving toward low points in the land surface (like river valleys and the Great Lakes coasts). As groundwater is found beneath the soil surface, occupying spaces in soil, sand, and porous rock (like sandstone), it is generally not visible. As a result, its critical ecological, economic, social, and cultural values can be overlooked. Michigan and the Great Lakes region host one of the world's largest surface freshwater ecosystems; the region includes 21% of the world's surface freshwater. Michigan groundwater represents a vast storage of freshwater, providing unparalleled water security to society; this is our state's treasure. This abundance of water can create a tendency to manage groundwater as a somewhat limitless resource. Given the unseen nature of groundwater, its apparent limitlessness in the Great Lakes region, and its unparalleled water security, it should not be taken for granted, and great care should be taken to manage this critical resource, especially given the uncertainty of changing climate and potential effects on groundwater. While groundwater has featured prominently in overall water use across the state and the region, we see evidence that this demand continues to grow.

This underscores the need to better understand groundwater resources and develop management plans based on data-driven models that cover the regional aquifers across the state.

ECOLOGICAL BENEFITS

Below the surface and at the land-water interface, groundwater interacts with soils and terrestrial and aquatic organisms to create groundwater-based ecosystems that provide a variety of valuable ecosystem services, including recreation, diverse and productive biota, water purification and storage, biodegradation of contaminants, nutrient cycling, and mitigation of floods and drought (Griebler and Avramov, 2015). Nearly all of Michigan's lakes, wetlands, and streams/rivers, during low-water seasons, are the visible expression of the groundwater system. Unique fens and certain wetlands exist solely from groundwater-to-surface interactions in the Great Lakes region. Groundwater discharge (groundwater moving upwards to the surface through hydraulic pressure) and exfiltration play a major role in supporting some of Michigan's most biodiverse ecosystems, such as the Hiawatha National Forest, which contains 20 types of groundwater-dependent wetlands (Slaughter and Cuthrell, 2016).

The services provided by groundwater are even more crucial as the impacts of climate change intensify—groundwater acts as a buffer against the impact of climate variability by providing a water source to crops, animals, and habitats and a steady baseflow to streams during drought conditions (Turral et al., 2011). The baseflow that groundwater provides to streams plays a critical role in regulating stable flows, water temperatures, and aquatic habitats. All perennial streams in Michigan are fed directly or indirectly through its tributary network by groundwater, which provides cool, steady baseflow. Several important fish species in Michigan and the Great Lakes region require cool or coldwater streams to thrive. For most of Michigan's streams, groundwater accounts for at least 60% of their annual flow, putting it among the highest baseflow-dominant states in the U.S. (Santhi et al., 2008). The accounting of this baseflow is one of the ways that Michigan manages its large-capacity water withdrawals.

ECONOMIC BENEFITS

Water is an essential requirement and catalyst for much of Michigan's economy. In particular, groundwater plays a vital role in facilitating commercial and industrial activities in the non-coastal parts of Michigan (the majority of the state's landmass) that do not have access to water from the Great Lakes. In agriculture, water is used for crop irrigation, food processing, and livestock watering, and it is the critical driver for the food and agriculture industries' $104.7 billion annual contribution to Michigan's economy (MDARD, 2019). The industrial/manufacturing sector is the third largest user of groundwater in Michigan's economy, withdrawing 31.3 billion gallons (15.9% of the total non-self-supplied residential groundwater withdrawals) in 2019 (EGLE, 2019).

Southwest Michigan is a well-known specialty crop production region where the primary crop acres (i.e., seed corn and chipping potatoes) are irrigated, as are the fields of snap beans, tomatoes, pickling cucumbers, peppers, and summer squash. In 2014, the farm gate value (market value of product minus any selling costs) of the seed corn industry in Michigan was over $100 million, while the farm gate value of chipping potatoes was about $33 million (MSUE, 2014). The combined farm gate value of the other specialty crops was about $74 million in 2014 (MSUE, 2014). Blueberry production is also concentrated in Southwest Michigan, contributing over $120 million in farm gate receipts annually to the local economy. About 79% of Michigan's blueberry acreage is irrigated (MSUE, 2014).

Accommodating these industries in Michigan are 2,400 licensed food processors, which collectively generate nearly $30 billion in economic activity (MDARD, 2022b). Michigan has abundant water treatment facilities to support the food processing industry. As an example, West Michigan has several large-scale wastewater treatment facilities currently with excess capacity. In Grand Rapids, businesses have access to over 10 million gallons per day of excess wastewater treatment capacity (Experience Grand Rapids, 2022).

SOCIAL BENEFITS

As a whole, society benefits from access to and development of groundwater. Development of groundwater plays an essential role in the food security of Michigan and the Great Lakes region by reducing the reliance of food imports from outside sources. This subsequently provides financial benefits and reduced costs for Michigan residents. Groundwater additionally provides access to clean drinking water. Groundwater is the source of drinking water for about 45% of Michigan's citizens (MDEQ, 2018), with Michigan businesses, farms, and residents using a total average of 700 million gallons of groundwater per day (MDEQ, 2018). Michigan is home to 9% of the nation's public groundwater supply systems—the highest share of any state (MDEQ, 2018). Throughout the state there are 1,381 community groundwater supply systems with 3,966 wells and 9,050 noncommunity groundwater supply systems utilizing 10,703 water wells (MDEQ, 2018). It is estimated that there are 1.25 million private household wells in Michigan, and more residential wells are drilled annually in Michigan (13,335 in 2019) than in any other state (MDEQ, 2018; EGLE-EAC, 2021).

Through its many uses, groundwater enhances economic, social, and recreational opportunities for communities in Michigan and abroad, supporting the concept of community vibrancy. Community vibrancy involves aspects of place, quality of life, community vitality, community resilience, and community well-being (Goralnik, 2022). In Michigan, groundwater enhances and strengthens these community connections, enhancing social wellness.

DATA, MODELS, AND RESEARCH PRIORITIES

Monitoring of groundwater in Michigan and the Great Lakes region is neither comprehensive nor rigorous enough to capture conditions across the state, making it difficult for state and local governments to assess current groundwater status, project future scenarios, and effectively manage groundwater resources. Addressing these priorities through the development of a groundwater management plan can greatly improve how Michigan manages its groundwater resources. The USGS groundwater database for Michigan consists of 112 observation well sites, only 27 of which are active today (Figure 1). Previously there was a more robust network of wells; however, the network was cut in the early 1990s because of cuts from State of Michigan cooperators. The remaining geographic distribution of these active monitoring wells is very patchy — 12 of them are clustered in the Kalamazoo area alone (supported by the city), while five of them are concentrated in the Lansing area (supported by the Lansing Board of Water and Light). There are two observation wells in Osceola County and the remaining eight wells are in eight separate counties. The 85 inactive wells have historical data records of various lengths. Available site-descriptive information includes well location (latitude and longitude), well depth, groundwater level, and aquifer.

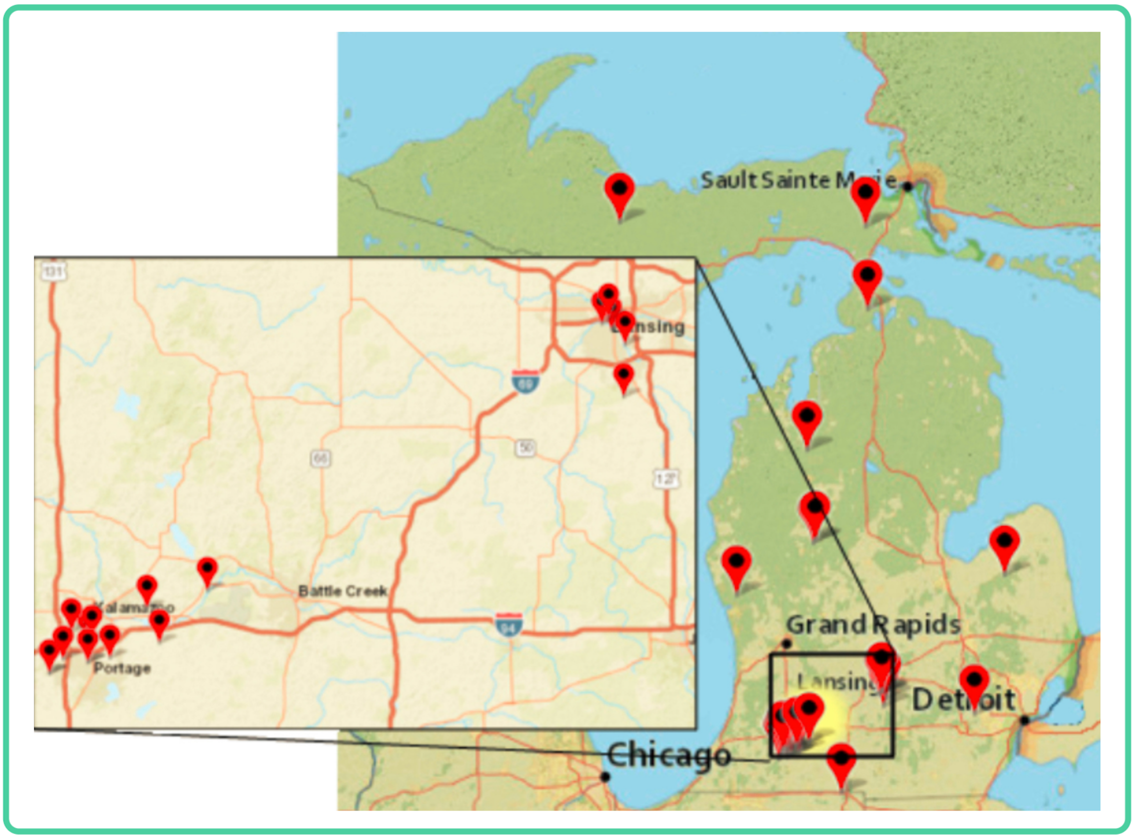


Figure 1. USGS active groundwater level observation wells.

Availability, consumability, and formatting of existing groundwater data are other significant barriers to its use by managers and the public. Large volumes of groundwater data in Michigan exist only in paper files or, if digital, are not formatted in a modern database structure, making them difficult to be integrated into software programs or analyzed models. Examples include monitoring well data collected under Parts 111 (Hazardous Waste Management), 115 (Solid Waste Management), 201 (Environmental Remediation), or 213 (Leaking Underground Storage Tanks) of the Natural Resources and Environmental Protection Act (PA 451 of 1994). Other data may not be readily available including a large and growing body of data on glacial geology, static water levels, and aquifer characteristics compiled by state and federal agencies (and by universities and private industry) that need to be collated, converted into a common set of accepted geologic and hydrogeologic terms and data fields, and publicized.

Detailed groundwater models are not available throughout the state. They have been developed in a piecemeal manner for various watersheds and locations around Michigan, using different models and data inputs. A new generation of modeling tools that connect model inputs and outputs can improve collaborative modeling and build upon other efforts. Utilizing and better integrating models, tools, and proposed datasets in this report will provide a greater understanding of the state of groundwater in Michigan and advance the management of our groundwater resources.

The Michigan Hydrologic Framework, included in the Water Use Advisory Council's (WUAC) 2020 recommendations and approved for funding, starts to build such a framework for addressing the modeling needs of the state but requires additional efforts outlined in this report to be most effective.

Some of the WUAC 2020 recommendations to the Michigan Legislature, including a comprehensive groundwater monitoring network, the Michigan Integrated Water Management Database (to facilitate geologic and hydrologic data collection in a common geospatial format), and the Michigan Hydrologic Framework, address some of the modeling and data needs for Michigan but are more focused on supporting Michigan's Water Withdrawal Assessment process and tool. Additional data, modeling, research, and frameworks are still required to help with broader groundwater management decisions and better understanding and assessing the region's groundwater resources.
We identified six topics for expanded research, modeling, and data collection. These topic areas and recommendations will provide a broad base for a comprehensive groundwater management plan. The proposed activities identified in Table 1 will support important research questions needed to address the current and future threats facing groundwater in Michigan and the Great Lakes region.

TABLE 1.

DATA, MODELS, AND RESEARCH PRIORITIES

Topic		Purpose/Need	Recommendation
1.	**Economic and Ecological Value of Infiltration in the Region**	Question: What is the economic and ecological value of infiltration in the region? Managing watersheds to optimize infiltration and establishing various markets to help fund those activities is a critically important step toward improving how we manage our groundwater resources. Currently, there is no established cost per unit of service established. Economic studies are recommended to help establish the value of infiltration on a per-unit basis to support local and regional markets.	• Support or conduct economic studies examining the value of infiltration or groundwater recharge. • Explore groundwater withdraw offset programs that can offset withdrawals through increased infiltration capacity. • Explore mechanisms such as preventative measures established in PART 327 of the Michigan Natural Resources and Environmental Protection Act that could enable water users to increase infiltration to prevent adverse harm from withdrawals.
2.	**Groundwater and Changing Precipitation Patterns**	Question: What is the relationship between seasonal variation and changing precipitation patterns in the region and groundwater levels? Changing precipitation patterns are influencing local rainfall intensities and timing, which can negatively alter groundwater recharge and availability for shallow wells. The impacts and relationships to management decisions are not well understood. Additional research to better understand the current trends, relationships, and impacts from changing precipitation patterns on groundwater is recommended.	• Support or conduct regionalized groundwater and recharge studies examining the rate of deep infiltration supporting groundwater recharge under a set of climate-mediated scenarios. • Establish a substantially more comprehensive groundwater level monitoring network throughout Michigan (see Topic #7).

Topic		Purpose/Need	Recommendation
3.	**Land Cover Changes, Infiltration, and Baseflow**	Question: What is the relationship between the expansion of impervious surfaces and the groundwater recharge rate at the township level of analysis? Impervious surfaces divert nearly 100% of the precipitation that falls on them to surface runoff, removing any possibility of groundwater recharge. While numerous studies have evaluated the ecological impact of impervious surfaces on surface water quality and quantity, few studies have been conducted to quantify the impact of impervious surfaces on groundwater recharge.	• Support or conduct groundwater modeling studies that quantify the rate of deep infiltration for groundwater recharge under a four-decade pattern of green-space urbanization and the associated expansion of impervious surfaces. • Support or conduct streamflow modeling studies that quantify the changes in baseflow associated with a four-decade pattern of expanding impervious surfaces.
4.	**Smart Stormwater Storage and Active Management Technologies**	Question: How do we utilize technologies to automate and actively manage water surpluses to minimize runoff and maximize infiltration?	Assess enhanced infiltration potential (with water quality considerations) and aquifer storage of water during periods of flooding.

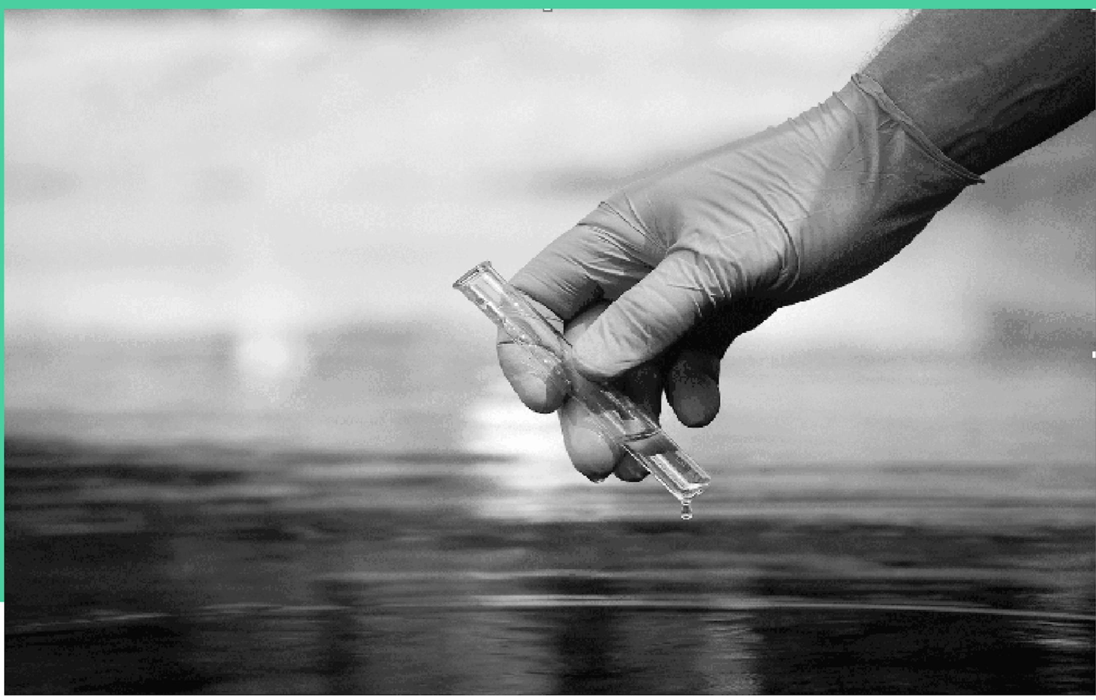
Topic		Purpose/Need	Recommendation
5.	**Long-term Costs of Management Strategies on Groundwater**	Question: How much is currently being invested in managing groundwater? What are the benefits and costs associated with this management?	Select three to five counties in Michigan and assess the totality of water management that pertains to groundwater. Assess a non-jurisdiction-specific enterprise budget for groundwater management within several Michigan counties. A groundwater enterprise budget is the total budget for groundwater-related management activities regardless of jurisdiction and could include a drain commissioner, municipalities, wellhead protection, and contaminated site management that are all managed through different entities.
6.	**Subsurface Drain Locations and Outlets**	Question: Where are the locations of agricultural tile drain outlets and what is their field coverage area? What are the cumulative impacts of subsurface drainage on infiltration to groundwater? Subsurface drains can alter local hydrology and reduce groundwater recharge. Without knowing the extent of subsurface drainage areas, it is difficult to manage water resources in a watershed and know how existing and future drainage installations impact groundwater resources. Currently there are very few tile drain maps or requirements to share tile drain installation locations and extents, and there is no central location to access them. Tracking sales of total lengths of drainage tile sold can also help identify expansion trends in the region.	Map the extent and change in tile drainage across the state with five-year updates. County drain commissioners may be a good local source for data collection. Model the cumulative impacts of subsurface tile drains on infiltration to groundwater at various watershed scales.

Topic		Purpose/Need	Recommendation
7.	**Groundwater Monitoring Wells**	Question: What is our current knowledge of groundwater levels at the township level of analysis; are any notable trends forming? Managing groundwater uses for sustainability requires knowledge of the trend in groundwater levels. The state's ability to monitor groundwater levels is currently very limited, due to an inadequate network of groundwater observation wells (only 27 currently active monitoring wells, with patchy distribution).	• Implement the funded WUAC (2020) recommendation to the legislature to develop a more comprehensive groundwater level monitoring network throughout Michigan. The current vision is to have at least two wells per county. When implemented, the network will be established, incrementally starting with approximately ten new observation wells in the first year and adding ten wells per year. Additional recommendations would be to track and install observation wells on a hydrologic unit basis to better represent aquifers. • For counties where significant groundwater extractions occur (i.e., >500 million gallons per year from all use sectors), at least 16–20 monitoring wells should be developed. The state should investigate whether the oil and gas industry would be willing to donate (rather than decommission) their high-capacity water wells (used to obtain drilling/fracking fluids) after completion of the oil/gas well, so they could be used as long-term groundwater monitoring wells.

THREATS TO GROUNDWATER

Managing groundwater comes with specific challenges due to the perception that it is an abundant resource and to the fact that it is not visible. Increasing competition for water resources, especially in certain parts of the state, amplifies the importance of groundwater systems for the direct supply of water and for buffering the variation in baseflow feeds to surface water bodies. Groundwater is much like a bank account where water flows in (through precipitation) and out (through baseflow to streams, wetlands, lakes, and withdrawals) of the account. Groundwater depletion can result in declining water tables and direct reductions of baseflow to surface water bodies, resulting in an increase in the cost of groundwater for all users of an aquifer and diminished ecological abundance. Additional consequences of groundwater depletion include increased energy use and pumping costs (having to pump water from greater depths), subsidence of land surfaces, and degraded groundwater quality due to the movement of human-caused contamination or the induced entry of naturally occurring contamination such as arsenic, brine, or radionuclides from sources deeper below the aquifer. Like the bank account concept, aquifer withdrawals (output) should be balanced with recharge (input). If these groundwater aquifers are overdrawn, they may never fully recover, especially if groundwater withdrawals continue to deplete the aquifer (account). Similarly, the cleanup of contamination of groundwater can be quite difficult and very costly.

One fundamental threat to groundwater in Michigan is contaminants. Michigan has had thousands of contaminated groundwater sites that have been identified over several decades. More recently, contamination involving per- and polyfluoroalkyl substances (PFAS, PFOS, and PFOA) is impacting human health and has risen to the forefront of planning, mitigation, and data collection for the state. Long-term sustainability of groundwater resources requires an examination of not only current but emerging threats. Identifying these threats and tracking their trends are critical needs for current management decisions to address likely future scenarios. In addition to contaminants, we identified several emerging key topics of concern in groundwater associated with climate variability, impervious surfaces, increasing groundwater use, subsurface drainage, water availability, undervaluation of groundwater, and overuse of institutional controls. These topics have the potential to influence or threaten future groundwater quality and quantity in the state and should be acknowledged or explored further when developing a groundwater management plan.



CONTAMINANTS

PER- AND POLY-FLUOROALKYL SUBSTANCES HAVE TAKEN CENTER STAGE AS EMERGING CHEMICAL CONTAMINANTS IN MICHIGAN

PER-AND POLYFLUOROALKYL CHEMICALS

Per- and polyfluoroalkyl substances (PFAS, PFOS, and PFOA) have taken center stage as emerging chemical contaminants in Michigan. In the Great Lakes region, and across North America. They have been detected in our surface water and groundwater, leading to concerns about impacts to fish, wildlife, and human health. These chemicals are a suite of synthetic organic compounds that have been used since the 1940s. PFOS, PFOA, and several other PFAS chemicals are highly effective at repelling water, grease, and oil; preventing corrosion; and acting as a surfactant. As a result, these chemicals were used as coatings in food packaging and in numerous industrial and manufacturing activities, including tanneries, metal plating factories, electronics, and semi-conductors. Although several of these "older" PFAS chemicals were voluntarily phased out and taken off the market over the last 5 to 15 years, they are persistent in our environment and are considered "forever chemicals."

According to EGLE (Michigan's Department of Environment, Great Lakes, and Energy), Michigan's environment and its residents have been exposed to widespread perfluoroalkyl chemical contamination (Delaney and DeGrandchamp, 2012). PFAS chemicals move freely in soil and water, making groundwater particularly susceptible to contamination. Once groundwater is contaminated, remediation can be challenging as many of the standard remediation methods are not sufficient to meet regulatory standards. As of December 3, 2021, 195 PFAS contamination sites had been identified in Michigan.

The effects of PFAS exposure on human health remain largely unknown due to a lack of long-term data. In 2019, EGLE began the process of developing standards for various PFAS chemicals in drinking water supplies. In August 2020, Michigan established maximum contaminant levels (MCLs) and sampling requirements for seven PFAS compounds to reduce exposure to PFAS in drinking water and help protect public health. These regulations will cover about 2,700 public water supplies around the state. The MCLs are stricter than the EPA's lifetime health advisory levels.

SALINIZATION OF SHALLOW GROUNDWATER

Deep underground in many areas of Michigan, salt water is stored in aquifers that are much deeper than the freshwater aquifers that many rely on for water sources. Curtis et al. (2019) documented widespread salinization of shallow groundwater due to natural upwelling of deep brines in the southern two-thirds of the Lower Peninsula. It has long been known that most of the groundwater volume in the Michigan basin is hypersaline, containing total dissolved solids of 100,000 mg/L or more (Wahrer et al., 1996); for comparison, the average salinity of ocean water is approximately 35,000 mg/L (Railsback, 1989).

Chloride concentration in groundwater is a useful proxy for salinity. In the mid-continent of North America, natural concentrations of chloride in most shallow aquifers are usually less than 15 mg/L (Hem, 1985). Curtis et al. (2019) documented three regions of the Lower Peninsula that exhibit widespread, elevated (>20 mg/L), or severely elevated (>250 mg/L) chloride concentrations (Figure 2). The salinization of shallow groundwater is most severe in the Saginaw lowlands, the coastal lowlands of the Thumb, and the southeast Lower Peninsula. It is also worth noting that many of these lowland areas also support intensive agriculture. Chloride intrusion is less severe in the west-central lowlands, but the notable increase in groundwater pumping in this region threatens the long-term sustainability of the regional bedrock aquifer by enhancing the upwelling of deep brines. Curtis et al. (2019) concluded that the major controls of brine upwelling in these impacted regions of the Lower Peninsula were (1) higher-order streams serving as master groundwater discharge sites that promote deep brine upwelling; (2) the widespread occurrence of low permeability rates in these regions, which severely restricts deep recharge and the associated dilution of upwelling saline groundwater; and (3) the increasing number and pumping capacity of water well withdrawals, which alter the natural discharge pathways of saline groundwater.

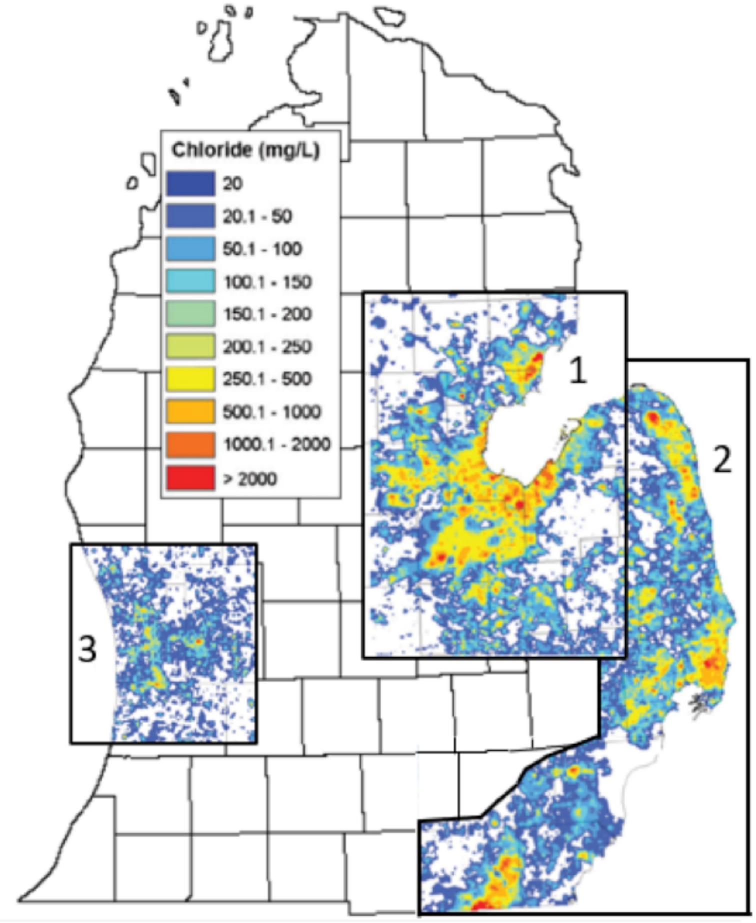


Figure 2. Chloride concentrations in groundwater, interpolated using 1 km x 1 km cells. Region 1: Saginaw lowlands. Region 2: Thumb and Southeast Michigan coastal lowlands. Region 3: West-central lowlands (adapted from Curtis et al., 2019).

AGRICULTURAL FERTILIZER & PESTICIDES

Fertilizer and pesticides used in agricultural and commercial settings have the potential to contaminate groundwater aquifers, posing threats to human health. Urea and other nitrogen source fertilizers are some of the most common commercial fertilizers applied to plants; these fertilizers easily convert to nitrate that can leach through the soil. Nitrates at heightened levels in groundwater used for drinking can lead to serious health issues such as blue baby syndrome, a potentially deadly condition of infants (Knobeloch et al., 2000). EPA's maximum contaminant level (MCL) for nitrate to protect against blue baby syndrome is 10 mg/L. Nitrate does occur naturally in groundwater, but concentrations greater than 3 mg/L generally indicate contamination (Madison and Brunett, 1985); another nationwide study found that concentrations greater than 1 mg/L indicate human activity (Dubrovsky et al., 2010). Recently, USEPA estimated that groundwater beneath 3,254 square miles (6%) of Michigan had nitrate concentrations greater than 5 mg/L (more than half of the MCL and indicating contamination), affecting 29% of the population with self-supplied drinking water (USEPA, 2021). In addition, 15 of Michigan's regulated community water supplies reported nitrate concentrations above the maximum contaminant level set by the USEPA (six of which remain unresolved).

Fertilizer use and sales have varied over time in Michigan, with use having increased steadily from the 1930s (when commercial fertilizers first became available) to the early 2000s when total consumption of fertilizers in Michigan leveled off (MDARD, 2022a). According to USEPA (2020), the amount of N fertilizer purchased in Michigan in 2007 contained 243.6 million kilograms of N. The longer-term trend shows an 8% decrease in N fertilizer sales in Michigan from the period of 2002–2006 to the period of 2007–2011. Despite a slight decrease in recent N fertilizer sales, legacy N in groundwater is still posing environmental and health risks to Michigan residents.

Virtually all agricultural commodities produced in Michigan require treatment with pesticides to prevent serious yield losses from pathogens and insect, nematode, vertebrate, and weed pests (MDARD, 2021). Atrazine and glyphosate are both common herbicides that can found in groundwater, streams, and sediment in Michigan and throughout the U.S. (Battaglin et al., 2014; Rendon-von Osten and Dzul-Caamal, 2017). Atrazine ingestion through contaminated drinking water sources has been linked to lower birth weights in children among other health concerns. In aquatic ecosystems, atrazine adversely impacts water bodies by lowering dissolved oxygen and pH and reducing macrophyte abundance (Cleary et al., 2019).

FAILING SEPTIC SYSTEMS

More than 1.3 million homes and businesses in Michigan depend on septic systems to treat wastewater (EGLE, 2016). If not maintained (emptied regularly), septic systems can fail to perform, discharging raw sewage that can contaminate groundwater and harm local waterways, releasing bacteria, viruses, and household toxins. In the Saginaw Bay area of Michigan, households with failing septic systems generate between 505 million and 1.26 billion gallons of sewage annually that may be entering the environment (PSC, 2018). In a separate study that sampled 64 streams in Michigan, *E. coli* and *B. thetaiotaomicron* (a human source-tracking marker) were routinely detected (Verhougstraete et al., 2015). This study pointed to septic systems as the primary driver of fecal bacteria levels in rivers. Watersheds with higher concentrations of septic systems exhibited significantly higher concentrations of *B. thetaiotaomicron*.

Michigan is the only state without a statewide sanitary code. Instead, the Michigan Public Health Code charges local health departments with developing and implementing codes regulating individual or small-quantity on-site wastewater treatment systems. Currently, local health departments in only 11 of Michigan's 83 counties conduct inspections of on-site wastewater systems at the time of real estate transactions. Michigan's Water Strategy, a 30-year plan for Michiganders to protect, manage, and enhance Michigan's water resources for current and future generations, outlines several recommendations to improve the management and maintenance of Michigan's on-site wastewater treatment systems including education and outreach, inventory and assessment of private water supplies and septic systems, and periodic inspection of on-site septic system performance (EGLE, 2016).

HAZARDOUS SUBSTANCES

Michigan groundwater also receives contamination from a broad list of industrial contaminates such as trichloroethylene (TCE), tetrachloroethylene (PCE), 1,4 – dioxane, arsenic, hexavalent chromium, chlorides, and PFAS, to name a few. The EGLE Remediation and Redevelopment Division, which oversees the remediation and redevelopment of contaminated properties in Michigan, currently lists 1,136 facilities under Part 201 (Environmental Remediation) of PA 451 (1994), or under Part 213 (Leaking Underground Storage Tanks) of PA 451 that have submitted response activity plans to EGLE (EGLE-Remediation and Redevelopment Division, 2022). Part 201 covers releases of hazardous substances or the potential release of discarded hazardous substances in quantities that are or may become injurious to the environment or to public health, safety, or welfare. Part 213 provides remedies for releases from underground storage tank systems. USEPA currently lists 90 Superfund sites in Michigan. Superfund sites are polluted locations in the U.S. requiring a long-term response to clean up hazardous material contaminations. Many of these sites have contaminated groundwater directly, and some pose human health risks from vapors released from volatile organic compounds that are trapped in the groundwater and soil beneath the site. Figure 3 shows Michigan's Part 201 and Part 213 contaminated sites. These tend to concentrate around urban areas, but contamination is broadly dispersed around the state.

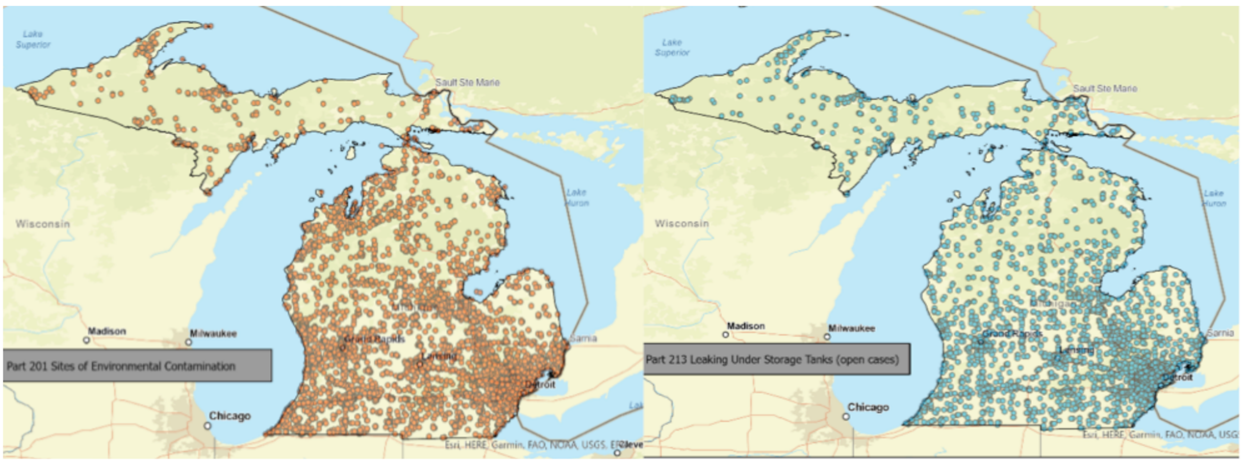


Figure 3. Michigan Part 201 (left) and Part 213 (right) contaminated sites with broad coverage across Michigan. Data sourced from Michigan GIS Open Data.

CLIMATE VARIABILITY

Changes in weather patterns including storm intensity, seasonality, and drought severity and frequency are having significant impacts on availability and services provided by groundwater. Annual precipitation in Michigan has been well above average in the 2000s, with the 5-year period (2010–2014) being the wettest on record (Frankson et al., 2017). Average annual precipitation in Michigan increased by 12.9% between the periods of 1960–1980 and 2000–2016, and the number of wet days that followed wet days increased by 3% (J. Andresen, topic expert speaker). Rain provides a major source of water to Michigan crops, but the increased precipitation that Michigan is experiencing comes at different times of the year and is increasingly unavailable during critical periods in the growing season (Wuebbles et al., 2019). In addition, heat waves and droughts have become more frequent and more intense since the 1960s (USGCRP, 2017). Despite this, future growing-season precipitation is predicted to increase in the short-term; however, it is likely to decrease 5-15% by the end of the century (Byun and Hamlet, 2018).

The climate change impact on groundwater in Michigan is counterintuitive. Although precipitation is projected to increase across Michigan, these increases will most likely occur outside of the growing season (Frankson et al., 2017), which, combined with higher temperatures, will increase the need for agricultural irrigation (most of which utilizes groundwater). Average annual temperatures in Michigan are projected to exceed historical record levels by the middle of the 21st century, which will increase evapotranspiration rates and the rate of loss of soil moisture (Frankson et al., 2017). Evapotranspiration is the main driver of losses to the surface water budget, so any increases in evapotranspiration can have a significant impact on water availability. Thus, future summer droughts are likely to be more intense, requiring even more irrigation use of groundwater.

Another counterintuitive impact of climate change in Michigan is the reduction of groundwater recharge. Large rainfall events often result in excess runoff due to the soil's inability to infiltrate water at a fast enough rate. Over the past decade, Michigan experienced the highest frequency of 2-inch rain events in the historical record (Frankson et al., 2017). Comparing the period of 1961–1990 with that of 2000–2010 in the Midwest, Saunders et al. (2012) found that the frequency of 3-inch per day or more storms has increased by 52%, and the total amount of precipitation in a year from all extreme storms has increased by 39%. Because the frequency of high-intensity rainfall events has greatly increased in the past several decades, many rainfall events are now producing mostly surface runoff and contributing little to groundwater recharge. Rainfall rates exceeding the saturated soil infiltration capacity produce surface runoff, which limits groundwater recharge.

Infiltration is the process of water soaking into soil. The infiltration rate (inches/hour) at which water can soak into soil during a rainfall event is equal to the infiltration capacity of the soil or the rainfall rate, whichever is lesser. The infiltration capacity is the maximum rate at which soil can absorb water. Generally, dry soils have much larger infiltration capacities than when they are fully saturated because most of the pores that occur between soil particles are empty and can store water at the beginning of a rain event. During a rainfall event, the transition from dry to saturated infiltration capacities takes 5-30 minutes, depending on the soil type (Figure 4). Saturated infiltration capacities vary from 9.3 inches/hour for sand, to 2.4 inches/hour for loamy sand, to 0.9 inches/hour for sandy loam, to 0.5 inches/hour for loam. Fine-textured soils (clay loam-clay) have saturated infiltration capacities of 0.08 inches/hour or less. However, intense rainfall on very dry soils does not evenly or initially readily infiltrate. A useful analogy is pouring water on a very dry sponge. Although the sponge has the potential to absorb water, a considerable amount of the initial water poured on the dry sponge runs off before the sponge starts to absorb and hold water up to its full capacity.

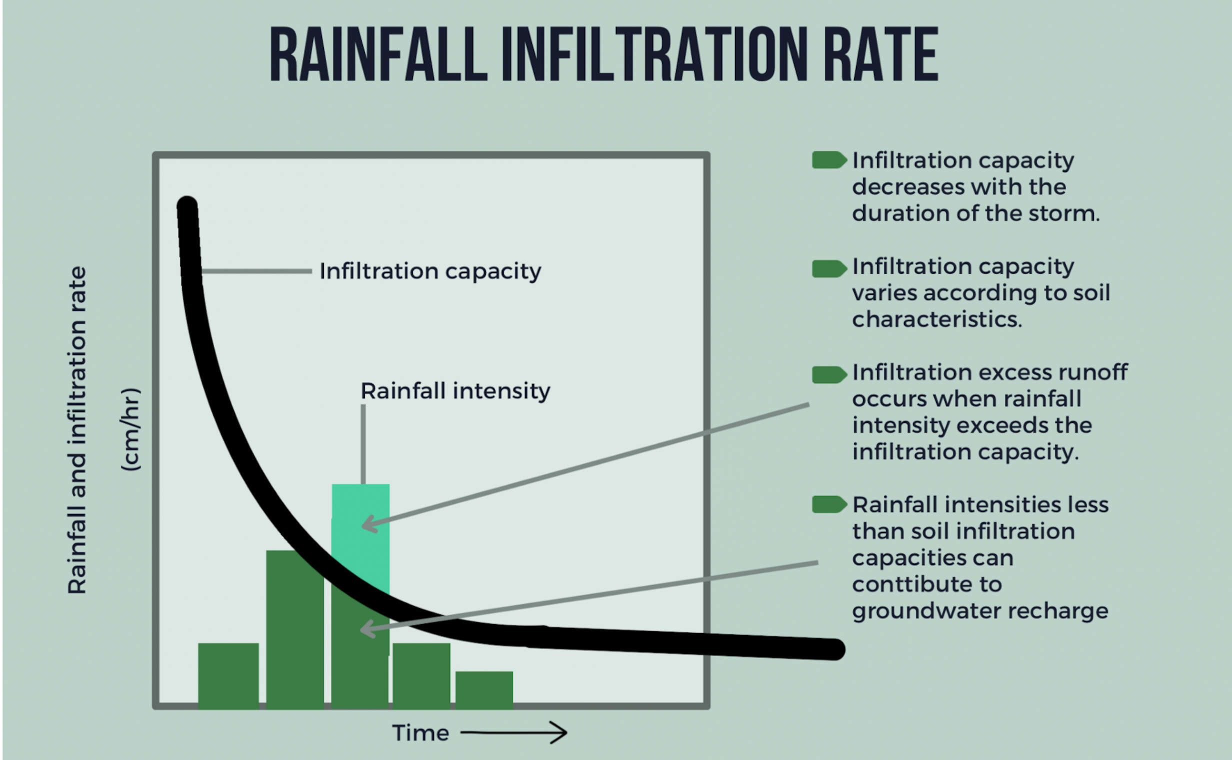


Figure 4. The relationship between rainfall and infiltration rates on groundwater recharge potential.

IMPERVIOUS SURFACES ALTER LOCAL HYDROLOGY

Impervious surfaces alter local hydrology by reducing groundwater recharge, altering stream flows, mobilizing pollutants, and increasing flooding risk. Impervious surfaces such as rooftops, streets, sidewalks, and parking lots divert nearly 100% of the precipitation that falls on them to surface runoff, eliminating groundwater recharge beneath those surfaces. These hard surfaces are associated with developed land, which has been increasing around the state. The Southeast Michigan Council of Governments (SEMCOG, 2003) reported that developed land in the seven counties of Southeast Michigan increased by 17% from 1990 to 2000.

Compounding this issue is the alteration of groundwater contributions to stream flows within these watersheds. Most of Michigan's streams get a sizable portion of their flow from groundwater; this contribution from groundwater is known as baseflow. This flow is characterized as steady and cool, typically entering the stream near 55˚F year-round. These cold temperatures and thermally stable conditions are critical to the survival and distribution of many fishes in Michigan, notably trout. In contrast, summer runoff from impervious surface is characterized as flashy and warm, typically entering the stream near 70˚F and reaching temperatures as high as 90˚F. Such flashy runoff events often carry pollutants from roads and parking lots, and their warm temperatures can negatively affect thriving fish populations in cold-transitional streams (streams on the verge of transitioning from one that supports coldwater fish to one that can only support fish that will tolerate warmer waters).

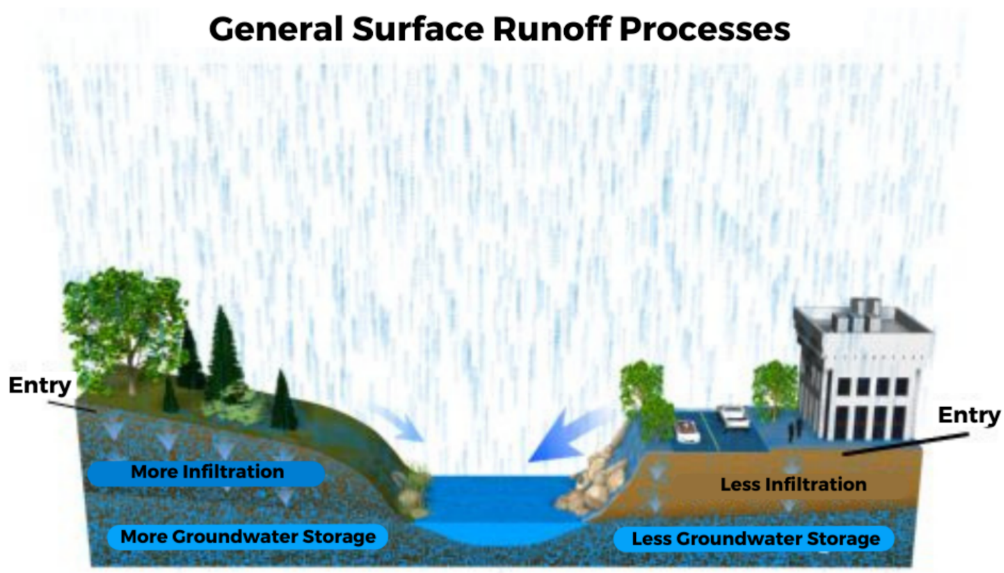


Image modified from The COMET Program

Lastly, increasing the percentage of impervious surfaces in a watershed increases flooding risk by increasing the volumetric load of runoff generated by storms. This runoff increase puts additional strains on conveyance systems such as ditches, culverts/bridges, and aging storm and wastewater infrastructure. According to a recent national flood risk report (First Street Foundation, 2020), Detroit ranked 16th in the country for the number of properties at substantial risk for flooding (21,615 properties — 6% of all properties in the city). This same report concluded that 315,600 properties statewide have a substantial risk of flooding and that this number will likely increase by 4.5% over the next 30 years. The First Street Foundation report ranked the following municipalities as the top ten in Michigan for the number of properties at risk for a 500-year flood event: Detroit, Warren, Grand Rapids, Sterling Heights, Lansing, Flint, Dearborn, Dearborn Heights, St. Clair Shores, and Grosse Pointe Woods. This was also supported by a recent study where 43% of the 4,667 Detroit households surveyed between 2012 and 2020 reported household flooding (Sampson et al. 2021).

INCREASING GROUNDWATER USE

Over the past decade, there has been a steady increase in the percentage of the state's total water use originating from groundwater and a slight increase in total groundwater use in this same period (Figure 5). Michigan tracks its high-capacity water withdrawals through EGLE's Water Use Program. It defines high-capacity withdrawals as those greater than 100,000 gallons per day. Water use data are reported under three sources: Great Lakes, groundwater, and surface water. In 2019 alone, large-capacity water users in Michigan extracted 197.3 billion gallons of groundwater, not including self-supplied residential water users (EGLE, 2019). The public water supply sector used the largest volume of groundwater in 2019 (76.2 billion gallons), followed by irrigation (76.1 billion gallons), industry (31.3 billion gallons), livestock (7.8 billion gallons), other (3.4 billion gallons), electric power generation (1.4 billion gallons), and commercial-institutional (1.1 billion gallons). The total groundwater extraction from these withdrawals has been increasing since 2010.

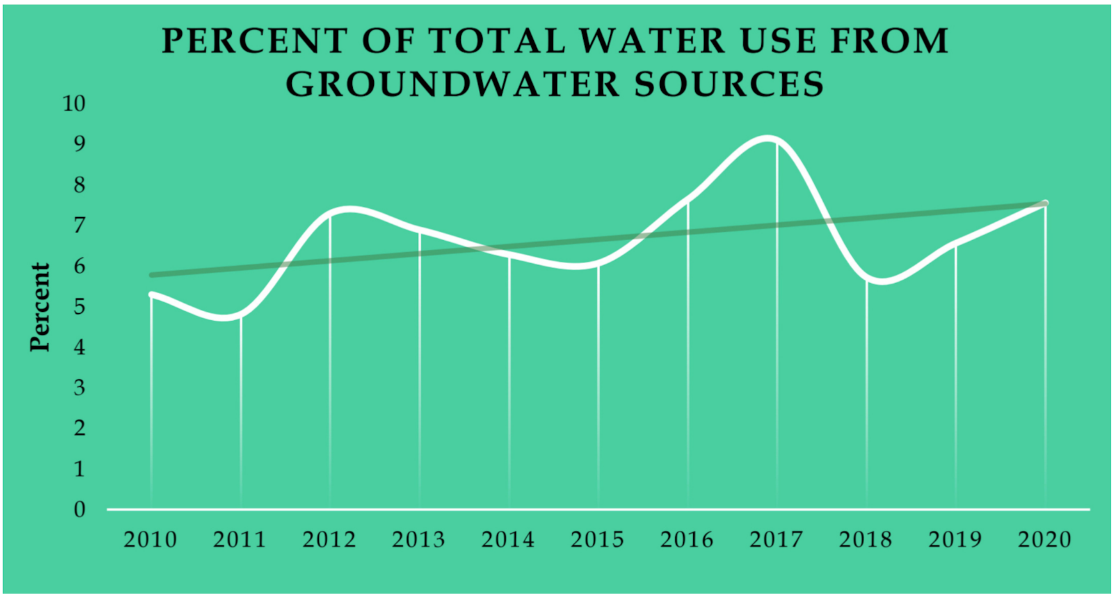


Figure 5. Trend in groundwater use as a percentage of other sources.

Groundwater extraction can divert critical groundwater flows to streams, impacting fish populations. Michigan manages these withdrawals through the Water Withdrawal Assessment Tool (WWAT), an online system that predicts withdrawal impacts to baseflow in streams and their likely effects on fish populations (Hamilton and Seelbach, 2011). However, there is little, if any, consideration of encouraging infiltration (recharge) back into the groundwater system outside of use-based return flow.

The use of groundwater as a water supply has significantly increased within the U.S. over the past 70 years, driven by the development of more energy-efficient pumps and rural electrification. This expansion of groundwater use has been notable in Michigan where increased need for irrigation has been driven by demand for production, requirements of seed corn and potato contractors, and climate variability. A 2006 report from the Michigan Department of Environmental Quality suggested a steady expansion of irrigation into the near future (EGLE-WUP, 2006). This expansion in irrigation was also noted through national surveys. Between 1997 and 2017, the amount of irrigated cropland in Michigan expanded by 263,141 acres — a 64.6% increase (USDA NASS 1997, 2017). During approximately the second half of this time frame (2008–2020), the number of agricultural irrigation wells in Michigan more than doubled, increasing by 152% (USDA NASS, 2008, 2018; EGLE-WUP, 2021).

Irrigation use of groundwater in Michigan is primarily agriculturally driven, and its increase in demand can be linked to the contract-grower nature of agriculture in parts of the state (e.g., seed corn and chipping potato production in Southwest Michigan). Many of these high-value crops require irrigation to ensure certain qualities or properties and to minimize risk associated with climate variability.

As discussed previously in the Climate Variability section, agricultural irrigation will likely need to expand to meet needs due to our changing climate, and groundwater is already being used as a physical hedge against climate risk. Increasing demand for agricultural production also has the potential to increase demand for fertilizer inputs, further increasing risks to groundwater quantity and quality.

Changing climate is already influencing growing degree days, lengthening the growing season in Michigan, and migrating agriculture northward (Krause, 2022). To support agriculture growth, irrigation is also following this trend of northward migration. Figure 6 shows the geographic mean of 6,199 new withdrawal requests submitted through the Michigan WWAT since January 5, 2009 (the first water withdrawal registration date on the year the WWAT was mandated). Comparing the geographic mean center for new registrations of a given year helps to clarify trends over time. The geographic mean center uses the average latitude and longitude of a sample of points to calculate a single, weighted location representative of the center of the point dispersion. Figure 6 displays the locations for each year from 2009 through 2022. The earlier years of water withdrawal requests are further south compared to requests in later years that are further north. It is likely that many of the same drivers (mitigating risk from climate variability and increasing demand for production; Steinman et al., 2022) that have increased groundwater use will continue to have an impact on the resource into the future.

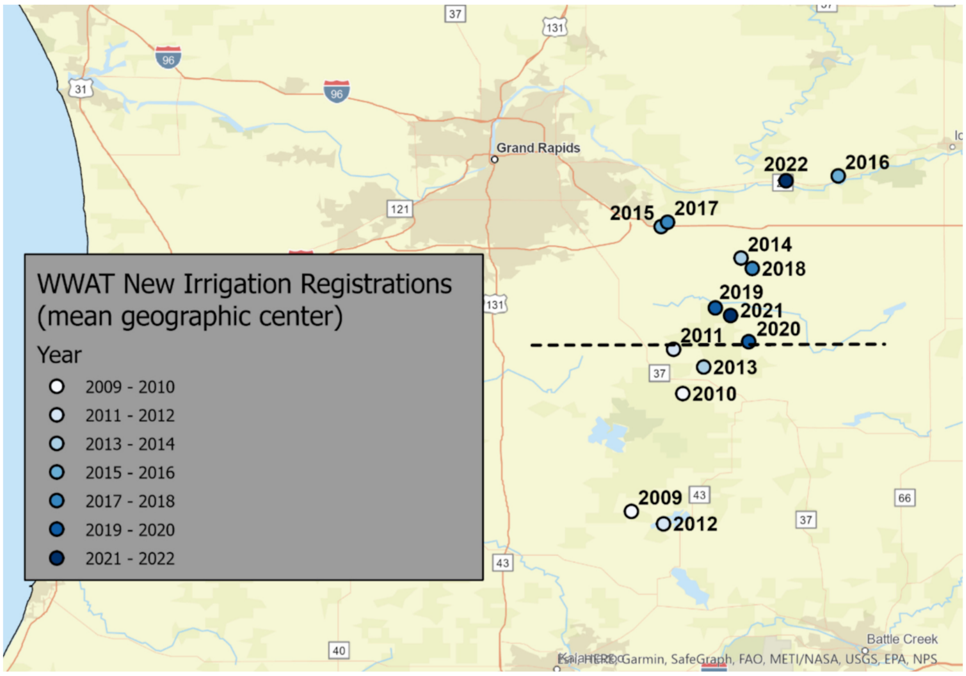


Figure 6: The mean geographic centers by year of water withdrawal requests submitted through the Water Withdrawal Assessment Tool. Institute of Water Research, MSU.

AGRICULTURAL SUBSURFACE DRAINAGE REDUCES AQUIFER RECHARGE

Ongoing increases in subsurface drainage continue to reduce aquifer recharge at a time when our reliance on groundwater is increasing. Michigan ranks in the top five states with the highest percentage of cropland classified as tiled at 38% (Michigan Farm News, 2019). Increases in subsurface drainage across the state have shunted to surface drainage, substantial portions of infiltrated precipitation that may otherwise have continued to percolate through soils to recharge groundwater aquifers. A modeling study conducted by IWR in the Saginaw River watershed indicated an average of 20% annual reduction in groundwater infiltration due to the presence of agricultural tile drains (Asher et al., 2016). Michigan has experienced a 17% increase in tile drain acres between 2012 and 2017 (USDA NASS, 2017).

We recognize the geographical and proximal linkages between subsurface drainage and the effects on local and regional groundwater recharge.

Drain tiling may in fact affect available water in groundwater systems far from the properties on which the drainage was installed. There is a growing recognition that groundwater recharge (at a specific location or locations) is an important public good that benefits many in the groundwater basin.

WATER AVAILABILITY FOR USE

Groundwater is not always abundant and available in all parts of Michigan. Due to certain geologic features and demand put on the aquifer, the quality or quantity may not be sufficient for use, as seen in parts of Southwest and Southeast Michigan as well as Saginaw. A study released by the MSU Department of Civil and Environmental Engineering, the MSU Institute of Water Research, and Ottawa County in 2018 confirmed years of anecdotal reports from residents and well drillers: Groundwater levels in parts of Ottawa County have declined over the past 50 years and the groundwater that remains has elevated chloride or salt levels (Curtis et al., 2019). Elevated levels of sodium chloride in water can corrode pipes, damage crops, and potentially exacerbate health concerns among individuals with high blood pressure. According to the study, which began in 2011, the static water levels (the levels in a well when the pump is not operating) had been declining in the area since the 1960s. Extensive historical data show that some areas of the county have seen a drop of as much as 40 feet over the past 50 years. Estimates show that if water consumption continues at the current rate without intervention, these areas will see another 10- to 15-foot decline in the next 20 years. A decline of this magnitude could result in wells that are inoperable due to reduced or minimally available water or unusable because of high chloride concentrations.

UNDERVALUATION OF GROUNDWATER

Given the historic abundance of groundwater and limited constraints to its access, very little work has been done in the Great Lakes region to understand the underlying economic value of it. In fact, groundwater withdrawn from natural systems has been essentially a costless function related to the resource itself (groundwater is free). The only costs associated with groundwater use have been the costs of well development, costs of pumping (energy), and potentially the cost of discharging used water back to the environment. The entire management of groundwater in the Great Lakes region is predicated on an ecological and health-risk basis (i.e., no adverse harm to stream flow, fishes, or human populations), rather than sustaining its inherent quantity and quality (and associated values). Threats to groundwater, either through (1) overuse, (2) contamination, or (3) how it is put back into nature from publicly owned treatment works (e.g., removing groundwater for municipal use and discharging that same water to surface water systems), all have material effects on the underlying short- and long-term values (ecological, economic, social, and cultural) of groundwater systems. All of these maladies (overuse and contamination) have their roots in a societal belief of an endless supply of groundwater. This can be observed in the common use and discard practices of most if not all groundwater. Thus, the politics and current belief of water abundance still dominates much of our current social construct and policy frameworks over groundwater and groundwater management. This perception poses a risk to sustainable long-term management of groundwater resources.

OVERUSE OF INSTITUTIONAL CONTROLS

Michigan's current legal framework aims to reduce the economic burden of groundwater contamination remediation through the use of restrictive management practices, commonly referred to as institutional controls (Beeler et al., 2020). These controls, typically in the form of restrictive covenants and ordinances, prevent exposure to contaminated water by forbidding the installation of new wells, abandoning contaminated ones, and prohibiting soil disturbance. When used as the sole response to a contamination, these controls effectively write-off the future use of the affected aquifer.

As of January 12, 2022, 2,654 restrictive covenants have been registered in Michigan covering 23,689 acres (37 square miles) of land. Additionally, six local units of government in the state have enacted groundwater ordinances that prohibit the installation or use of water wells on any parcel within a defined restricted zone (residences on these parcels were all connected to public water supplies at no cost to the owners). Collectively, these ordinances currently restrict groundwater use on another 9,395 acres (14.7 square miles) of land. The law also makes it difficult for state agencies to fully track contamination under the present reporting requirements. Furthermore, liable parties can self-implement cleanup measures without notifying the state, unless an institutional control is placed on the property.

While institutional controls may provide certain flexibility to landowners and operators (allowing them to maintain operations on contaminated properties if the risk is managed), until recently, no attempt had been made to measure the associated long-term economic or social costs of such practices. Michigan State University's IWR began leading a study in 2021, funded by EGLE, to look at the long-term cost of institutional controls and provide a decision support framework to aid state administrators when considering the use of institutional controls. Current policy enables aquifers in part or whole to be set aside indefinitely if cleanup is deemed too difficult or costly. The removal of these aquifers from future use may pose long-term risks to freshwater resource security and public health as the frequency of this practice increases.

OPPORTUNITIES FOR IMPROVED GROUNDWATER MANAGEMENT AND PROTECTION

Proper integration of data, models, tools, technology, and outreach can provide new opportunities to improve management and protection of groundwater resources in Michigan. Table 2 outlines five topic areas with recommended actions that can be taken to better manage emerging threats facing Michigan's groundwater.

Integrating existing groundwater data and efforts can maximize the benefit of models, tools, and technologies, better supporting decision-making in Michigan and the Great Lakes region. A network or portal through which stakeholders, researchers, and policy makers could access monitoring data, model outputs, news, published reports, and scientific articles would greatly aid the coordination of groundwater management in Michigan and help avoid the duplication of efforts.

INTEGRATION OF EXISTING AND NEW DATA

There are existing platforms that provide some of these features but not a comprehensive approach, such as EGLE's MiWaters system[1], the USGS Water Data clearinghouse[2], and the Michigan Groundwater Association website[3]. A centralized, actively managed groundwater hub could connect users to easily searchable databases; model outputs and scenarios; interactive maps that show past and current groundwater projects with access to their published data and reports; links to resources on groundwater policy in Michigan; news articles; and current funding opportunities. The system would serve as a one-stop shop for groundwater activity, akin to the USGS National Water Census[4], but focused on Michigan.

The Michigan Hydrologic Framework will facilitate statewide sustainable water management of both surface and groundwater by providing open access to integrated hydrologic models, up-to-date hydrologic and hydrogeologic data, and comprehensive hydrologic analyses. The Michigan Hydrologic Framework will support the dynamic creation of hydrologic models by integrating GIS-linked databases, existing models (input and output), and a statewide interpolation of the water table surface. To assist professionals and the public in understanding and utilizing hydrologic information, the Michigan Hydrologic Framework will function as a statewide "smart map" that describes the distribution, abundance, status, and trends of the linked atmospheric, surface water, and groundwater systems. In addition, EGLE is working to consolidate groundwater data housed by its programs, and the WUAC was funded to create a "Michigan Integrated Water Management Database." As the data, models, and knowledge around groundwater in Michigan are slowly built, we need to provide a means by which all these new disparate data and existing sources can be synthesized so they may better inform groundwater management in the state. Although the Michigan Hydrologic Framework will not address all the needs of a fully developed groundwater hub, it can provide a significant base platform to build the groundwater hub described above.

1 https://miwaters.deq.state.mi.us/miwaters/external/home
2 https://waterdata.usgs.gov/nwis/gw
3 https://michigangroundwater.com/news
4 https://www.usgs.gov/mission-areas/water-resources/science/national-water-census groundwater?qt-science_center_objects=0#qt-science_center_objects

DATA COLLECTION

LOW-COST SENSORS

The Internet of Things (IoT), which is a term used to describe a connected network (Internet or other communication network) of physical objects with sensors and other technologies, has grown exponentially in recent years, opening the door for low-cost sensor development and deployment. Low-cost sensors have been developed for many environmental monitoring applications, including water levels, irrigation management, water sampling, and much more. By utilizing these new low-cost sensors, high-density monitoring networks can be established at a fraction of the cost of traditional monitoring methods. Arduino, an open-source electronics platform based on easy-to-use hardware and software, is the most used platform for the development of these monitoring devices. It has enabled enthusiasts to develop environmental sensors at home, many of which are comparable to research-grade sensors (Chan et al., 2021).

The MSU Institute of Water Research and the University of Michigan have used both decision support technology and low-cost water level sensors to develop a smart stormwater management system for the Clinton River watershed. This system uses Arduino-based sensors to measure water levels in rivers, streams, and holding ponds, and reports these levels in real time to inform hydrologic models and to support planning and management decisions.

IoT technologies should continue to be explored to deploy low-cost, high-density monitoring networks for various water resources throughout the state. Examples include groundwater monitoring wells, lake and stream temperatures and water levels, and weather monitoring. Groundwater influences lake and stream flows and temperature, which can assist with monitoring changes in groundwater contributions to these resources.

CROWDSOURCED DATA

Leveraging the collective power of individuals can augment the automated potential of IoT in collecting groundwater data. The use of citizen science and crowdsourcing in water monitoring has grown over the past decade. Examples include Crowd Hydrology[5] (Lowry and Fienen, 2013) in which passers-by of stream-level gauges can simply text observations to a listed phone number. The system then stores the results in a central database and makes it accessible through a public website. Michigan has more than 30 such sites clustered in its Lower Peninsula. The Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS)[6] gathers volunteer-collected precipitation data throughout the U.S., with over 100 stations scattered across Michigan. EGLE maintains the Michigan Clean Water Corps (MiCorps)[7] as a network of volunteer monitors for surface water quality.

None of these resources, however, specifically address groundwater, and there have only been limited efforts reported in literature. Little et al. (2016) administered a crowdsourced monitoring project for groundwater monitoring for a county in Alberta, Canada, in which citizen scientists were provided 50 monitoring kits ($700 each) to gather data from private wells over a five-year period. Jamieson et al. (2020) created a successful citizen-driven groundwater monitoring network in Queensland,

Australia, in response to concerns about coal and gas extraction in the region. The City of Boston experimented with smart well caps that could aid in regular crowd-sourced monitoring of groundwater levels.[8] USGS is utilizing citizen science to monitor land subsidence caused in part by groundwater withdrawals in the Chesapeake Bay Region.[9] EPA plans to employ crowdsourcing in its National Groundwater Resource Survey, but this project is only in the planning stage.[10] These efforts provide guidance on how Michiganders can actively participate in managing their groundwater, but it will take support from state agencies, universities, and NGOs comparable to what has been invested in citizen-driven water quality monitoring.

5 http://www.crowdhydrology.com/
6 https://www.cocorahs.org/
7 https://micorps.net/
8 https://thebostonsun.com/2017/06/30/interactive-groundwater-well-caps-allows-people-to-crowd source-data-through-mobile-app/
9 https://www.usgs.gov/centers/cba/science/new-crowd-sourcing-will-contribute-study-land subsidence-and-sea-level-rise?qt-science_center_objects=0#qt-science_center_objects
10 https://www.citizenscience.gov/catalog/530/

ONLINE TOOLS AND DECISION SUPPORT SYSTEMS

Decision support systems provide a great opportunity to improve groundwater management by providing users the ability to explore "what-if" scenarios and seek management strategies that bring them closer to their intended outcomes or goals. A wide range of online DSSs exist for exploring the impacts of land cover change, agricultural management, and spatial variability on surface water resources, but there are relatively few focused on groundwater. Michigan's Water Withdrawal Assessment Tool (WWAT)[11], IWR's Great Lakes Watershed Management System (GLWMS)[12], and the Multiscale Adaptive Global Network (MAGNet) for Water[13] provide cloud-based platforms that allow users to explore various aspects of groundwater management in Michigan and are initial efforts toward providing integrated surface water and groundwater tools. In Michigan's Saginaw Bay and Maple River watersheds, the GLWMS uses the Soil and Water Assessment Tool to simulate how land management affects groundwater recharge. The WWAT estimates the degree to which proposed groundwater withdrawals in Michigan may affect baseflows and fish habitat in nearby streams. MAGNet for Water, which is available globally, utilizes topographic data and well records to three-dimensionally simulate groundwater flow directions and contaminant transport. While none of these tools individually are a one-stop shop for groundwater analysis in Michigan, collectively they represent a growing network of analytical capability that can aid groundwater management in the state.

EDUCATING LOCAL OFFICIALS

Local officials can improve their knowledge and understanding of groundwater concepts and basic management, given access to more groundwater-focused education modules. Most local officials have little or no prior experience in water resource management or community drinking water protection activities. While state and federal regulations help to protect our drinking water, which in Michigan is often from groundwater sources, the most effective groundwater protection activities occur at the local level and involve planning and zoning boards, pollution prevention planning, and firefighter right-to-know inspections, which enable requests and access to chemicals and hazardous materials used at sites in the community. Hosted by Michigan Sea Grant and MSU Extension, the Michigan Water School is a program to help elected and appointed officials increase their knowledge about water management and gain access to tools and resources to help impact their local economy. Water School focuses on these themes: (1) water quantity, (2) water quality, (3) water economics, finance, and planning, and (4) water policy. These programs should be emphasized more broadly and include additional components related to groundwater management.

11 https://www.michigan.gov/egle/0,9429,7-135-3313_3684_45331_45335-477090--,00.html
12 https://iwr.msu.edu/glwms2/
13 https://www.magnet4water.com/

Another resource for educating local officials, ***Drinking Water 1-2-3 Guide for Local Officials and Community Leaders*** (Metropolitan Planning Council July 2021), is available for free at https://www.canr.msu.edu/resources/drinking-water-1-2-3-guide-for-local-officials-and-community-leaders. This guide is designed to support local officials in understanding the key aspects of water management and the critical questions to discuss with their water system managers and engineers, municipal planners, public works officials, finance directors, developers, residents, and businesses. The guide covers concepts about groundwater, groundwater recharge, and withdrawals, which can benefit local officials regarding groundwater management and sustainable use. Although this guide focuses on Northeastern Illinois, its guidance and lessons are applicable to most of the Great Lakes region.

FUNDING INFILTRATION

Funding infiltration through private companies and federal agencies can increase recharge opportunities throughout the state and should be pursued further as part of a management strategy for optimizing recharge and sustaining groundwater resources. In the Maple River watershed, MSU IWR and 14 partnering organizations have increased nearly 12,000,000 gallons of groundwater recharge annually through adoption of agricultural conservation practices that improve water infiltration. This project and others help address state and federal natural resource concerns while also helping private companies source their products more sustainably.

There has been a growing interest in sustainable sourcing and net zero impacts from corporations seeking to reduce their environmental footprint. Companies such as Coca-Cola, Method Company, Keurig Green Mountain, and others that are heavily reliant on groundwater are seeking opportunities to make their operations water neutral. To achieve these goals, companies have started working with organizations like The Nature Conservancy to offset their water withdrawals from watersheds where they source their water. These efforts to become water neutral have created opportunities for monetizing infiltration.

FUNDING INFILTRATION THROUGH PRIVATE COMPANIES AND FEDERAL AGENCIES CAN INCREASE RECHARGE OPPORTUNITIES THROUGHOUT THE STATE AND SHOULD BE PURSUED FURTHER AS PART OF A MANAGEMENT STRATEGY FOR OPTIMIZING RECHARGE AND SUSTAINING GROUNDWATER RESOURCES.

In 2012 and 2016, The Nature Conservancy collaborated with IWR to develop online tools that could succinctly estimate changes in infiltration or groundwater recharge based on land cover changes or conservation practice adoption. These online tools were used with Coca-Cola in the Paw Paw River watershed and Method Company in the Saginaw Bay watershed to assist them in achieving water-neutral operations. In these watersheds, local conservation district technicians would use the tools through the Great Lakes Watershed Management System[14] to quantify the groundwater recharge benefits (gallons of recharge) of changing a management practice on the farm (e.g., changing crop rotations or converting a field to pasture). The landowner could then enter into an agreement to adopt the practice and receive a per-gallon payment rate based on the estimated recharge value from the tool.

Building on the same concept, IWR received a grant the following year through the Natural Resources Conservation Service (NRCS) Regional Conservation Partnership Program (RCPP) (Office of Debbie Stabenow, 2018) to improve fish habitat in the Maple River watershed by increasing infiltration. Managing watersheds to maximize infiltration provides many ecological benefits and has enormous potential to improve both water quality and quantity locally and regionally.

As consumer preferences evolve, there has been a shift toward buying locally produced goods and brand preference based on responsible and sustainable production. This has led companies like Kellogg's and General Mills to include topics like sustainable sourcing and natural resource conservation as sustainability goals (Kellogg's, 2019). They actively report on the number of farmers being supported and conservation adoption in watersheds where they source their grains. General Mills states in their responsibility and sustainability section of their website that *"We will advance regenerative agriculture on 1 million acres of farmland by 2030"* (General Mills, 2019). Regeneration International (https://regenerationinternational.org/2017/02/24/what-is-regenerative-agriculture/) describes regenerative agriculture as *"farming and grazing practices that, among other benefits, reverse climate change by rebuilding soil organic matter and restoring degraded soil biodiversity – resulting in both carbon drawdown and improving the water cycle."* Regenerative agriculture and conservation adoption can directly improve infiltration and groundwater recharge. Companies seeking to achieve these sustainability goals can indirectly fund infiltration as they invest in farming communities while also advancing the concept of infiltration more broadly.

14 https://iwr.msu.edu/glwms2/

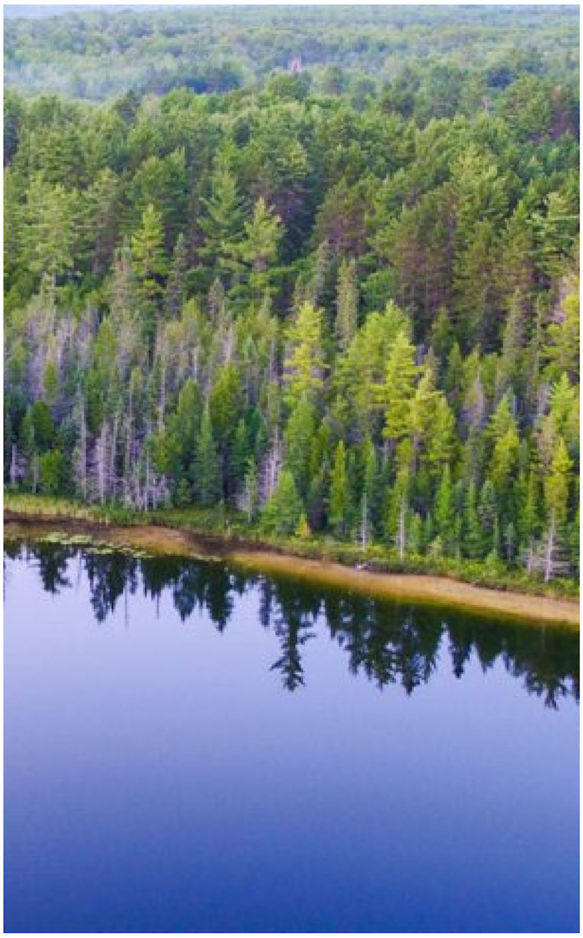
TABLE 2.

OPPORTUNITIES FOR IMPROVED GROUNDWATER MANAGEMENT AND PROTECTION

Topic		Purpose/Need	Recommendation
1.	**Integration of Models and Existing Data**	Question: How can we optimize use of new and existing data and information with models to better understand the states groundwater condition? Models enable users to test complex relationships and data to better understand the groundwater interactions and make future predictions. They can help integrate existing data and guide design for new data. There are a variety of existing datasets on lithology, wells, groundwater, and other information that can benefit stakeholders if they are more easily accessible and in forms readily consumed by models.	• Create a network or online hub to allow stakeholders, researchers, and policy makers to access monitoring data, news, published reports, model outputs, and scientific articles to aid in the coordination of groundwater management in Michigan and help avoid the duplication of efforts. • Integrate and build off new technologies such as the Michigan Hydrologic Framework anticipated to be built for and supported by EGLE. • Utilize or develop more interoperable model platforms to take advantage of cloud-based datasets, sharing of model input/outputs, and real-time data where available.
2.	**Data Collection**	Question: How can we maximize groundwater-related data collection while minimizing the associated costs? Lower-cost data collection using Arduino-based sensors and crowdsourced data can supplement data required for models and decision making while keeping costs low.	• Explore and utilize high-density, low-cost sensor networks to enhance available data. • Utilize existing crowdsourced data or explore developing crowdsourced data collection networks.

Topic		Purpose/Need	Recommendation
3.	**Online Tools and Decision Support Systems**	Question: How can we improve management and inform decision making on complex management decisions? Decision support tools can help inform complex decisions by allowing users to conduct "what-if" scenarios to see the effects of their decisions.	• Utilize existing decision support tools and online model applications to better inform decision making and explore decision outcomes. Examples include (1) Multiscale Adaptive Global Network for Water, (2) Michigan's Water Withdrawal Assessment Tool, and (3) the Great Lakes Watershed Management System.
4.	**Educating Local Officials**	Question: How can we increase the knowledge and understanding of groundwater concerns and protection within communities? Local officials can improve their knowledge and understanding of groundwater concepts and basic management with more groundwater-focused education modules.	• Develop education modules focused on groundwater education (systems, benefits, risks, protection, and awareness). • Utilize existing courses/training available such as Drinking Water 1-2-3 Guide for Local Officials and Community Leaders and Michigan Water School.
5.	**Funding Infiltration**	Question: How do we fund and support locally enhanced groundwater recharge? Partnering with private companies and federal agencies interested in enhancing fish and wildlife, achieving a water neutral footprint, or supporting agricultural conservation can increase recharge opportunities throughout the state.	• Develop public and private partnerships with agencies and companies interested in enhancing fish and wildlife, achieving a water neutral footprint, or supporting agricultural conservation.

CONCLUSION



Groundwater is becoming increasingly important to Michigan's economy, health, and well-being of its residents, yet a strategic plan is lacking to guide its sustainable use and ensure its beneficial services for future generations. Emerging threats to groundwater in Michigan are focused on a combination of compounding factors, which have the potential to reduce sustainable use of the resource over time. To address this, stakeholders including state agencies, universities, conservation organizations, the business community, and others should organize discussions with the goal of establishing a strategic plan to enhance aquifer recharge, protect groundwater quality and quantity, and establish continuous monitoring to track the resource more closely. This report provides recommendations for data, model development and delivery, and research priorities needed to better understand and manage Michigan's groundwater. It also recommends five areas of opportunity for improved groundwater management and protection. Addressing the emerging risks, conducting research, and utilizing some of the novel approaches described will improve Michigan's sustainable use of groundwater, increasing its groundwater security for future generations.

ADDRESSING THE EMERGING RISKS, CONDUCTING RESEARCH, AND UTILIZING SOME OF THE NOVEL APPROACHES DESCRIBED WILL IMPROVE MICHIGAN'S SUSTAINABLE USE OF GROUNDWATER, INCREASING ITS GROUNDWATER SECURITY FOR FUTURE GENERATIONS.

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