Evaluation of Modeling Framework and Social Perspectives Regarding Sustainable Groundwater Management in Michigan

by

Ivan Steven Jayawan

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Environmental Engineering)
in the University of Michigan
2019

Doctoral Committee:
    Professor Avery H. Demond, Co-Chair
    Assistant Professor Brian R. Ellis, Co-Chair
    Professor M. Clara Castro
    Associate Professor Valeriy Ivanov

Ivan Steven Jayawan

ijayawan@umich.edu

ORCID: 0000-0002-4544-7012

DEDICATION

This dissertation is dedicated to
my wife to be, Winnie,
my grandmother, Thiam Hiong
my parents, Sugiar and Hanna,
my sister and brother, Steffy and Karl,
and my other family members, whom I can’t mention one by one,
who have offered me unconditional love, support, and encouragement to pursue a doctoral degree and finish my dissertation

my high school science and mathematics teachers,
who made me fascinated by science and influenced my decision to pursue a degree in engineering

especially for my parents,
thank you for nurturing me with curiosity very early on my life, encouraging me to experiment with the world and teaching me to approach problems methodically and scientifically

and for all other people who have had an impact in my life helping to make me the person I am today

ACKNOWLEDGEMENTS

First and foremost, I would like to express my greatest appreciation and deepest gratitude to my two advisors, Professor Avery H. Demond and Assistant Professor Brian R. Ellis, for their guidance and support throughout my graduate school years. Prof. Demond was willing to give me an opportunity to do research with her group during my last semester of my M.S. study and this inspired me to pursue my Ph.D. Brian has been both a great advisor and a great friend for me as we have shared many things outside of research. Both my advisors always provided me with helpful suggestions with patience whenever I struggled with my research. They were also very understanding and supportive when I fell ill halfway through my study, and I really appreciate that gesture when I needed it the most. I would also like to acknowledge the helpful feedback and constructive comments of my dissertation committee members: Assoc. Prof. Valeriy Ivanov and Prof. M. Clara Castro.

I would like to also thank many people within the Department of Civil and Environmental Engineering (CEE), School for Environment and Sustainability (SEAS), and the Consulting for Statistics, Computing and Analytics Research (CSCAR) at the University of Michigan. Colin Sullivan and Leyi Yin from the CEE Department for helping with solving some of the streamflow depletion analytical solution and for helping with the hierarchical clustering analysis code, respectively, Dr. Jason Duvall of SEAS for the guidance in setting up and reviewing the plan for mental model and co-orientation analysis, Dr. Avik Basu of SEAS for providing me with the code for hierarchical clustering analysis, Dr. Paul Seelbach of SEAS for providing many insights

regarding the Water Withdrawal Assessment Tool in Michigan, and Dr. Manish Verma of CSCAR for providing consultations in the statistical analysis for the streambed hydraulic conductivity study. I also wanted to acknowledge Dr. Howard W. Reeves of the USGS Michigan - Ohio Water Science Center for providing me with the STRMDEPL08 code as well as offering help and reviewing an early version manuscript of Jayawan et al., 2016, Professor David W. Hyndman of the Michigan State University (MSU) Department of Earth and Environmental Sciences for providing streamflow data of Black Creek, Monica Day of the MSU Extension office for offering to put the co-orientation online survey link on MSU's extension website, Dr. Nick D. Ward of the University of Canterbury in New Zealand for providing the code for the Ward and Lough (2011) analytical solution for streamflow depletion, Dr. Bryan Burrough of the Michigan Trout Unlimited and Mrs. Jacque Rose for providing me with many valuable insights regarding the WWAT and groundwater management in Michigan.

My doctoral study in the University of Michigan was sponsored by the National Science Foundation under grant number 1214416 and the Water Center of the Graham Sustainability Institute at the University of Michigan. I am also grateful for the Graduate Student Instructor appointments in the CEE department which provided funding as well as invaluable experience in the development of my teaching and communication skills.

Last but not least, I would not have been able to finish my doctoral degree without the support and encouragement of my wife to be, my parents, my grandmother, my brother, my sister, my other family members, my friends, and the Indonesian community here in Ann Arbor. My deepest gratitude to both of my parents for the moral and financial support for my bachelor's degree in Singapore and my master's and doctoral degree in the U.S. Thank you to my brother (despite of his Buckeye affiliations) who flew from Columbus to Ann Arbor to take care of me in the hospital for a few days. Thank you to my sister who has helped a lot with my wedding preparation so that I can focus on finishing this dissertation. Thank you to my friends and the Indonesian community here, whom I viewed as a family away from home and have provided me with support and encouragement. Most importantly, I would like to thank my wife to be, Winnie, for her love, patience, tolerance, understanding, and company; these mean everything to me.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

TABLE

LIST OF FIGURES

FIGURE

LIST OF EQUATIONS

EQUATION

LIST OF APPENDICES

APPENDIX

A. Supplemental Information for Chapter 3

B. Supplemental Information for Chapter 5

ABSTRACT

Ensuring sustainable management of groundwater resources is important even in a water-rich state such as Michigan. Large Quantity Withdrawals (LQW) associated with hydraulic fracturing and industrial activities (e.g., Nestle's water withdrawal request in Evart, MI) in the Northern Lower Peninsula as well as LQW related to irrigation wells in the Southern Lower Peninsula have become an issue in recent years. The objectives of this dissertation were to evaluate the groundwater management in Michigan from two different perspectives: (1) from the modeling framework where the approach currently used to evaluate LQWs were assessed and possible strategies to improve it were explored, and (2) from the social perspectives where the mental model and degree of understanding between the 'experts' and 'non-experts' stakeholders regarding groundwater management in Michigan were evaluated.

As part of its groundwater management framework, the State of Michigan developed the Water Withdrawal Assessment Tool (WWAT) to screen proposed LQWs. However, it has been criticized by the public as both too conservative and not conservative enough. To evaluate the WWAT's groundwater model, a 3-D numerical groundwater model was developed and the estimates of streamflow depletion calculated using this model were compared with those generated by the WWAT. Two issues were found with the groundwater model of the WWAT: conceptualization of the hydrogeologic setting and assignment of parameters. The modified Hunt (1999) analytical solution used by the WWAT assumed a single layer, unconfined aquifer, and it does not capture important hydrogeological heterogeneities. As a result, Ward and Lough (2011) streamflow depletion analytical solution was evaluated as an alternative approach that could be implemented as part of the online tool. Furthermore, streambed parameters used in the WWAT were poorly defined. A new approach to improve this parameter was developed by using soil and land cover data to estimate the streambed hydraulic conductivity (K_S) and the resulting K_S values from this approach were statistically compared against 23 locations with known K_S values, resulting in an improved K_S values estimation using publicly available soil and land cover data.

To understand the perspectives of groundwater resource management, cognitive maps of ‘experts’ and ‘non-experts’ were developed using a Conceptual, Content, Cognitive Mapping (3CM) approach. The study found that ‘experts’ have a more structured and detailed knowledge than ‘non-experts’. It was also apparent that ‘non-experts’ lacked knowledge about the regulatory framework. ‘Non-experts’ were also found to consider the users of the water in determining the impact of LQW, whereas ‘experts’ were more interested in the environmental impacts of these LQWs regardless of the users.

Co-orientation surveys were utilized to assess the degree of understanding between ‘experts’ and ‘non-experts’ pertaining to water resource management in Michigan. It was found that ‘experts’ and ‘non-experts’ shared many similar views except on topics related to Great Lakes water diversions and LQWs associated with hydraulic fracturing and industrial activities. It was also found that ‘experts’ were more concerned about the impacts on the environment than they were given credit for, while ‘non-experts’ were more knowledgeable than they were given credit for. The areas of disagreement between ‘experts’ and ‘non-experts’ found in these studies could be used to foster better communication between the public and government agencies in moving towards a common goal of sustainably managing groundwater by encouraging more public involvement through community forums or meetings.

CHAPTER 1

Introduction

1.1 Groundwater as a Resource

1.1.1 Groundwater Usage

Groundwater is the world's most extracted natural resource with an estimated global withdrawal rate of 800 – 1000 km^3 per year, comprising about 30% of the total global water consumption (Margat and Van der Gun, 2013). It is estimated that groundwater makes up more than 50% of the world's drinking water and is the sole source of water for approximately 2.5 billion people (Van der Gun, 2012). Although surface waters can often meet the water demand, precipitation patterns and hydrogeological conditions are highly varied across geographic regions. Areas with limited access to surface water supplies are, by necessity, heavily dependent on groundwater resources.

In 2015, the total daily water consumption in the U.S. was estimated at approximately 322,000 million gallons per day (Mgal/d) and groundwater withdrawals were estimated to supply about 84,700 Mgal/d or roughly 26% of it (Dieter et al., 2018). The majority of the groundwater withdrawn was used for irrigation (± 68%), public supply (± 18%), and domestic use (± 4%). The total water consumption in the US has dropped by 9.3% since 2010, but groundwater withdrawals have increased by 3% due to an 8% increase in groundwater use for irrigation (Maupin et al., 2014). Regionally, groundwater withdrawals in the U.S. vary greatly. In 2015, Mississippi and Kansas relied on groundwater for 84% and 70% of their total water withdrawals. In contrast,

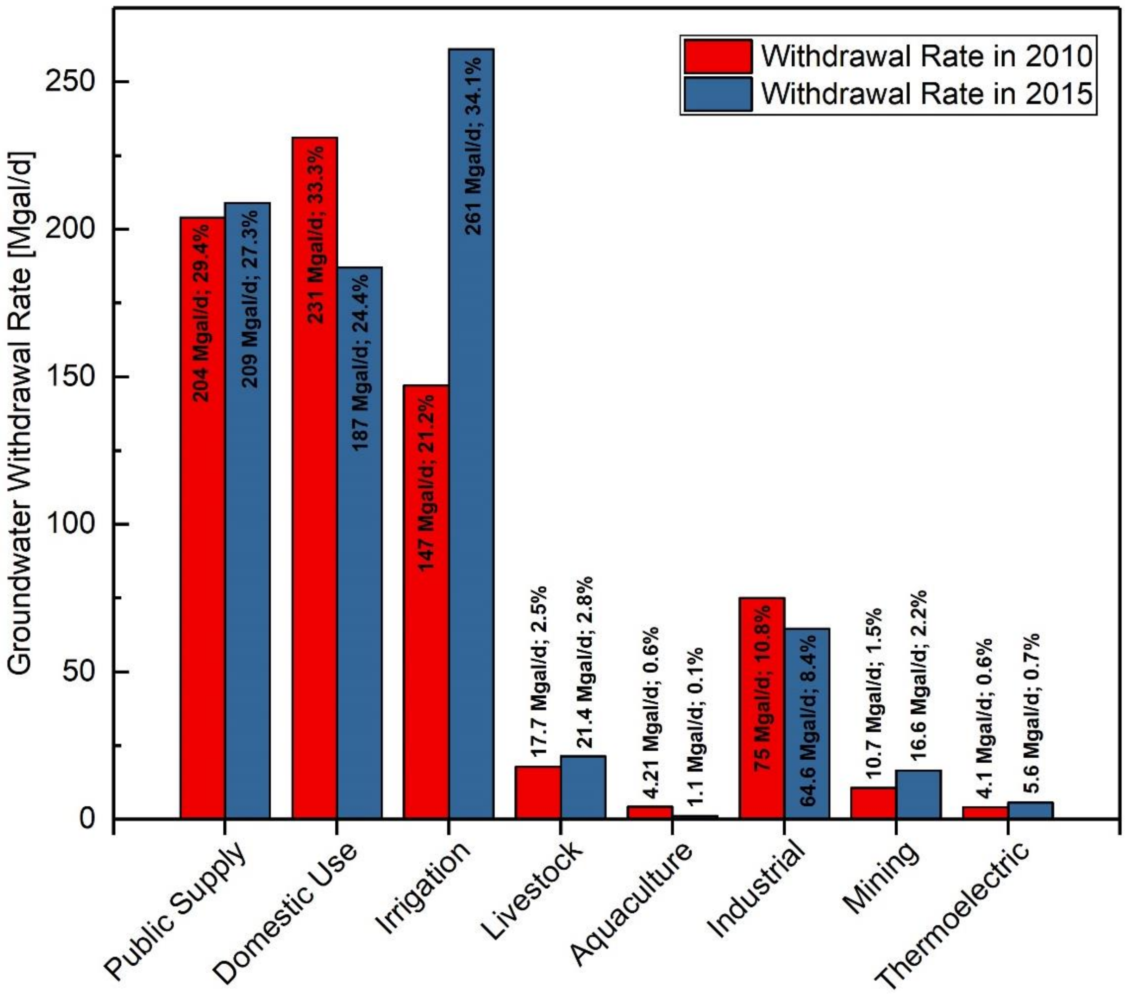


Figure 1.1. Groundwater use categories and their relative contribution to the State of Michigan's total groundwater withdrawal rate in 2010 and 2015. Data from Dieter et al., 2018 and Maupin et al., 2014.

states like Maryland, Virginia, Connecticut, and Montana only rely on groundwater for less than 5% of their total water withdrawals. California, Arkansas, Texas, Nebraska, and Idaho were the five states with the largest total groundwater withdrawal rates in 2015, comprising about 54% of the total nation's groundwater withdrawal.

In the State of Michigan, the total water consumption in 2015 was at 10,100 Mgal/d (approximately 3% of the nation's total water consumption) and groundwater withdrawals accounted for 767 Mgal/d or about 7.6% (~0.1% of U.S. total groundwater withdrawal) of the state's total water consumption. Irrigation was the major use for the withdrawn groundwater (±

34%), followed by public supply (± 27%), domestic use (± 24%), and industrial (± 8%) (see Figure 1.1). Compared to 2010, the total water consumption dropped by 6.5% while total groundwater withdrawals increased by a significant 10.5%. The increment in groundwater withdrawals was mainly due to a 77% growth for irrigation use. This category overtook domestic water as the largest groundwater use in 2010, underscoring the observation that groundwater is being relied upon more and more to meet not only the nation's but also state's agricultural water demand.

1.1.2 Problems Associated with Groundwater Depletion

Large quantity water withdrawals can lead to unsustainable water management scenarios if the withdrawal rates far outpace the groundwater recharge rate. In coastal regions, where many of the world's largest cities and human population are concentrated, excessive groundwater withdrawals have caused seawater intrusion, reducing the quality of the available fresh groundwater (Post, 2005; Purwoarminta et al., 2018). Many other areas in the world have experienced problems related to groundwater depletion, including, but not limited to, the northwest region of India (Rodell et al., 2009), the North China Plain (Feng et al., 2013), the Guarani aquifer in South America (Foster et al., 2009), the Greater Jakarta Basin in Indonesia (Delinom, 2017), the Sahel region in South Africa (Wada et al., 2010), and the High Plains aquifer in the central U.S. (McGuire et al., 2003; Scanlon et al., 2012). In areas where groundwater is severely depleted, the extraction of groundwater for irrigation has become almost impossible or cost prohibitive (Dennehy et al., 2002). In other regions, the extraction of the easily recoverable groundwater leaves a residual groundwater with inferior quality due to induced leakage from adjacent aquifers that may contain less pristine water. In regions with ample surface water bodies, such as Michigan, excessive groundwater extractions at high pumping rates can actually cause a reduction in the flow from aquifers to streams, a phenomenon known as streamflow depletion, Q_s (Barlow and Leake, 2012). A reduction in groundwater baseflow to a stream may adversely affect the health of the ecosystem of that stream, resulting in detrimental effects to the fauna dependent on that stream.

Excessive groundwater use has been a growing issue in Michigan and in the Great Lakes Basin. Recently, new demands for water have been associated with development of high volume hydraulic fracturing (HVHF) as an unconventional way to extract oil and natural gas (Rahm and Riha, 2014). Hydraulic fracturing well completions in the U.S. use an average of 14,000 m^3 (3.8 million gallons) of water, with several wells in Michigan reporting the use of over 75,000 m^3 (20 million gallons) (Ernstoff and Ellis, 2013a; Jackson et al., 2014). There have been numerous other concerns about excessive water withdrawals which led to conflicts and litigations between large capacity well owners and small capacity private well owners (Gilchrist, 2010). For example, Nestlé requested to increase their groundwater withdrawals rate at their water bottling facility in Evart, MI (Kaffer, 2017; LaFond, 2014). This request was met with resistance at both the community and the governmental level (Ellison, 2017; Gerstein, 2017). Despite the initial rejection, the MI-DEQ finally approved the permit in April 2018, allowing Nestle to increase their groundwater withdrawal from 250 to 400 gallons per minute (Gray, 2018). On the other hand, farmers and communities at the Southwestern part of Michigan were having difficulties in getting irrigation well permit as their proposed LQWs were declined and referred to additional review (Southwest Michigan Water Resources Council, 2014; Southwestern Michigan College, 2015). There was also an issue involving a request for Great Lakes water resource diversion by the City of Waukesha, WI. It requested to divert water resource from the Great Lakes Basin to fulfill their water needs and it was opposed by many Great Lakes mayors and community members (Ellison, 2016a, 2016b; Martinez, 2016). The concern is that Waukesha, WI is located outside of the Great Lakes Basin border and it may open the path for other similar neighboring cities located just outside of the Great Lakes Basin border to access Great Lakes water without meeting the condition of the Great Lakes Compact (Mlive.com, 2016a). These issues highlight the importance of ensuring sustainable groundwater management in Michigan.

1.2 Regulation of Groundwater Withdrawals

1.2.1 Regulatory Framework

Water resources are a classic common-pool resource problem. If the use is unconstrained, each user is free to withdraw an unlimited amount of the limited resource. The allocation of water as a resource falls within the purview of each individual state, with little federal intervention. Each state has its own regulatory system to allocate both surface and groundwater within its jurisdiction. While there are primarily two regulatory doctrines for the allocation of surface water, multiple doctrines are often used for groundwater withdrawal allocation. For surface water withdrawals, states located to the east of the Mississippi River typically use riparian law where a landowner has the right to make “reasonable use” of watercourses adjacent to or within the owned parcel of land. On the other hand, almost all states located to the west of the Mississippi River are generally more arid, and as a result, these states use prior appropriation law where the first user has the right to continue using the water perhaps to the exclusion of the rights of those who come later. (The exceptions are for California and Texas where a hybrid of both prior appropriation and riparian law are used.)

Groundwater withdrawal regulations initially followed surface water regulations, but as the use of groundwater has increased, the regulations have also evolved. The Absolute Dominion Rule, Correlative Rights Doctrine, Reasonable Use Rule, and Restatement of Torts Rule are derivatives of the riparian rule which allow a landowner to pump and use groundwater beneath his parcel of land. The Absolute Dominion Rule does not limit the withdrawal rate and a landowner has unlimited access to the entire aquifer without incurring any liability. The Correlative Rights Doctrine allocates a reasonable share of the aquifer's total supply for every landowner that withdraws water from the same aquifer. The Reasonable Use Rule requires that groundwater be put to a reasonable use on the overlying tract of land and does not permit water to be utilized elsewhere. The Restatement of Torts Rule is viewed as a merger between Absolute Dominion and Reasonable Use Rule where a landowner is permitted to withdraw groundwater and use it for a beneficial purpose without liability unless it causes harm to the watercourse, the environment or interferes with neighboring landowners' access to the aquifer. Just like the surface water rules, these groundwater rules are mainly used by states located east to the Mississippi River, whereas many western states have adopted prior appropriation law for groundwater allocation. This rule is like the surface water prior appropriation law where groundwater access is based on a "first-come, first-served" basis. Nevertheless, many states actually use a combination of two or more of these doctrines as one doctrine alone is usually insufficient to regulate a vast area with varying hydrogeological settings (Getches et al., 2015). For example, Nebraska uses Reasonable Use along with Correlative Rights Doctrine and Wyoming uses the Reasonable Use Rule along with the prior appropriation law. The State of Michigan itself has adopted the Reasonable Use Rule to regulate its groundwater withdrawals.

1.2.2 Regulatory Approach in Michigan

In 2008, the Great Lakes – St. Lawrence Basin Water Resource Compact (the Great Lakes Compact) was enacted as a legal platform for the governors and premiers of the Great Lakes states and provinces, respectively, to conserve the water resources in the Great Lakes Basin. The Great Lakes Compact mandated all member states to implement a measure to protect the water in the Great Lakes Basin based on a consistent standard. It has been long known that surface and groundwater are hydraulically connected (Barlow and Leake, 2012; Hunt, 2014). However, a study by Megdal et al. (2014) has shown that while all states have groundwater laws, not all of them recognize the connection between surface water and groundwater and how it influences groundwater-dependent ecosystems. Effective governance of groundwater is easier when the use of groundwater and its interaction and possible negative impact on surface water can be easily and cheaply monitored and verified (Dietz et al., 2003). Pursuant to the Great Lakes compact, the State of Michigan recognized that an effective water management process should explicitly account for the interconnection between surface and groundwater. Although surface water withdrawals from streams directly reduce the streamflow, groundwater withdrawals only indirectly deplete the streamflow by diverting the subsurface flow that would otherwise replenish the stream. Protecting streamflow is key to safeguarding aquatic ecosystems in the Great Lakes environment, as changes in stream flow characteristics can alter an entire aquatic system. In addition, understanding the cumulative impacts of multiple withdrawals within a drainage basin is essential to ensuring sustainable use of groundwater resources for both the aquatic ecosystem and human users (Hamilton and Seelbach, 2011).

To accomplish all these objectives, the State of Michigan developed the Water Withdrawal Assessment Tool (WWAT). This tool is used to screen all proposed large quantity withdrawals (LQWs), defined as a withdrawal rate larger than 100,000 gallons per day (378 m^3 per day), to determine whether there is a potential for adverse impacts on the fish assemblages living in nearby streams (Hamilton and Seelbach, 2011; Steinman et al., 2011). The WWAT comprises three different models: a stream model, a groundwater model, and a fisheries model. These models are tied together by a web-based geospatial tool that allows a relatively fast and easy evaluation of a proposed LQW. The stream model provides the estimated lowest streamflow during the driest month for all streams in Michigan. The groundwater model provides the estimated streamflow depletion on nearby streams as a result of a proposed LQW. The fisheries model provides the estimated impact of the predicted streamflow depletion on the fish assemblage on nearby streams. Any withdrawals predicted to have an adverse impact to the nearby streams and its fish assemblages would be flagged and would require additional reviews before being approved.

Due to the innovation in combining scientific approaches to efficiently regulate water withdrawals, the WWAT has received multiple awards since being enacted into law in 2008 (Shekell and Cameron, 2010). However, this tool also has its share of critics. As a screening tool, the WWAT was designed to be conservative and thus, it limits the quantity of water that can be withdrawn from a watershed. Thus, this approach creates an "artificial amount" of water that can be legally withdrawn. In some areas with abundant groundwater resources, there has been no evidence of wells drying out due to existing LQWs. The conservative approach of WWAT may unnecessarily decline applications for LQWs and therefore, hindering economic development. On the other hand, some people consider the WWAT to be not conservative enough to protect sensitive trout streams, especially from LQWs associated with short term HVHF and/or irrigation activities (Burton et al., 2014, 2013). For example, there were concerns about the diversion of the North Branch Manistee River (a sensitive cold water trout stream) in Kalkaska County due to LQWs associated with hydraulic fracturing situated less than 500 meters from the river (Lui, 2013). Some communities in Ottawa and Saginaw County also reported issues of local water stress due to LQWs associated with agricultural activities in their area (Burton et al., 2014, 2013; Gilchrist, 2010;

Kukla, 2012). It was suggested that regional models would work better and the WWAT, although designed to be conservative, is not suitable to evaluate groundwater withdrawals due to the limited data points upon which it is based (Southwest Michigan Water Resources Council, 2014; Southwestern Michigan College, 2015)

The groundwater model in the WWAT uses a modified analytical model developed by Hunt (1999) to estimate the streamflow depletion on nearby streams as a result of a proposed LQW. Due to the ease of use and only minimum hydrogeological data were required (i.e., simple and cheap), the use of mathematical analytical models have been popular among water resource manager in managing groundwater rights, specifically to evaluate the effect of groundwater withdrawals on streamflow depletion (Hunt, 2014; Sophocleous et al., 1995). Yet, analytical models use many assumptions for simplification purposes. Hydrogeologists often develop numerical 3-D groundwater models which allow for a more detailed evaluation of a stream – aquifer interaction by considering elevation variation, groundwater recharge variation due to precipitation and evapotranspiration, aquifer anisotropy, multiple aquifer layers, and variation in stream and pumping parameters. Therefore, numerical models have often been considered as the preferred method to evaluate complex surface water – groundwater interactions despite it requires longer time and more resources. However due to these drawbacks, numerical models cannot really be used as a rapid evaluation tool for regulatory framework purposes. In addition, the two opposite views regarding the management and tool used to regulate groundwater withdrawals in Michigan (i.e., not conservative enough vs. too conservative) prompted another interesting aspect regarding the people’s perception in this topic.

1.3 People's Perception about Groundwater Governance in Michigan

Studies have shown that public knowledge on water is lacking (Robelia and Murphy, 2011; Suvedi et al., 2000). For example, they often consider groundwater as a renewable resource even though it may require a few decades, centuries or even millennia to recharge an aquifer (McMahon et al., 2011). A previous study showed that when the public thinks about groundwater issues, they tend to think about the quality, rather than the quantity (Lichtenberg and Lessley, 1992; Mahler et al., 2006). Another study showed that most people in Michigan have a correct understanding about basic groundwater knowledge and issues, however, there were some misconceptions about other issues (e.g., they perceived a moderate to high risk of groundwater contamination in the state and county level, but lower in their own properties) (Suvedi et al., 2000).

Given the characteristic of groundwater as a common-pool resource, it is inherently vulnerable to the "tragedy of the commons" in the utilization of groundwater resource where users act solely in their own short-term interest, rather than taking into account the community's long-term interest. According to Ostrom (1990), management of common-pool resources, such as groundwater, can be done sustainably if (1) the rights of the local community to organize resource use are formally recognized; (2) the collective participation of stakeholders in decision-making is arranged; and (3) mechanisms for conflict-resolution which are accessible, rapid and inexpensive are implemented (Dietz et al., 2003; Ostrom, 1990). Groundwater resources may be abundant regionally, but heavy groundwater withdrawals in centralized areas can create local stresses (Reilly et al., 2008). Despite efforts by the federal government in managing groundwater, local groundwater management agencies with some form of stakeholder participation are essential in implementing groundwater governance locally. The key for an effective groundwater resource management is accountability where both the groundwater resource managers and stakeholders voice their concerns that empower both parties to reach consensus. Nevertheless, stakeholders and the general public generally insist that resource managers are more responsible in improving the groundwater resource status. As a result, understanding the state of mind and degree of understanding of the relevant stakeholders (i.e., both the regulators and the public) regarding groundwater management would be beneficial for everyone in ensuring sustainable groundwater use in the present and in the future (Foster and Garduño, 2012; Megdal et al., 2014).

1.4 Research Objectives

This dissertation aims to evaluate the modeling framework and social perspectives regarding groundwater resource management in the State of Michigan. The research is divided into four chapters, each addressing different aspects of groundwater resource management and practices in Michigan. The research objectives are:

1. To evaluate the estimation of Q_s as a result of LQWs associated with irrigation and mining industries using the WWAT and numerical models,
2. To provide more accurate estimate of Q_s in a rapid analytical manner used in regulatory framework,
3. To understand the state of minds of the parties involved in water resources management practices in Michigan based on their prior knowledge and education, and
4. To assess the degree of understanding between the parties involved in Michigan's water resources management practices based on their prior knowledge and education.

Each of the subsequent chapters in this dissertation addresses one of the specific research objectives.

CHAPTER 2

Using an Analytical Solution Approach to Permit High Volume Groundwater Withdrawals

2.1 Introduction

In compliance with the Great Lakes Compact, the State of Michigan developed a formal process for evaluating applications for Large Quantity Withdrawals (LQWs). Although freshwater resources in Michigan are considered to be abundant, some streams in the state are home to sensitive fish populations, and therefore are designated as “cold transitional” or “cool water” streams. As surface waters are usually hydraulically connected to groundwater, pumping-related variation in groundwater baseflow to these streams can result in fluctuations in stream temperature that may adversely impact these fish populations (Baker et al., 2003; Cott et al., 2008; Grannemann et al., 2000; Richter et al., 2003; Wehrly et al., 2006; Zorn et al., 2002). Water quality may also be impaired as lower baseflow can reduce the dilution of loadings of solids or other contaminants (Grannemann et al., 2000; Polizzotto et al., 2008). Thus, the objective of the process for evaluating LQWs in Michigan is the protection of ecologically important flows, utilizing information regarding groundwater hydrogeology, river flow, and aquatic health to determine the potential adverse resource impact (ARI) due to a new LQW well. The centerpiece of the process is the Water Withdrawal Assessment Tool (WWAT) which screens LQW (defined as a pumping rate >378 m^3/day at any point during its use) permit applications to identify those wells that require a more thorough site-specific review based on an assessment of potential risk to the aquatic health of nearby streams (Hamilton and Seelbach, 2011). The State of Michigan utilizes the WWAT to

Table 2.1. Water withdrawal management zones for different stream types (Hamilton and Seelbach, 2011) based on maximum values of streamflow depletion as a percentage of stream index flow $(Q_{s,\max} / Q_{index} \times 100)$.

Stream Type		Water Withdrawal Management Zone			
		Zone A	Zone B	Zone C	Zone D
Cold	Stream	< 14%	NA	14 to < 20%	≥ 20%
	Small River	< 10.5%		10.5 to <21%	≥ 21%
Cold Transitional	Stream	NA	< 4%	NA	≥ 4%
	Small River		< 2%		≥ 2%
	Large River		< 3%		≥ 3%
Cool	Stream	< 6%	6 to < 15%	15 to < 25%	≥ 25%
	Small River	< 15%	15 to < 19%	19 to < 25%	≥ 25%
	Large River	< 14%	14 to < 19%	19 to < 25%	≥ 25%
Warm	Stream	< 10%	10 to < 18%	18 to < 24%	≥ 24%
	Small River	< 8%	8 to < 13%	13 to < 17%	≥ 17%
	Large River	< 10%	10 to < 16%	16 to < 22%	≥ 22%

The WWAT automatically requires a site-specific review for any LQW proposal that falls into either Zone C or Zone D. NA: not applicable. Cold stream types do not have a Zone B; cold transitional stream types do not have Zones A or D.

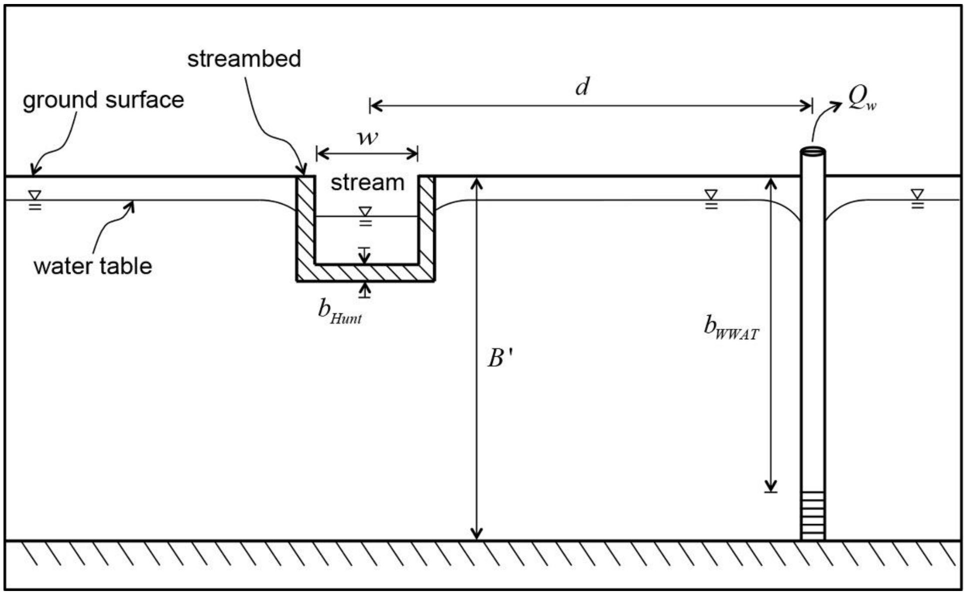


Figure 2.1. System schematic for the analytical solution of Hunt (1999) employed by the WWAT. *d* is the distance between the stream and the pumping well, *w* is the width of the stream, B' is the thickness of the surficial glacial deposits and Q_w is the pumping rate of the well. b_{Hunt} and b_{WWAT} denote the streambed thickness used by Hunt (1999) and in the WWAT (Reeves et al., 2009), respectively.

determine if an ARI is likely to occur due to a given pumping activity. The criterion for an ARI occurrence is a sufficiently large reduction in streamflow that a negative impact on a stream's characteristic fish population is triggered (Hamilton and Seelbach, 2011).

The WWAT is comprised of three different modules that are linked together through an online geospatial information system to determine the impact of potential groundwater withdrawals on stream ecology. These three modules comprise a groundwater model, a stream model and a fisheries model (Hamilton and Seelbach, 2011). The groundwater model is based on a modification of the analytical solution presented by Hunt (1999) and is used to calculate the resulting stream depletion, Q_s, from a given pumping activity (Reeves et al., 2009). The stream model is used to determine the index flow, Q_{index}, which is defined as the lowest median stream flow rate for the dry summer months. An estimate of Q_{index} is calculated for each stream segment through the use of a regression model based on 147 streamflow gaging stations across Michigan with records of 10 or more years. This estimate is then halved to yield a more conservative value on which to base the prediction of an ARI (Hamilton et al., 2008). The fisheries model uses the Michigan Department of Natural Resources fisheries database, coupled with statistical modeling, to predict how fish assemblages in different types of Michigan streams would respond to decreased streamflows (Seelbach et al., 2006; Zorn et al., 2012). An ARI is defined to occur when an LQW causes a reduction in stream flow above a set fraction of the stream's index flow (*i.e.*, Q_s/Q_{index} must be above a certain threshold; see Table 2.1 for values of the threshold Q_s/Q_{index} for ARIs.) If the WWAT predicts the occurrence of an ARI, the application for the new LQW well is referred for a site-specific review (Hamilton and Seelbach, 2011; Zorn et al., 2012).

The WWAT was implemented as in Internet screening tool in 2008 (Michigan Legislature, 2008, sec. 94th Legislature). Between its implementation and the time this dissertation is written, close to 5,000 applications had been submitted for permitting, with approximately 3,400 approved by the WWAT and the remaining referred for site-specific review (Michigan Department of Environmental Quality, n.d.). There are critics who feel that the WWAT is too conservative by referring LQW permit applications for site-specific review in areas where water is abundant and there has been no evidence of wells drying out or significant reductions in streamflow as a result of existing LQW wells. Such referrals may be viewed by stakeholders as inaccuracies in the values of Q_s predicted by the WWAT, when, in fact, the model may be simply providing a conservative estimate, as intended. There are also critics who feel that the WWAT is not conservative enough; for example, the values for Q_{index} are based on gaged streams and may be too high in the case of certain sensitive streams that are not gaged. Therefore, this chapter focuses on the groundwater component of the WWAT and seeks to evaluate its ability to characterize Q_s for proposed LQW activities, in both agricultural and HVHF settings.

Figure 2.1 shows the situation considered by Hunt (1999) in the development of the analytical solution upon which the stream depletion component of the WWAT is based. The solution assumes a one-dimensional aquifer that is homogeneous, isotropic and of infinite extent containing a fully penetrating pumping well. Furthermore, it assumes that the ratio of vertical to horizontal velocities is small, and that the drawdown is small relative to the saturated thickness. The stream is straight and extends to negative and positive infinity in the y-direction at $x = 0$, has horizontal and vertical dimensions that are small relative to the aquifer and changes in its water surface elevation are small relative to changes in the water table elevation. Based on these assumptions, the streamflow depletion rate can be calculated as (Hunt, 1999):

$$Q_s = Q_w\left[\operatorname{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right)\operatorname{erfc}\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{Sd^2}{4Tt}}\right)\right] \qquad \text{(Equation 2.1)}$$

where Q_s is the streamflow depletion rate, Q_w is the well pumping rate, d is the shortest distance between the well and the stream, S is the storage coefficient or specific yield of the aquifer in which the well is screened, T is the transmissivity of the aquifer, t is the time from the start of pumping, and λ is the streambed conductance, calculated as:

$$\lambda = \frac{w}{b} K_s \qquad \text{(Equation 2.2)}$$

where w is the width of the stream, and b and K_s are the thickness and hydraulic conductivity, respectively, of the streambed.

In the application of the Hunt (1999) solution in the context of the WWAT, the primary difference is in the calculation of the streambed conductance. The hydraulic conductivity and thickness of the streambed are actually unknown. In the WWAT, the hydraulic conductivity of the streambed is considered to be 1/10 of the hydraulic conductivity of the surficial aquifer. Furthermore, the solution by Hunt (1999) assumes a fully penetrating well. Yet, in reality, wells are screened at discrete depths and those screened at deeper depths will have a lower impact on surface streams. To reflect this, the vertical distance from the land surface to the top of the well screen, b_{WWAT}, is introduced as the streambed thickness in the WWAT. Thus, the streambed conductance, λ, in the WWAT is calculated as (Reeves et al., 2009):

$$\lambda = \frac{w}{b_{WWAT}} \left(\frac{T}{10B'} \right) \qquad \text{(Equation 2.3)}$$

where b_{WWAT} is the vertical distance from the land surface to the top of the well screen (or open interval for a well in bedrock), and B' is the mean thickness of the surficial glacial deposits. The WWAT apportions streamflow reductions from a proposed well to streams in multiple watersheds using an inverse distance-weighting scheme. The duration of pumping in WWAT is set to five years and the user can specify either a constant or a time-varying pumping rate. In the case of a time-varying rate, the principle of superposition is used to calculate the streamflow reduction over time and the maximum depletion, $Q_{s,max}$, during that five-year period is used to determine the possibility of an ARI.

3-D groundwater numerical models (e.g., MODFLOW which was developed by the USGS) have been commonly used to assess the surface water – groundwater interactions by solving the 3-D groundwater flow and transport equation by using a 3-D control volume finite element as follows:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}+W \qquad \text{(Equation 2.4)}$$

where K_x, K_y, K_z are the aquifer hydraulic conductivity in the x, y, and z direction, respectively; S_s is the specific storage of the aquifer; W is the sources and/or sinks; and $\partial h/\partial x$, $\partial h/\partial y$, $\partial h/\partial z$ and $\partial h/\partial t$ are the partial derivative of the hydraulic head in the x, y, z direction and time, respectively. Many studies have used groundwater numerical models to assess the stream – aquifer interaction due to pumping associated with irrigation, municipal, and mining activities where analytical models are too simple and insufficient. For example, Best and Lowry (2014) used numerical model approach to evaluate the effect of LQW associated with fracking in the Marcellus Shale development in the New York State. They found that groundwater pumping at narrow valley might diminish the stream's recharge. Luukkonen et al., (2004) also used numerical model to evaluate the groundwater resources in Kalamazoo County, MI and found that streamflow would be depleted due to pumping for irrigation in the summer months.

Given that the solution of Hunt (1999) is based on a number of assumptions, and, in addition, its implementation in the WWAT incorporates additional assumptions, it is important to assess how well the WWAT estimates the amount of streamflow depletion resulting from LQWs that might be associated with water intensive utilization activities such as HVHF or large-scale agriculture. This objective is accomplished by comparing estimates of streamflow depletion calculated by the groundwater component of the WWAT with estimates generated by a 3-D numerical simulator (i.e., Visual MODFLOW) at two different locations in the State of Michigan, where LQW wells have been permitted by the Michigan Department of Environmental Quality (MI-DEQ). In this chapter, two selected sites, one in Northern Michigan and the other in Southwestern Michigan, present two different groundwater hydrology scenarios and two sectors of water use in the State of Michigan.

2.2 Methods

2.2.1 Set-up of Models

Figure 2.2. Map of the State of Michigan showing two study site locations in Kalkaska and Calhoun Counties (MI). Lines delineate the counties of the State of Michigan.

The first study location is in Bear Lake Township in Kalkaska County where LQW wells have been approved in anticipation of HVHF activities in the vicinity (see Figure 2.2). The wells are located in the Manistee River watershed approximately 1,000 m from Black Creek, a groundwater-fed stream classified as a “cool stream” by the WWAT. The bedrock geology is dominated by Coldwater Shale and Marshall Sandstone while the surficial geology is dominated by glacial outwash (mainly sand and gravel), with an average depth to bedrock of ± 215 m (Ferrand et al., 1982; Reed and Daniels, 1987). In this location, groundwater generally flows from north to south at a rate of about 0.18 m/day, following the direction of flow in the Black Creek. Almost all groundwater wells in the area are screened in shallow glacial aquifers, with depths ranging from 20-30 m.

The second site is located in Emmet Charter Township in Calhoun County where a well has been approved by the MI-DEQ for agricultural use (see Figure 2.2). The well is located in the Kalamazoo River watershed, approximately 1,000 m from Dickinson Creek, a groundwater-fed stream classified as “cold transitional” (the most sensitive type of stream) by the WWAT (Hamilton and Seelbach, 2011). Due to this stream classification, any proposed LQW well within the Dickinson watershed would automatically require a site-specific review (Hamilton and Seelbach, 2011). The bedrock geology is mainly dominated by Marshall Sandstone, while the surficial geology is dominated by a combination of moraine and glacial outwash (Ferrand et al., 1982; Reed and Daniels, 1987). The thickness of the drift in this area is relatively thin compared to that at the study site in Kalkaska County, with an average depth to bedrock of ± 25 m. The general direction of groundwater flow is from east to west, following the direction of the Kalamazoo River, at a rate of about 0.26 m/day. The streamflow direction of Dickinson Creek, however, is from northeast to southwest. Because of the thinness of the glacial deposits, only about

10% of the groundwater wells within this area are screened in the shallow glacial aquifers, with the remaining 90% screened in bedrock.

To calculate streamflow depletion based on the algorithm used in the WWAT, the program STRMDEPL08 was used. STRMDEPL08 calculates Q_s using Equations 2.1 and 2.3, in the same manner as the WWAT (Reeves, 2008). The values for all the parameters used by the WWAT for the two study sites are given in Table 2.2. Both the values of T and B' came from the Michigan Groundwater Inventory and Mapping (GWIM) Project database which provides aquifer property estimates on a 1-km x 1-km grid across the State. The stream width w was estimated using a regression equation developed for the WWAT to relate stream width to drainage area in the State of Michigan (Reeves et al., 2009):

$$w = 3.28 \times \left(10^{\left(\left(0.522358 \times \log\left(da \times 1.6093^2 \right) \right) - 0.18786 \right)} \right) \qquad \text{(Equation 2.5)}$$

where da is the drainage area in square miles and w is the stream width in feet. Storage coefficients, S, reported across the State vary over five orders of magnitude (3×10^{-6} to 0.4 for wells completed in glacial deposits). However, they do not correlate well with geography or surficial geology (Reeves et al., 2009). In the absence of a compelling justification otherwise, the WWAT assumes that the storage coefficient is equal to 0.01, consistent with reported values for leaky aquifers (Reeves et al., 2009).

The pumping rate, Q_w, at the Kalkaska site was set to 2,530 m^3/day. This rate was determined by taking the maximum permitted withdrawal volume of 35 million gallons (Mgal) of water and dividing it by an arbitrary period for well development of 52 days. Q_w for the Calhoun County site was assumed to be 6,500 m^3/day, which is the maximum permitted pumping rate for this site. The pumping pattern for both sites was pumping at the respective rates given above for

Table 2.2. MODFLOW and WWAT parameters for the study sites in Kalkaska and Calhoun Counties.

Description		Kalkaska Site	Calhoun Site
Aquifer Parameters			
Transmissivity of Screened Aquifer[a], T [m^2/d]	MODFLOW	718	0.432
	WWAT	521	435
Storage Coefficient[b], S	MODFLOW	0.16	1×10^{-3}
	WWAT	0.01	
Aquifer Diffusivity, T/S [m^2/d]	MODFLOW	4,488	432
	WWAT	52,100	43,460
Aquitard (Layer #2) Thickness [m]	MODFLOW	1-20	1-5
Average Glacial Formation Thickness[c], B' [m]	WWAT	180	25
Surficial Aquifer Recharge Rate[d] [cm/yr]	MODFLOW	22.9	28.0
Stream Parameters			
Streambed Thickness[e], b [m]	MODFLOW	1	1
	WWAT	37	31
Streambed Width[f], w [m]	MODFLOW	1	1
	WWAT	6.8	6.0
Streambed Conductance[g], λ [m/d]	MODFLOW	0.026	0.026
	WWAT	0.053	0.274
Streamflow Rate[h], Q_i [m^3/d]	MODFLOW	4,155	488
	WWAT	15,750	5,870
Pumping Well Parameters			
Distance between Well and Stream, d [m]	MODFLOW	1,000	
	WWAT		
Pumping Rate, Q_w [m^3/d]	MODFLOW	2,530	6,500
	WWAT		
Pumping Schedule	MODFLOW	3 months of pumping followed by 9 months of shutoff annually for 5 years	
	WWAT		
Well Screen Depth from Ground Level [m]	MODFLOW	37	31

[a] The values for T for the WWAT are from the Michigan Groundwater Inventory and Mapping (GWIM) Project database,(Michigan Department of Environmental Quality et al., 2006a; Reeves et al., 2009) whereas those for MODFLOW are based on calibrated K_x values and aquifer thicknesses of 180 m and 100 m for the Kalkaska and Calhoun study sites, respectively; [b] The value of S for the WWAT is constant and consistent with reported values for leaky aquifers,(Reeves et al., 2009) whereas those for MODFLOW are based on typical values presented in Morris and Johnson.(Morris and Johnson, 1967); [c] The value of B' is from the GWIM Project database. [d] The values for recharge are from the Michigan Groundwater Inventory and Mapping (GWIM) Project database,(Michigan Department of Environmental Quality et al., 2006a; Reeves et al., 2009); [e] The value of b for the WWAT is the vertical distance from stream to the top of the well screen,(Reeves et al., 2009) whereas that for MODFLOW is based on typical values of streambed thickness.(Toran et al., 2013); [f] The value of w for the WWAT was calculated using Equation 2.5, whereas that for MODFLOW was set equal to 1 m based on satellite images; [g] The value of λ for the WWAT was calculated using Equation 2.3, whereas that for MODFLOW was calibrated based on a reported measured streamflow of 4×10^3 m^3/day for the Kalkaska site (Hyndman, 2013), with the same value being used for the Calhoun site in absence of additional information; [h] The values of Q_i for WWAT are equal to Q_{index} (Michigan Department of Environmental Quality, n.d.), whereas those for MODFLOW were set as equal to $Q_{initial}$, the streamflow determined by the model in the absence of pumping.

Table 2.3. MODFLOW parameter values for the study site in Kalkaska County.

Description	Layer #1	Layer #2	Layer #3
Boundary Conditions			
North Boundary	Constant Head 361.8 m (N.W.) to 346.4 m (N.E.)	Constant Head 361.8 m (N.W.) to 346.4 m (N.E.)	Constant Head 361.8 m (N.W.) to 346.4 m (N.E.)
East Boundary	Constant Head 346.4 m (N.E.) to 337 m (S.E.)	No Flow	No Flow
West Boundary	Constant Head 361.8 m (N.W.) to 331 m (S.W.)	No Flow	No Flow
South Boundary	Constant Head 331 m (S.W.) to 337 m (S.E.)	Constant Head 331 m (S.W.) to 337 m (S.E.)	Constant Head 331 m (S.W.) to 337 m (S.E.)
Thickness [m]	20 – 120	1 – 20	200 – 230
Horizontal Hydraulic Conductivity[a], $K_x = K_y$ [m/d]	3.97	8.64×10^{-6}	1.10×10^{-2}
Vertical Hydraulic Conductivity[b], K_z [m/day]	3.97×10^{-1}	8.64×10^{-7}	1.10×10^{-3}
Storage Coefficient[c], S [-]	0.16	0.10	0.16
Elevation of Bottom of Layer #3	100 m		
Spatial Discretization	200 m × 200 m (largest cell) to 25 m × 25 m (smallest cell)		
Specific Discharge of Screened Aquifer in the Absence of Pumping [m/d]	0.18		
Elevation of Stream Bottom (North – South) [m]	359 – 339		
Streambed Slope [-]	2.6×10^{-3}		
Manning's Roughness Coefficient for Stream Bed[d] [-]	0.025		

[a] The horizontal hydraulic conductivities were calibrated values.

[b] K_z was assumed to be 1/10 of the horizontal hydraulic conductivity.

[c] The values of *S* were based on typical values presented in Morris and Johnson.

[d] Manning's roughness coefficient was based on typical values presented in Arcement and Schneider (1990).

Table 2.4. MODFLOW parameter values for the study site in Calhoun County.

Description	Layer #1	Layer #2	Layer #3
Boundary Conditions			
North Boundary	Constant Head 253.0 m (N.W.) to 279.3 m (N.E.)	No Flow	Constant Head 253.0 m (N.W.) to 276.0 m (N.E.)
East Boundary	Constant Head 279.3 m (N.E.) to 281.0 m (S.E.)	No Flow	Constant Head 276.0 m (N.E.) to 273.2 m (S.E.)
West Boundary	Constant Head 253.0 m (N.W.) to 274.5 m (S.W.)	No Flow	Constant Head 253.0 m (N.W.) to 281.0 m (S.W.)
South Boundary	Constant Head 274.5 m (S.W.) to 281.0 m (S.E.)	No Flow	Constant Head 281.0 m (S.W.) to 273.2 m (S.E.)
Thickness [m]	7 – 40	1 – 5	90 – 105
Horizontal Hydraulic Conductivity[a], $K_x = K_y$ [m/day]	9.50×10^{2}	8.64×10^{-6}	4.32×10^{-3}
Vertical Hydraulic Conductivity[b], K_z [m/day]	95.0	8.64×10^{-7}	4.32×10^{-4}
Storage Coefficient[c], S [-]	0.16	0.10	10^{-5}
Elevation of Bottom of Layer #3	150 m		
Spatial Discretization	400 m × 400 m (largest cell) to 25 m × 25 m (smallest cell)		
Specific Discharge of Screened Aquifer in the Absence of Pumping [m/day]	0.26		
Elevation of Stream Bottom (North – South) [m]	269 – 265 m		
Streambed Slope [-]	7.8×10^{-4}		
Manning's Roughness Coefficient for Stream Bed[d] [-]	0.025		

[a] The horizontal hydraulic conductivities were calibrated values.

[b] K_z was assumed to be 1/10 of the horizontal hydraulic conductivity.

[c] The values of S were based on typical values presented in Morris and Johnson.

[d] Manning's roughness coefficient was based on typical values presented in Arcement and Schneider (1990).

three months (to simulate water withdrawal during the dry summer months) followed by nine months where Q_w equaled zero, on an annual cycle for the five-year period proscribed by the

WWAT. The impact of the pumping was not apportioned but, instead, was confined to a single watershed.

As a comparison, Visual MODFLOW 2011.1 (Schlumberger Water Services, Kitchener, ON) was used to compute stream depletion at the same two locations. The stream was assumed to be rectangular, 1 meter in width (based on satellite imagery), with a streambed thickness equal to 1 meter (based on typical values, see Table 2.2) (Toran et al., 2013). The Stream Flow-Routing package (SFR1) was used to calculate the flow between the stream and the aquifer using the option of Manning's equation for a rectangular stream channel (Prudic et al., 2004). Values of Q_s were obtained by subtracting the streamflow at a particular time step from the streamflow determined in the absence of pumping, $Q_{initial}$. The domains at both locations were constructed with dimensions of 10,000 m in length (x-direction) and 10,000 m in width (*y*-direction) (see Figure 2.3), whereas the total thicknesses (z-direction) were 300 m and 150 m for the Kalkaska and Calhoun County sites, respectively. In both cases, the resolution of the grid varied between 25 m x 25 m in the vicinity of the pumping well and near the stream to 400 m x 400 m towards the perimeter of the domain.

An analysis of hydrogeological formations of the area from well logs obtained from the MI-DEQ Wellogic (Michigan Department of Environmental Quality, 2000) database suggested that the lithology at both study sites can be simplified into three layers. The Kalkaska County site essentially consists of a glacial drift layer (Layer #1), varying in thickness between 10-50 m on the northern boundary to 30-85 m on the southern boundary, a thin aquitard (Layer #2) and a lower semi-confined glacial drift layer (Layer #3). The Calhoun County site consists of a glacial drift layer (Layer #1), varying in thickness between 10-25 m in the northeast to 5-20 m in the southwest, a thin aquitard (Layer #2) and a semi-confined bedrock layer (Layer #3).

The MODFLOW parameter values for the Kalkaska County site are given in Tables 2.2 and Table 2.3. For the Kalkaska County site, constant head boundary conditions were used for all boundaries of the first layer (Layer #1). For the thin aquitard and semi-confined glacial drift layers (Layers #2 and #3), no-flow boundary conditions were used for the eastern and western boundaries while constant head boundary conditions were used for the northern and southern boundaries, consistent with the dominant direction of groundwater flow. The constant head values were derived from an interpolation of 51 head values measured during the summer, as reported in Wellogic (Michigan Department of Environmental Quality, 2000). Calibration of the horizontal hydraulic conductivity using 17 head observations resulted in a root-mean-squared error (RMSE) of ± 15 m, and the subsequent validation using two wells resulted in a RMSE of ± 12 m. The vertical hydraulic conductivities were assumed to be 1/10 of the horizontal conductivities. The recharge rate was set equal to 22.9 cm/year based on reported values in the GWIM Project database (Michigan Department of Environmental Quality et al., 2006). The streambed conductance was calibrated based on a reported streamflow in Black Creek of about 4,000 m^3/day (Hyndman, 2013). A single well screened at 37 m below the ground surface, pumping at a rate of 2,530 m^3/day, was used to represent the permitted HVHF withdrawal wells. Actual HVHF pumping may occur for only a few weeks or a month during the completion of a given well. However, in this study, the pumping pattern was set so that well was pumped for three months, followed by nine months of shut-off on an annual cycle, for a total duration of five years.

The MODFLOW parameter values for the Calhoun County site are given in Table 2.2 and Table 2.4. For the Calhoun County site, constant head boundaries were used on all sides for the top glacial drift layer (Layer #1) and bottom bedrock layer (Layer #3). For the thin aquitard (Layer #2), it was assumed that the predominant flow direction was vertical; hence no-flow boundaries

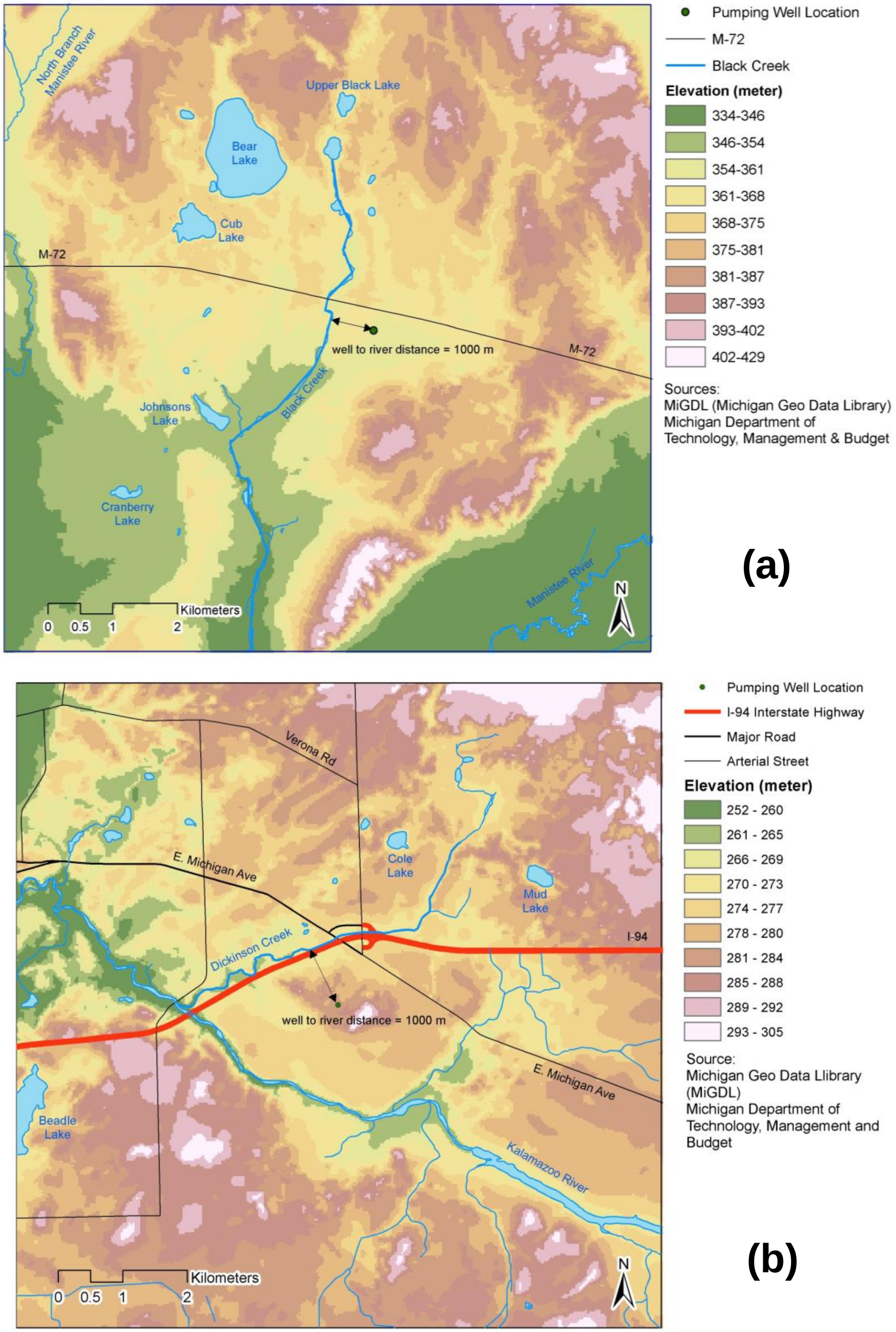


Figure 2.3. (a) Map of the study site in Kalkaska County in the northern Lower Peninsula of Michigan; and **(b)** Map of study site in Calhoun County in the southwestern Lower Peninsula of Michigan.

were used on all sides. A total of 62 head observation values from the Wellogic database were used to set the constant heads (Michigan Department of Environmental Quality, 2000), with 36 values for the unconfined glacial aquifer (Layer #1) and 26 values for the bedrock aquifer (Layer #3). A total of 19 head observations measured during the summer were used for calibration of the horizontal hydraulic conductivities and two were used for validation, giving RMSEs of ± 3 m and ± 2 m, respectively. The vertical hydraulic conductivities were assumed to be 1/10 of the horizontal conductivities. The recharge rate was set equal to 28 cm/year based on reported values in the GWIM Project database(Michigan Department of Environmental Quality et al., 2006a). In the absence of additional information, the same value of streambed conductance calibrated for the Kalkaska study site was used for the Calhoun site (see Table 2.2). The pumping well was screened in the bedrock layer at 31 m, as this is the depth of the permitted well at the site in Calhoun County. The assumed pumping rate was 6,540 m^3/day with the well being actively pumped for three months, followed by nine months of shutoff on an annual cycle, for a total duration of five years (Michigan Department of Environmental Quality, n.d.).

2.2.2 Type of Analyses

Values of Q_s calculated by STRMDEPL08 were compared with those calculated using MODFLOW. Discrepancies between the results could be attributed to two sources, as the models were not only based on different assumptions, but also used different values for the same parameters. To assess whether the difference in the output of the analytic and numerical models was based on parameter values rather than on model assumptions, additional calculations were performed using STRMDEPL08 with parameter values used in MODFLOW for the screened aquifer (Table 2.2) and using MODFLOW with all layers having the parameter values assigned by the WWAT for the screened aquifer (Table 2.2).

Sensitivity and error propagation analyses were also performed to investigate which system parameters have the largest influence on estimated streamflow depletion. In stream-aquifer interactions, the aquifer hydraulic diffusivity, defined as T/S, influences both the rate and timing of streamflow depletion (Barlow and Leake, 2012). If the aquifer hydraulic diffusivity is large, the aquifer will be more sensitive to pumping events. The storage coefficient also represents, in a sense, the buffer capacity of an aquifer in transient or cyclical pumping events. The smaller the value of S, the less buffer capacity the aquifer has and, as a result, pumping will reduce the baseflow to a stream more rapidly. In an extreme pumping event, groundwater withdrawal could cause a gaining stream to become a losing stream (Barlow and Leake, 2012). In addition, streambed conductance has been previously demonstrated to strongly influence the impact of HVHF groundwater withdrawals on nearby water resources (Best and Lowry, 2014; Chen and Yin, 1999; Christensen, 2000; Lackey et al., 2015a). Highly conductive streambeds allow for more rapid stream-aquifer communication, which results in both a larger groundwater contribution to streamflow and a greater potential for LQWs to cause a reduction in streamflow.

Parameters evaluated in the sensitivity analysis included the aquifer diffusivity, T/S, and the streambed conductance, λ. T/S and λ were varied independently over several orders of magnitude, while holding all other model parameters constant, and the resulting value of $Q_{s,max}/Q_w$ was recorded. Monte Carlo analysis is often the method of choice for determining parameter uncertainty in non-linear equations (Tellinghuisen, 2001). Nevertheless, the distribution of the relevant parameters, T, S, and λ, is unknown in this situation. Therefore, Gaussian uncertainty analysis was used here, as this approach has been demonstrated to provide an adequate assessment of uncertainty for non-linear functions (Tellinghuisen, 2001). The influence of T, S, and λ on Q_s was examined by determining the uncertainty based on the partial derivatives of Q_s as given by Equation 2.1 as $\partial Q_s/\partial T$, $\partial Q_s/\partial S$, and $\partial Q_s/\partial \lambda$ using Wolfram Alpha (Champaign, IL), as follows:

$$dQ_s = \sqrt{\left(\frac{\partial Q_s}{\partial S}dS\right)^2 + \left(\frac{\partial Q_s}{\partial T}dT\right)^2 + \left(\frac{\partial Q_s}{\partial \lambda}d\lambda\right)^2}$$

(Equation 2.6)

$$\begin{aligned}\frac{\partial Q_S}{\partial S} &= \frac{Q_w \exp\left(-\frac{Sd^2}{4Tt}\right)\sqrt{\frac{Sd^2}{Tt}}}{2S\sqrt{\pi}} + \frac{Q_w \lambda^2 t \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right)\operatorname{erfc}\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{Sd^2}{4Tt}}\right)}{4S^2T} \\ &+ \frac{2Q_w\left(\frac{d^2}{4Tt\sqrt{\frac{Sd^2}{Tt}}} - \frac{\lambda^2 t}{4S^2T\sqrt{\frac{\lambda^2 t}{ST}}}\right)\exp\left[-\left(\frac{1}{2}\sqrt{\frac{Sd^2}{Tt}} + \frac{1}{2}\sqrt{\frac{\lambda^2 t}{ST}}\right)^2 + \frac{\lambda d}{2T} + \frac{\lambda^2 t}{4ST}\right]}{\sqrt{\pi}}\end{aligned}$$

(Equation 2.7)

$$\begin{aligned}\frac{\partial Q_S}{\partial T} &= \frac{Q_w \exp\left(-\frac{Sd^2}{4Tt}\right)\sqrt{\frac{Sd^2}{Tt}}}{2T\sqrt{\pi}} + \frac{2Q_w\left(-\frac{Sd^2}{4T^2t\sqrt{\frac{Sd^2}{Tt}}} - \frac{\lambda^2 t}{4ST^2\sqrt{\frac{\lambda^2 t}{ST}}}\right)\exp\left(-\left(\frac{1}{2}\sqrt{\frac{Sd^2}{Tt}} + \frac{1}{2}\sqrt{\frac{\lambda^2 t}{ST}}\right)^2 + \frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right)}{\sqrt{\pi}} \\ &- Q_w \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right)\left(-\frac{\lambda d}{2T^2} - \frac{\lambda^2 t}{4ST^2}\right)\operatorname{erfc}\left(\frac{1}{2}\sqrt{\frac{\lambda^2 t}{ST}} + \frac{1}{2}\sqrt{\frac{Sd^2}{Tt}}\right)\end{aligned}$$

(Equation 2.8)

$$\begin{aligned}\frac{\partial Q_S}{\partial \lambda} &= \frac{Q_w \lambda t \exp\left(-\left(\frac{1}{2}\sqrt{\frac{Sd^2}{Tt}} + \frac{1}{2}\sqrt{\frac{\lambda^2 t}{ST}}\right)^2 + \frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right)}{ST\sqrt{\pi}\sqrt{\frac{\lambda^2 t}{ST}}} \\ &- Q_w \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right)\left(\frac{d}{2T} + \frac{\lambda t}{2ST}\right)\operatorname{erfc}\left(\frac{1}{2}\sqrt{\frac{\lambda^2 t}{ST}} + \frac{1}{2}\sqrt{\frac{Sd^2}{Tt}}\right)\end{aligned}$$

(Equation 2.9)

Equation 2.6 shows the total uncertainty in stream depletion Q_s, due to errors in the storage coefficient, S, transmissivity, T and streambed conductance, λ. Equations 2.7, 2.8, and 2.9 show the partial derivatives of Equation 2.1 with respect to storage coefficient, S, transmissivity, T, and streambed conductance, λ, respectively. The absolute values of $\partial Q_s/\partial T$, $\partial Q_s/\partial S$, and $\partial Q_s/\partial \lambda$ for a unit value of Q_w were then compared to determine which parameters impart the greatest uncertainty in the calculation of Q_s.

2.3 Results and Discussion

2.3.1 Comparison of Streamflow Depletion Calculations

Figure 2.4 shows the streamflow depletion, Q_s, calculated using STRMDEPL08 and the calibrated MODFLOW model for cyclical pumping over a five-year time period for both the Kalkaska (Figure 2.4a) and Calhoun (Figure 2.4b) County sites. For each site, both STRMDEPL08 and MODFLOW were used with the parameter values assigned by the WWAT as well with those utilized in the MODFLOW simulations (Table 2.2). Since the concern is whether an ARI warning would be triggered, attention was focused on the maximum streamflow depletion rate, $Q_{s,max}$, over the five-year period.

The results presented in Figure 2.4a suggest that, in the case of the Kalkaska site, the large discrepancies in the estimations of Q_s stem from the differences in the input parameters, as the use of the same values produced similar order of magnitude estimates (within 24-38% of one another) of the maximum streamflow depletion, $Q_{s,max}$. This observation suggests that, for this study site, the assumptions employed by Hunt (1999) to develop his analytical solution, such as homogeneous lithology and a fully penetrating well, did not significantly influence the calculations. On the other hand, the selected values of the hydrogeologic parameters had a large influence on $Q_{s,max}$, with those utilized by the WWAT yielding estimates of $Q_{s,max}$ that were an order of magnitude greater for both the analytic and numerical model simulations. An examination of the parameter values in Table 2.2 shows that, for example, the value of T/S used by the WWAT was over an order of magnitude larger than that in the numerical model simulations. This difference is largely due to the setting of S equal to 0.01 in the WWAT, a value typical of a leaky confined aquifer (Reeves et al., 2009), whereas the aquifer storage coefficient used in the MODFLOW simulations was 0.16 (Morris and Johnson, 1967), a value more typical of an unconfined aquifer. Furthermore, the value of the streambed conductance in the WWAT for the Kalkaska site was twice that in MODFLOW (Table 2.2). Given the importance of λ, the larger value used in WWAT may also contribute to the six-fold greater value of $Q_{s,max}$ yielded by the WWAT relative to that generated by MODFLOW.

Calculations of Q_s for the Calhoun County site over the cyclical five-year pumping period are shown in Figure 2.4b. Of the four situations considered, the only one that predicted a value of $Q_{s,max}$ greater than 25 m^3/day was STRMDEPL08 using WWAT-assigned parameters, which yielded a value of $Q_{s,max}$ of 2,354 m^3/day. The observation that using the WWAT parameter values in MODFLOW did not cause a significant difference in the calculation of $Q_{s,max}$ stands in contrast with the results obtained in the case of the Kalkaska County site. A major difference in the two study sites is the lithology relative to the screened depth of the pumping well. The glacial deposits are much thicker at the Kalkaska site, with an average depth to bedrock of 180 m versus only 25 m at the Calhoun site. Due to the thickness of the glacial deposits in Kalkaska County, the LQW well was screened in this layer, while the well was screened in the bedrock aquifer at the Calhoun County site, separated from the surficial aquifer by a 1 to 5 m thick aquitard. The presence of this lower-conductivity layer helped to confine the impact of pumping to the bedrock aquifer, reducing the impact on the stream located in the surficial glacial deposits. The discrepancy resulting from different conceptualizations of the hydrogeology is exacerbated by the use of a value of λ in the WWAT that is an order of magnitude larger than that in MODFLOW, again making the stream more responsive to the simulated pumping event than it might be in reality.

To analyze the impact of the aquitard to a greater extent, the site lithology was simplified in MODFLOW by setting the horizontal and vertical hydraulic conductivities of the aquitard (Layer #2) equal to those of the surficial glacial deposits (Layer #1), essentially eliminating the aquitard. The result, also shown in Figure 2.4b (labelled 'modified MODFLOW'), was that $Q_{s,max}$ now equaled 16.3 m^3/day, nearly 25 times larger than the value estimated using the MODFLOW model with WWAT parameters of 0.65 m^3/day, and of a similar order of magnitude to the value predicted by the analytic solution with MODFLOW parameters of 23.7 m^3/day. This finding underscores a key circumstance in which the analytical solution of Hunt (1999) may fail to reflect streamflow depletion behavior adequately. As Barlow and Leake pointed out, aquifer heterogeneity is a critical factor in determining whether an analytic solution is adequate to predict aquifer behavior (Barlow and Leake, 2012). The findings here suggest that an essential consideration is the placement of the pumping well relative to the layering in the stratigraphy. Although these results demonstrate the importance of the well screen location relative to the heterogeneity in the subsurface geology in predicting $Q_{s,max}$, the fact that the estimate of $Q_{s,max}$ yielded by the analytic solution using parameter values selected by the WWAT was still two orders of magnitude higher underscores the importance of the parameters aquifer diffusivity and streambed conductance.

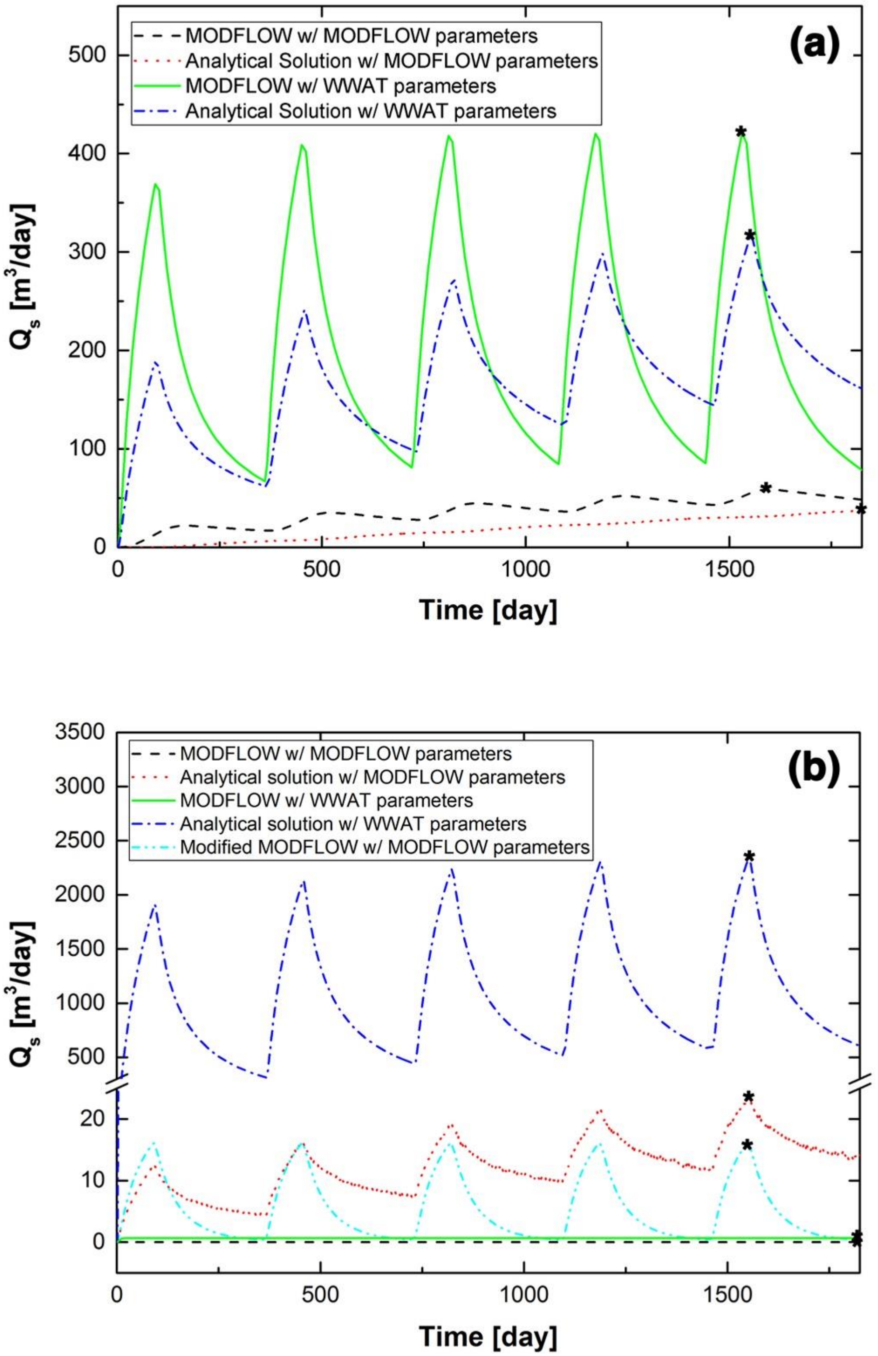


Figure 2.4. Streamflow depletion, Q_s, vs. time, t, calculated by MODFLOW and STRMDEPL08 using both MODFLOW and WWAT parameter values (Table 2.2) for the study sites in **(a)** Kalkaska County and **(b)** Calhoun County. The asterisks denote the maximum stream depletion, $Q_{s,max}$ over the five-year period. In **(b),** note the break in the scale of the y-axis between 20 and 500. $Q_{s,max}$ for the MODFLOW simulations in **(b)** are 5×10^{-4} and 0.65 m^3/d when using MODFLOW and WWAT assigned parameters, respectively. Also shown are results from a simulation using a modified MODFLOW domain where the parameter values for the aquitard (Layer #2) were set equal to those for Layer #1.

2.3.2 Sensitivity Analysis

The analysis of the results presented in Figure 2.4 pointed to the importance of aquifer diffusivity and streambed conductance to the determination of $Q_{s,max}$. To explore the sensitivity of the estimates of streamflow depletion to aquifer diffusivity, T/S was varied over two orders of magnitude, from 10^3 m^2/d to 10^5 m^2/d, with the results shown in Figure 2.5a. This figure indicates that the values of $Q_{s,max}/Q_w$ calculated using the analytic solution in the WWAT were consistently larger than those given by the numerical model. Furthermore, the discrepancy increased with increasing T/S, with the size of the difference depending on the study site. The discrepancy between the values of $Q_{s,max}/Q_w$ calculated using the analytical and numerical approaches was greatest at large values of T/S at the site in Calhoun County. At this site, the value of $Q_{s,max}/Q_w$ predicted by the numerical model was close to zero regardless of the value of T/S because the pumping well is screened in the bedrock layer, overlain by an aquitard with a low hydraulic conductivity. On the other hand, the value of $Q_{s,max}/Q_w$ predicted by the analytical solution increased with the value of T/S as this solution assumes that the system is homogeneous and the well is located in the same geologic unit as the stream. Thus, the discrepancies between the estimated streamflow depletion due to a well screened in a semi-confined bedrock aquifer versus that due to a well in an unconfined glacial aquifer depended on the value of T/S, with larger differences occurring at high values of T/S.

To assess the influence of streambed conductance on estimates of $Q_{s,max}/Q_w$, λ was varied over four orders of magnitude. The calculations of $Q_{s,max}/Q_w$ under these circumstances, shown in Figure 2.5b, indicate that, at low values of λ, the values of $Q_{s,max}/Q_w$ were small for all modeling scenarios, due to the impedance of stream-aquifer communication caused by low streambed conductance. At higher values of λ, the degree of stream depletion increased in all cases; however, the analytical solution yielded values of $Q_{s,max}/Q_w$ that were approximately three to five times larger than those predicted by MODFLOW for both study sites. This difference may be attributable to the larger hydraulic diffusivities used by the WWAT, which, when coupled with high values of streambed conductance, resulted in the stream being more sensitive to pumping. Since the value of the streambed thickness used by the WWAT is the vertical distance from the stream to the top of the well screen, it would be generally much greater than the true streambed thickness, with the result being a reduction in the value of streambed conductance (see Equation 2.3). The value of λ calculated in MODFLOW based on the measured index flow in the Black Creek is smaller than that used in the WWAT for both site locations (Table 2.2); however, the value of λ in WWAT would be smaller if the wells were screened at greater depths. Based on the findings presented in Figure 2.5b, low values of λ would result in the calculations of $Q_{s,max}/Q_w$ being insensitive to other system parameters. Furthermore, the value of $Q_{s,max}$ estimated by the WWAT would be smaller and thus, less conservative in the prediction of an ARI. Even though, generally, the WWAT calculations of $Q_{s,max}$ were greater than those of MODFLOW (see Figure 2.4) and, as such, were more conservative. Using the depth of screening as the streambed thickness may counteract the overall degree of conservatism of other assumptions used in the WWAT.

However, in the WWAT, streamflow is partially decoupled from groundwater in that water can flow from the stream to the aquifer but not vice versa. In the WWAT, $Q_i = Q_{index}$ is assumed to be constant and is based on a regression model of streamflow in gaged streams. In MODFLOW, however, $Q_i = Q_{initial}$ was calculated for the specific stream of interest and was dependent on the streambed conductance (Figure 2.6). Figure 2.5b shows that, for small values of λ, Q_s is always small regardless of the modeling scenario. Yet, for small values of λ, Q_i is small in MODFLOW

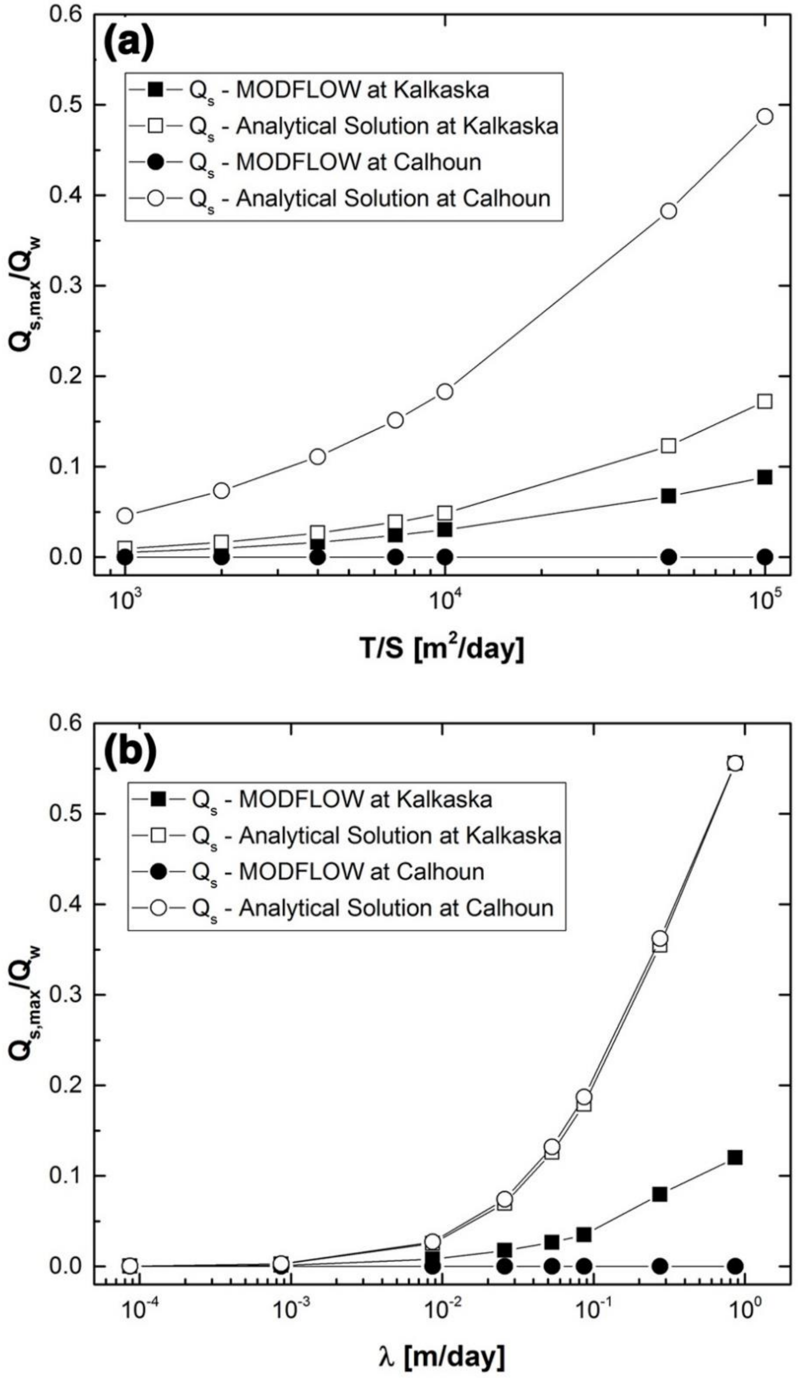


Figure 2.5. Maximum streamflow depletion, $Q_{s,max}$, normalized by well pumping rate, Q_w, for both the Kalkaska and Calhoun County study sites as a function of **(a)** aquifer diffusivity (T/S) and **(b)** streambed conductance, λ, calculated using MODFLOW and STRMDEPL08 and their respective values for other parameters (Table 1).

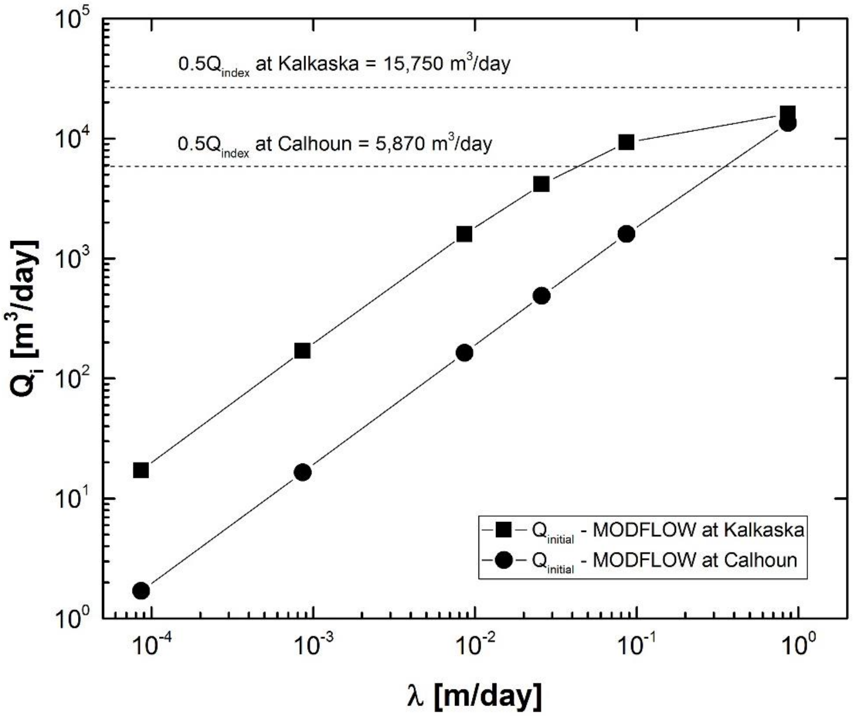


Figure 2.6. Streamflow rate, $Q_{initial}$, calculated by MODFLOW as the streamflow rate in the absence of pumping for both the Kalkaska and Calhoun County study sites as a function of streambed conductance, λ. 50% of Q_{index} for each site (the value used by the WWAT to predict an ARI) is indicated by the dashed lines.

but not in the WWAT (Figure 2.6). Thus for small values of λ, the ratio of $Q_{s,max}/Q_i$ may trigger an ARI in MODFLOW but not in the WWAT.

2.3.3 Uncertainty Analysis

The influence of S, T, and λ on Q_s was further examined by determining the partial derivative of Q_s with respect to S (Equation 2.7), T (Equation 2.8), and λ (Equation 2.9), assuming a unit value of Q_w (see Figure 2.7). The values for S, λ, and T determined in the WWAT for the Kalkaska site were 0.01, 0.053 m/day, and 521 m^2/day, respectively. For this set of values, $|\partial Q_s/\partial S|$, $|\partial Q_s/\partial \lambda|$, and $|\partial Q_s/\partial T|$ are 7.61, 4.48, and 7.14×10^{-5}, respectively, suggesting that transmissivity does not have a significant influence on the calculations of Q_s/Q_w. S is the largest contributor to

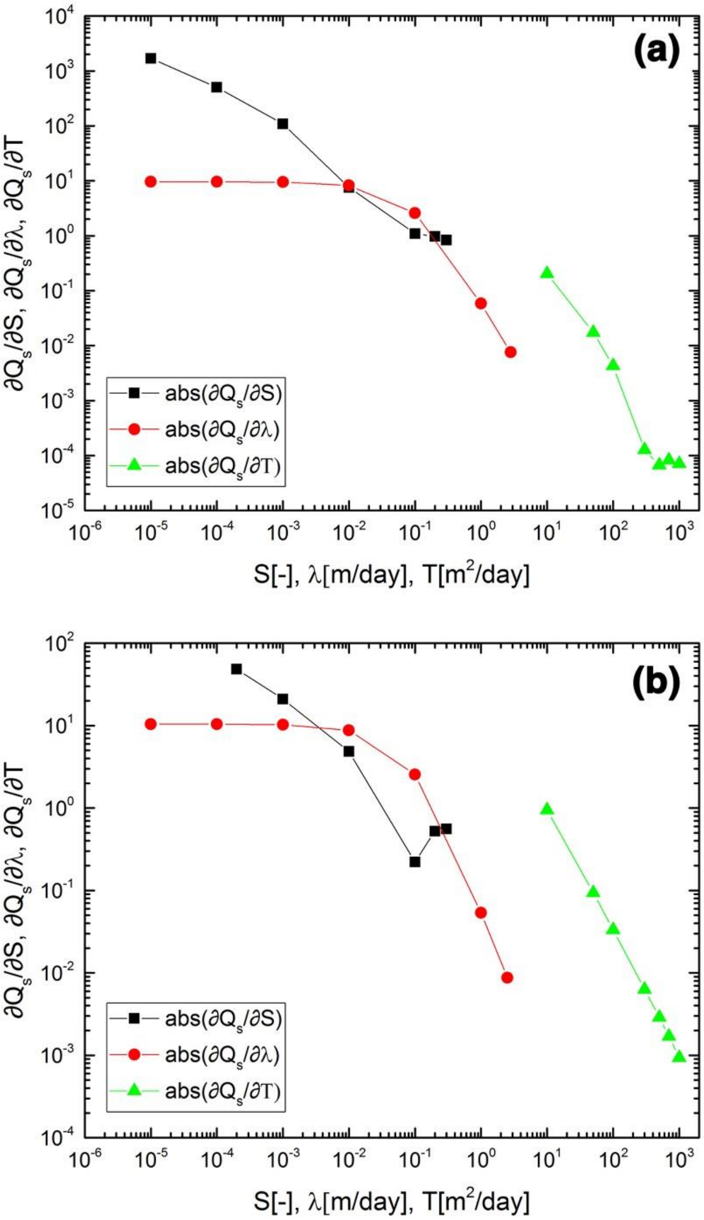


Figure 2.7. Absolute values of the partial derivatives of Q_s (Eqn. 1) with respect to S, T and λ ($|\partial Q_s/\partial S|$, $|\partial Q_s/\partial T|$ and $|\partial Q_s/\partial \lambda|$) calculated using Equations 2.7, 2.8, and 2.9 and the WWAT parameter values for the study sites in **(a)** Kalkaska, and **(b)** Calhoun Counties.

the uncertainty in the calculations when its value is less than 0.01 or larger than 0.2, whereas λ is the largest contributor when its value is between 0.01 to 0.1 m/day.

At the Calhoun site, the values for S, λ, and T determined by the WWAT were 0.01, 0.274 m/day, and 435 m^2/day, respectively. For this set of values, the $|\partial Q_s/\partial S|$, $|\partial Q_s/\partial \lambda|$, and $|\partial Q_s/\partial T|$ are

4.87, 0.603, and 3.58×10^{-3}, respectively, again suggesting that the aquifer transmissivity does not have a significant influence on the value of Q_s/Q_w. S is the major contributor when its value is smaller than 0.005 or larger than 0.2, whereas the streambed conductance is the largest contributor when its value falls between 0.05 and 0.2 m/day. If the streambed conductance were of the same order of magnitude at both study sites, then S and λ would contribute similarly to the error in Q_s/Q_w. However, given that S is a fixed value in the WWAT, the uncertainty in Q_s is essentially governed by the magnitude of λ.

2.4 Conclusion

To protect ecologically important surface waters, the State of Michigan has developed an analytic tool, the WWAT, to screen proposed LQW wells, based on the streamflow depletion solution of Hunt (1999). To evaluate the tool's performance, a case study of two sites in Michigan, one in Kalkaska County and one in Calhoun County where LQW wells have been permitted, was undertaken. A three-dimensional numerical groundwater model was developed in MODFLOW for each of these sites and was used to estimate the depletion in streams near the wells. These estimates were then compared to those provided by the WWAT.

This study suggests that this screening tool generally overestimates streamflow depletion in an effort to provide a conservative assessment of potential impact from a given LQW well, as is its intention. Yet, the WWAT still allows the majority of proposed LQWs to proceed without site-specific review. Thus, the level of conservatism in the screening tool does not appear to pose an undue hindrance to the permitting process. However, it is believed that the intention of the tool is to reflect the physics of the system and with that in mind, several points need to be considered based on the results of this study. An analysis of the lithology of the two sites showed that both sites could be modeled as three-layer systems. At the Kalkaska site, the layering was not of particular significance because the well was screened in the surficial glacial aquifer, whereas at the Calhoun site, the layering influenced the outcome of the estimates of streamflow depletion, since the well was screened below the aquitard in the bedrock aquifer. In such a situation where heterogeneity is important, an analytic solution, such as that presented by Ward and Lough (2011) which extends the solution of Hunt (1999) to consider pumping from a semi-confined aquifer, may give more accurate results.

The sensitivity and uncertainty analyses suggest that storativity and streambed conductance may have a similar impact on the estimates of stream depletion. Given that the value of storativity is fixed in the WWAT, the role of streambed conductance becomes more significant. Despite its importance in determining the level of conservatism of the stream depletion estimates, it is a parameter whose value is not well defined. The streambed conductance is based on streambed thickness which, in the WWAT, is set equal to the vertical distance between the stream and the top of the well screen. Since this value is more than likely greater that the actual streambed thickness, the streambed conductance may be unrealistically low. A low value of λ may suggest that the aquifer is poorly connected to the stream, resulting in smaller estimates of stream flow depletion. As multiple studies have also suggested the importance of this parameter (Chen and Yin, 1999; Christensen, 2000; Lackey et al., 2015a), its estimation in the WWAT merits additional scrutiny.

The WWAT flags a proposed LQW for site-specific review if Q_s exceeds a certain percentage of Q_i. In the WWAT, the value of Q_i is fixed and is based on a regression analysis of a set of river gage station data of larger rivers and streams. Thus, the role that streambed conductance has in regulating the baseflow of small streams in the absence of pumping may not be adequately represented in the analysis. If the conductance is low, then the baseflow may also be low, increasing the likelihood that a given Q_s would result in the prediction of an ARI. Based on a streambed conductance of 0.026 m/day and other parameters (such as Manning's roughness coefficient), MODFLOW estimated a value of Q_i of 488 m^3/day for Dickinson Creek, versus a value of 5,870 m^3/day given by the WWAT. Thus, more information regarding λ is critical for determining potential ARIs due to the installation of new LQW wells. Such information would be of use not only for the State of Michigan, but also for other states that have implemented, or are considering implementing, screening procedures based on the impact of groundwater withdrawals on surface water.

2.5 Acknowledgement

This work has been published in a similar form in Environmental Science Water Research and Technology (Jayawan et al., 2016). This work was supported in part by funding from the University of Michigan Water Center and from the National Science Foundation under grant number 1214416. The authors would like to thank Howard W. Reeves for providing access to STRMDEPL08 code. This chapter represent the views of the authors and should not be construed to represent the views of the Michigan Department of Environmental Quality or the U.S. Geological Survey.

CHAPTER 3

Improvement of Analytical Solution in Permitting Large Quantity Groundwater Withdrawals

3.1 Introduction

The study presented in the previous chapter showed that the estimation of streamflow depletion, Q_s, will depend on the hydrogeological setting and the analytical solution used. In the context of the analytical solution, streambed conductance has been shown to be the most sensitive parameter in estimating streamflow depletion. The first stream – aquifer unsteady state analytical models for Q_s estimation were developed by Theis (1941) and Glover and Balmer (1954). In their models, the simplest hydrogeologic settings (i.e., a straight, fully penetrating river; a homogenous, isotropic, unconfined aquifer with semi-infinite extent; and a constant pumping rate from a fully penetrating well) were used to estimate Q_s (Figure 3.1a). Since then, numerous improvements have been made that take into account greater complexity in the hydrogeologic settings. For example, Hantush (1965) added a clogging layer in between the stream and the aquifer to include the effect of the streambed in stream – aquifer interaction (Figure 3.1b). Hunt (1999) developed an analytical solution to estimate Q_s for a partially penetrating stream in a semi-infinite aquifer by a fully penetrating well (Figure 3.1c). Butler (2001) revised the analytical solution for the hydrogeologic setting considered by Hunt (1999) but with finite aquifer boundaries (Figure 3.1d). Hunt (2003) developed another analytical model for a partially penetrating stream located in a semi-infinite aquitard on top of a pumped aquifer with a fully penetrating well (Figure 3.1e). Sun

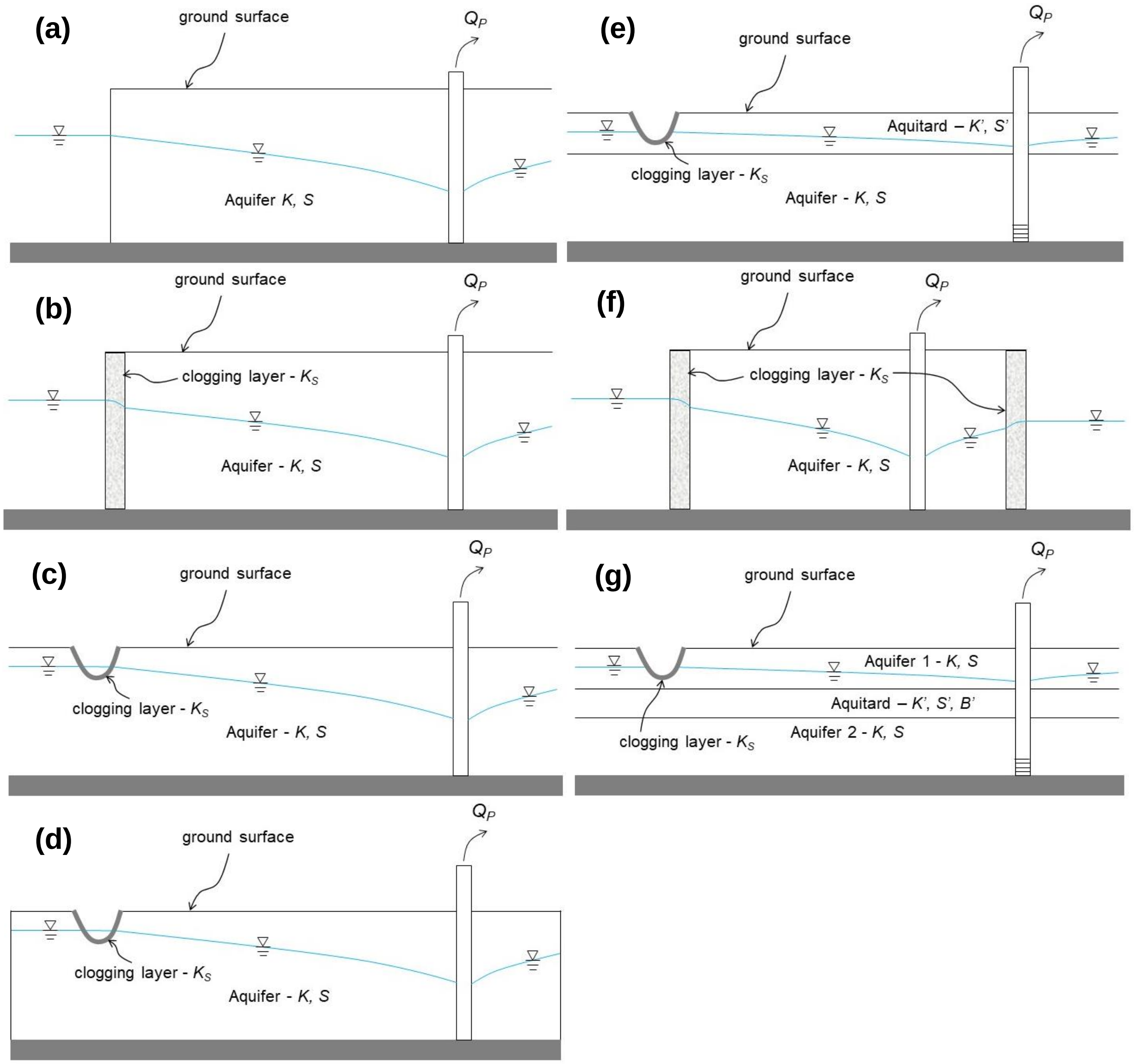


Figure 3.1. The hydrogeologic setting considered in the analytical solutions developed by **(a)** Theis, 1941 and Glover and Balmer, 1954; **(b)** Hantush, 1965; **(c)** Hunt, 1999; **(d)** Butler et al., 2001; **(e)** Hunt, 2003; **(f)** Sun and Zhan, 2007; and **(g)** Ward and Lough, 2011.

and Zhan (2007) developed an analytical model for the hydrogeologic setting considered by Hantush (1965) with an additional stream (Figure 3.1f). Most recently, Ward and Lough (2011) developed a Q_s analytical model for a partially penetrating stream located in a finite top aquifer with an aquitard and pumped aquifer beneath it and a fully penetrating well (Figure 3.1g).

While many of the analytical solutions often assume a pumping well exists in a relatively simple homogeneous unconfined aquifer, Hunt (2003) and Ward and Lough (2011) provided alternative analytical solutions giving streamflow depletion in scenarios involving multiple geologic layers. The hydrogeologic setting assumed by the Ward and Lough (2011) analytical solution suits the hydrogeologic setting at Dickinson Creek in Calhoun County where the stream is located in an aquifer on top of a clay layer and the pumping well is screened in an aquifer beneath the clay layer. In this region, there have been complaints that the WWAT is too conservative such that many applications for LQWs were rejected when there was no evidence of wells drying up or streams being depleted due to existing LQWs (Alexander, 2013; Wilson, 2013). Ward and Lough (2011) used the following equations to describe the stream flow depletion in the conceptual model shown in Figure 3.2:

$$S_1 \frac{\partial s_1}{\partial t} = T_1 \nabla^2 s_1 - \frac{K^{'}}{B^{'}} \left(s_1 - s_2 \right) - \lambda \delta \left(x \right) s_1 \qquad \text{(Equation 3.1)}$$

$$S_2 \frac{\partial s_2}{\partial t} = T_2 \nabla^2 s_1 + \frac{K^{'}}{B^{'}} \left(s_1 - s_2 \right) + Q \delta \left(x - L \right) \delta \left(y \right) \qquad \text{(Equation 3.2)}$$

where s_1 and s_2 are the drawdowns in the upper and lower aquifers, respectively; ∇^2 is the two-dimensional Laplacian operator; L is the pumping well distance from the stream; Q is the pumping rate; T_1 and S_1 are the transmissivity and specific yield of the upper aquifer, respectively; T_2 and S_2 are the transmissivity and storativity of the lower aquifer, respectively; B' and K' are the thickness and the hydraulic conductivity of the aquitard layer, respectively, and λ is the streambed conductance. For simplification, the variables in Equation 3.1 and 3.2 can be converted to dimensionless variables as shown in Equation 3.3:

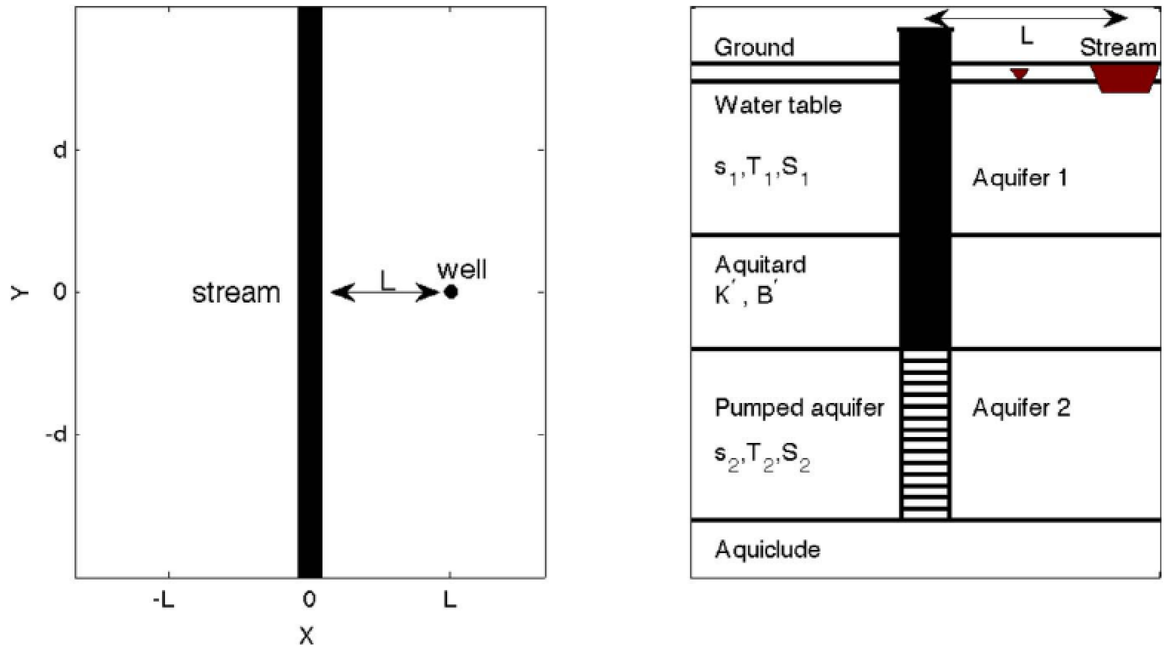


Figure 3.2. Plan and cross-sectional view of the Q_s analytical model considered by Ward & Lough (2011). Figure from Ward and Lough, 2011.

$$\left(s_1^*, s_2^*, x^*, y^*, T^*, S^*, K^*, \lambda^*\right) = \left(\frac{s_1 T_2}{Q}, \frac{s_2 T_2}{Q}, \frac{x}{L}, \frac{y}{L}, \frac{t T_2}{S_2 L^2}, \frac{T_1}{T_2}, \frac{S_1}{S_2}, \frac{\left(K'/B'\right) L^2}{T_2}, \frac{\lambda L}{T_2}\right) \quad \text{(Equation 3.3)}$$

Inserting these dimensionless variables in Equations 3.1 and 3.2 yield the following equations as given in Ward and Lough (2011):

$$S^* \frac{\partial s_1^*}{\partial t^*} = T^* \nabla^2 s_1^* - K^* \left(s_1^* - s_2^*\right) - \lambda^* \delta\left(x^*\right) s_1^* \quad \text{(Equation 3.4)}$$

$$\frac{\partial s_2^*}{\partial t^*} = \nabla^2 s_2^* + K^* \left(s_1^* - s_2^*\right) + \delta\left(x^* - 1\right) \delta\left(y^*\right) \quad \text{(Equation 3.5)}$$

The results in the previous chapter suggested that the modified Hunt (1999) solution did not provide a good estimate of stream depletion at the site in Calhoun County, MI. As a result, this study aims to evaluate the suitability of the Ward and Lough (2011) analytical solution to evaluate Q_s for the situation at that site. This is achieved by comparing estimates of Q_s results obtained

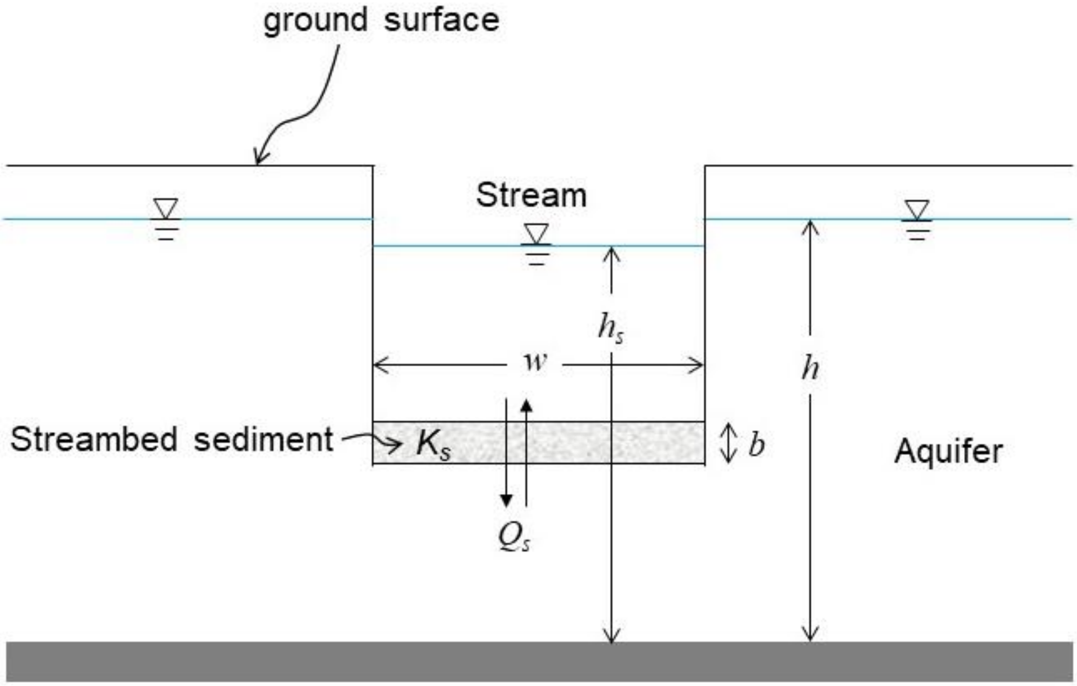


Figure 3.3. Cross-sectional view of a gaining stream considered in MODFLOW stream (STR) package. The hydraulic head of the stream (h_s) and the aquifer (h) are shown relative to the datum. Q_s is the flow across the streambed sediment layer; w is the stream width; K_s and b is the hydraulic conductivity and the thickness of the streambed sediment, respectively. For a losing stream, Q_s is flowing from the stream to the aquifer, whereas for a gaining stream, Q_s is flowing from the aquifer to the stream.

using the modified Hunt (1999) and the Ward and Lough (2011) models with those using MODFLOW.

In addition to well placement with respect to the layering in the subsurface stratigraphy, the results presented in Figure 2.7 showed that streambed conductance, λ, is the most critical parameter in the estimation of Q_s by the WWAT. Streambed conductance describes the degree to which the stream and the aquifer are connected. Equation 2.2 describes the streambed conductance as used in the Hunt (1999) analytical solution derived using the idealized general cross-section of stream – aquifer interface shown in Figure 3.3. In this figure, Q_s represents the flow across the streambed layer which can be calculated using Darcy's Law as:

$$Q_s = \frac{wLK_s}{b}\left(h_s - h\right) \qquad \text{(Equation 3.6)}$$

where w and L are the stream width and length, respectively; K_s and b are the streambed hydraulic conductivity and thickness, respectively; Q_s is the flow across the streambed layer; h_s and h are the total hydraulic heads in the stream and aquifer, respectively. In the event of pumping, the rate of change in the flowrate across the streambed is proportional to the rate of change of the head difference between the stream and the aquifer (Eqn. 3.1). Expressed as a flow per unit length, the change in the flowrate can be represented as:

$$\frac{\Delta Q_s}{L} = \frac{wK_s}{b}\Delta\left(h_s - h\right) = \lambda\Delta\left(h_s - h\right) \qquad \text{(Equation 3.7)}$$

where $\Delta Q_s/L$ is the rate of change of the streamflow depletion per unit stream length; λ is the streambed conductance; and $\Delta(h_s\text{-}h)$ is the rate of change of the head gradient between the stream and the aquifer due to pumping. The λ derived from Equation 3.7 is the basis for Equation 2.2 showing that λ is governed by the stream width, w; the streambed thickness, b; and the streambed hydraulic conductivity, K_S.

Most creeks and brooks have stream widths between roughly 1 to 10 meters. Larger streams usually have widths in the order of 10 to 10^3 meters (Allen and Pavelsky, 2015; National Park Service, n.d.). The streams of concern in the State of Michigan are sensitive trout streams whose streamflow rates are small enough that they may be adversely impacted by nearby LQWs. Thus, the stream widths would fall at the smaller end of this range and can be assumed to vary from 1 up to 100 m. Regarding streambed thicknesses, it is reasonable to assume that they are usually on the order of less than a meter up to a few meters (Sophy et al., 2010). On the other hand, values of K_S vary widely. Previous measurements at 23 different locations in the U.S. (see Table 3.1) and other studies suggest a range of four orders of magnitude for K_S (Calver, 2001; Cardenas and

Zlotnik, 2003; Chen, 2005; Fox, 2003; Genereux et al., 2008; Kennedy et al., 2010; Kollet and Zlotnik, 2007; Song et al., 2009). Because K_S varies over the greatest number of orders of magnitude, this parameter will play the largest role in determining the streambed conductance in the context of small sensitive streams.

K_S has been widely recognized for its crucial role in governing stream-aquifer interactions (Brunner et al., 2017; Calver, 2001; Chen, 2000; Fox, 2007; Kalbus et al., 2006; Lackey et al., 2015b; Sophocleous, 2002). It can vary with direction; hence there are conceivably two values that may influence stream-aquifer interactions: horizontal and vertical K_S. The focus in this study is on K_S in the vertical direction due to the direction of water flow in stream – aquifer interactions; hence the term K_S in this chapter refers the value in the vertical direction.

Hydrogeologists and surface water hydrologists have utilized a range of methods to characterize K_S (Brunner et al., 2017; Kalbus et al., 2006; Sophocleous, 2002). The most widely used methods rely on the application of Darcy's Law (Equation 3.6) to estimate the value of K_S by knowing the hydraulic head gradient and water flux between two different points in the field. This principle is the underlying foundation of many point estimate methods used such as constant-head, falling-head or other modified permeameter based-tests (Baxter et al., 2011; Cardenas and Zlotnik, 2005; Chen, 2005, 2000; Duwelius, 1996; Fox, 2003; Fox et al., 2011; Genereux et al., 2008; Kennedy et al., 2010; Landon et al., 2001; Sebok et al., 2014) , and seepage meter tests (Isiorho and Meyer, 1999; Kennedy et al., 2010; Landon et al., 2001). Alternatively, point values of K_S are sometimes obtained using lab-based grain size analysis (Song et al., 2009). However, it appears that grain-size-based methods consistently overestimate the hydraulic conductivity value as they exclude the consideration of vertical heterogeneity and preferential pathways within the streambed (Chen, 2000; Lu et al., 2011; Song et al., 2009; Strasser et al., 2015). Pump tests have also been used to characterize aquifer parameters and K_S on a larger scale than the point measurement methods; however these methods are often considered too costly and logistically challenging (Kalbus et al., 2006; Kollet and Zlotnik, 2007; Norris, 1983). Freeze-coring with X-ray computer tomography analysis is viewed as a promising alternative method to characterize K_S, but it is also considered as logistically challenging and its application are limited to the availability of an X-ray computer tomography scanning apparatus which may not be readily available (Strasser et al., 2015). In addition to the methods discussed above, there are many other alternative methods that have been used to characterize K_S, such as a heat tracer method (Anderson, 2005; Constantz, 2008), geophysical methods (Binley et al., 2015; Wojnar et al., 2013), structure imitating models (Cardenas and Zlotnik, 2003), and groundwater numerical model calibration (Fleckenstein et al., 2006; Jayawan et al., 2016). Even though one can make a point measurement of K_S in a stream, this parameter is known to vary spatially and temporarily within a stream reach (Genereux et al., 2008; Min et al., 2013; Rosenberry and Pitlick, 2009; Song et al., 2010; Wu et al., 2015). For example, Genereux et al. (2008) found K_S to vary spatially by almost three orders of magnitude at a section of West Black Creek in North Carolina.

Our literature review on K_S measurement in the U.S. has shown that, other than numerical modeling, all K_S measurement methods require a field trip to the stream location. Table 3.1 shows the measured K_S values at 23 different observation locations at 15 different streams in the U.S. used in this study while Figure 3.4 shows the location of these 15 different streams in the U.S. In the context of regulatory frameworks, it can be challenging to come up with an appropriate K_S value for a stream reach using conventional field measurement methods, let alone for multiple streams across a state. As a result, alternative methods have been used to come up with reasonable estimates of K_S for groundwater resource management purposes. For example, the WWAT

Table 3.1. 23 different measurement locations at 15 different streams in the U.S. and their respective data references used in this study. Streams are sorted alphabetically by state's name. The site number corresponds to Figure 3.4.

Obs. No.	Site No.	Stream Name and Location	Reported K_S value [m/d] [a]	Reference for K_S	Reported Aquifer K values [m/d]	References for Aquifer K
1	1	South Platte River near Crook, CO	71 ± 18 [#]	Fox, 2003	37 – 464.5 [b]	Fox, 2003
2	2	Cedar River near Cedar Rapids, IA	19 [&]	Barlow et al., 2000	94.2	Barlow et al., 2000
3	3	Grand Calumet River near Gary, IN	0.09 – 22.25 [#]	Duwelius, 1996	0.2 – 109.7	Duwelius, 1996
4	4	White River near Indianapolis, IN	2.20 [+]	Meyer, 1978	108	Meyer, 1978
5	5	Blackstone River near Worcester, MA	0.43 [#]	Barlow et al., 2000	61	Barlow et al., 2000
6	6	Gulf Brook near Pepperell, MA	0.02 – 0.82 [# +]	de Lima, 1991	81.7 [c]	de Lima, 1991[b]
7	7	Morse Brook near Devens, MA	1.01 – 1.52 [+]		152.4 [c]	
8	8	West Bear Creek near Goldsboro, NC	0.01 – 66 [#]	Genereux et al., 2008; Kennedy et al., 2010	0.8	North Carolina DEQ, 2000
9	9	Elkhorn River near Stuart, NE	2.7 – 19.66 [#]	Song et al., 2010	0.3 – 30.5	Gutentag et al., 1984
10		Elkhorn River near Atkinson, NE	7.77 – 104.85 [#]		0.3 – 30.5	
11		Elkhorn River north of Ewing, NE	7.33 – 36.07 [#]		0.3 – 30.5	
12		Elkhorn River south of Ewing, NE	16.33 – 22.28 [#]		0.3 – 30.5	
13		Elkhorn River near Neligh, NE	25.64 – 31.24 [#]		0.3 – 30.5	
14		Elkhorn River near Meadow Grove, NE	17.64 – 32.09 [#]		0.3 – 30.5	
15		Elkhorn River near West Point, NE	14.14 – 28.98 [#]		0.3 – 30.5	
16	10	Platte River near Ashland, NE	3 – 65 [#]	Chen, 2005	0.3 – 30.5	
17	11	Prairie Creek near Silver Creek, NE	15 – 20 [#]	Cardenas and Zlotnik, 2005; Kollet and Zlotnik, 2007	0.3 – 7.6	
18	12	Republican River near Bloomington, NE	35.4 – 45.9 [#]	Chen, 2000	7.6 – 61	
19		Republican River near McCook, NE	17.3 – 20 [#]		7.6 – 61	
20	13	Connetquot Brook near Islandia, NY	3.35 – 4.57 [#]	Prince et al., 1988	13.2 – 91.5 [b]	Chu, 2006; McClymonds and Franke, 1972[a]
21	14	Susquehanna River near Kirkwood, NY	0.03 – 0.15 [+]	Yager, 1993	152 – 3048	Yager, 1993
22	15	Scioto River near Wakefield, OH	3.6 [+]	Norris, 1983	108.8 – 187.4	Norris, 1983
23		Scioto River near Piketon, OH	0.98 – 6.28 [+]		207.3	

[a] Measured K_S was reported as a single value, a range of values, or mean with a standard deviation.

[#] [&] [+] denotes measured K_S were acquired through Darcy's Law based testing (e.g., constant or falling head permeameter tests), numerical modeling, and pump tests, respectively.

[b] denotes Aquifer K was calculated using $K = T/B$; where K, T and B are the aquifer hydraulic conductivity, transmissivity, and mean saturated thickness, respectively.

[c] denotes Aquifer K was calculated using $T = \dfrac{2.303Q_w \log\left(t_2 - t_1\right)}{4\pi\left(s_2 - s_1\right)}$ and then $K = T/B$; where s_1 and s_2 are the drawdowns corresponding to times t_1 and t_2 since pumping began, respectively, and Q_W is the aquifer pumping rate. Table A.1 shows the calculation of aquifer-derived K at observation number 1, 6, 7, and 20.

Figure 3.4. The location of the 15 different streams in the contiguous U.S. where K_S has been measured. The numbers correspond to the site number in Table 3.1.

approximates the K_S values for all streams in Michigan as 1/10 of the adjacent screened aquifer hydraulic conductivity, K (hereafter defined as aquifer-derived K_S). The aquifer K values were acquired from the groundwater mapping project database (Michigan Department of Environmental Quality et al., 2006b; Reeves et al., 2009). From Table 3.1, it can be observed that this approach did not give a good enough estimate for the actual measured K_S. A better approach to estimate measured K_S would therefore be beneficial to prevent any under- or over-estimation of λ and subsequently Q_s.

Streambed properties are considered to be related to the local geologic materials and flow dynamics within the watershed. Previous studies have looked at the source of the streambed sediments and it was found that streambed sediments were mainly composed of topsoil and channel banks materials (Walling, 2005). Sediment fingerprinting studies have highlighted the importance of different land covers in influencing streambed sediment loading (Gellis et al., 2009; Gellis and Noe, 2013; Lamba et al., 2015; Mukundan et al., 2010). Land cover contributions to streambed sediment loading can be calculated by comparing the relative streambed sediment loading with the relative land cover as follows:

$$\mathrm{LCF} = \frac{\frac{m_{lc}}{m_{total}}}{\frac{A_{lc}}{A_{total}}} \qquad \text{(Equation 3.8)}$$

where LCF is the land cover contribution factor, m_{lc} is the sediment mass load from a particular land cover of interest, m_{total} is the total sediment mass load from the contributing watershed, A_{lc} is the area of a particular land cover of interest, and A_{total} is the total watershed area. Previous studies of streambed sediment fingerprinting in the continental U.S. have shown that cropland has the highest LCF (varying from 1.3 – 4.5), followed by pasture land (1.9 – 3.7), whereas forest land actually abates the erosion of topsoil towards the stream (LCF varying from 0.1 – 0.9). The relative contribution of stream banks to the sediment load depends on the stream head gradients. Previous sediment fingerprinting studies in the U.K. have shown that streams with head gradients higher than 0.002 m/m would have stream bank sediment contributions higher than 30%. On the other hand, more gentle streams (i.e., a stream head gradient less than 0.002 m/m) have an average stream bank contribution of about 10% or less (Walling, 2005).

In evaluating the streambed sediment load, it is also important to consider its travel distance, as sediment loading depends on the streamflow velocity and the streambed surface roughness. Most studies on streambed sediment translation distances were performed in a controlled environment where the streamflow velocity is known (Siddiqui and Robert, 2010). In one of the few studies in an actual river, Hodge et al. (Hodge et al., 2011) showed that in the Allt

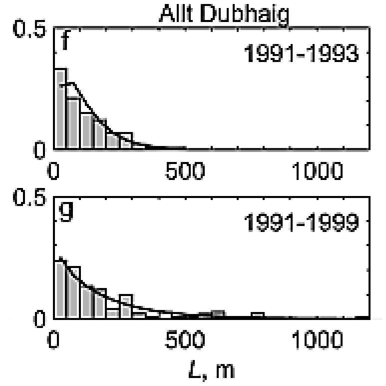


Figure 3.5. Distributions of tracer travel distances (*L*) from the Allt Dubhaig in Scotland, U.K over **(f)** 2 years and **(g)** 8 years. The y-axis shows the proportion of data. Modified from Hodge et al., 2011.

Dubhaig (a stream with 100% sediment cover) in Scotland, U.K., streambed sediment can travel up to 500 meters after two years (Figure 3.5f) and up to 1,500 meters after eight years (Figure 3.5g).

Since the streambed sediments are composed of soils in the watershed, streambed properties such as K_S should be correlated with the parameters of the soil in the watershed, such as the soil's saturated hydraulic conductivity, K_{soil}. However, to the best of our knowledge, K_S values were only derived from either field tests for point measurement and pump tests for non-point measurements and there are no studies that evaluate the relationship between streambed sediment and soil from the watershed in estimating K_S. The objective of this study is to improve the analytical models used by water resource managers to evaluate the impact of LQW on a nearby stream. The objective was achieved by: (1) evaluating the appropriateness of the Ward and Lough (2011) analytical model for a site with vertical heterogeneity by comparing results from this model to those from a numerical model; and (2) developing a method that utilizes soil hydraulic conductivity and land cover data to provide an alternative method to quickly estimate reasonable K_S values for the computation of λ and Q_S. The estimated K_S values were then compared with previously measured K_S from 23 different measurement points in 15 different streams (see Table 3.1). This approach was also used to estimate the K_S values for the WWAT application.

3.2 Methods

3.2.1 Ward and Lough (2011) Analytical Solution

In this study, Ward and Lough (2011) analytical solution was used to estimate the streamflow depletion at Dickinson Creek in Calhoun County, Michigan where the stream is located in a surface aquifer overlying a clay layer and a pumping well is screened in the aquifer beneath the clay layer. This result was then compared to the simulation results performed using the numerical and the modified Hunt (1999) models presented in the previous chapter. Matlab R2017a (MathWorks, Natick, MA) was used to solve Equations 3.4 and 3.5 and to subsequently calculate Q_s. Visual MODFLOW 2011.1 (Schlumberger Water Services, Kitchener, ON) and STRMDEPL08 were used to estimate the Q_s using the numerical model and modified Hunt (1999) analytical solutions, respectively as presented in the previous chapter.

Parameters used to estimate Q_s using the Ward and Lough (2011) solution have the same values as those in the WWAT where possible, otherwise the values from MODFLOW were used instead (see Table 2.4). For example, the surficial aquifer's T and S are similar to those of the WWAT (T = 435 m^2/d; S = 0.01). An aquitard layer, however, is absent from the WWAT, and therefore, the parameters for this layer followed those of the calibrated numerical model (K' = 8.64×10-7 m/d; B' = 1 – 5 m). For the semi-confined bedrock aquifer beneath the clay layer where the well in Calhoun County was screened, the bedrock aquifer parameters were assumed to be much larger than the MODFLOW calibrated bedrock aquifers and set to be the same as the surficial aquifer parameters (i.e., T = 435 m^2/d; S = 0.01). The reason is because in WWAT, the

Table 3.2. Summary of the parameters used to estimate streamflow depletion at Calhoun Site using Ward and Lough (2011), modified Hunt (1999) as used by the WWAT, and numerical model (MODFLOW). W&L denotes Ward & Lough analytical solution.

	Ward & Lough (2011)	WWAT	MODFLOW [i]
Surface Aquifer Parameters (Layer #1)			
Transmissivity [a], T_1 [m^2/d]	435		6650 - 38000
Storage coefficient [b], S_1 [-]	0.01		0.16
Surficial aquifer recharge rate [c] [cm/year]	n/a		28
Aquitard Parameters (Layer #2)			
Hydraulic conductivity, K' [m/d]	8.64×10^{-7}	n/a	8.64×10^{-7}
Thickness [d], B' [m]	1	n/a	1 – 5
Parameters of the Aquifer underlying the Aquitard (Layer #3)			
Transmissivity [a], T_2 [m^2/d]	435	n/a	0.432
Storage coefficient [b], S_2 [-]	0.01	n/a	10^{-3}
Stream Parameters			
Streambed thickness [e], b [m]	31		1
Streambed width [f], w [m]	6.0		1
Streamflow rate [g], Q_i [m^3/d]	5870		488
Streambed hydraulic conductivity [h], K_S [m/d]	1.74		0.026
Streambed conductance [i], λ [m/d]	0.274		0.026
Pumping Parameters			
Distance between well and stream, d [m]	1000		
Pumping rate, Q_w [m^3/d]	2530		
Pumping schedule	3 months pumping followed by 9 months shutoff annually for 5 years		

[a] The values for T_1 and T_2 for both the Ward & Lough (2011) solution and the WWAT are from the Michigan Groundwater Inventory and Mapping (GWIM) Project database (Michigan Department of Environmental Quality et al., 2006a; Reeves et al., 2009) whereas those for MODFLOW are based on calibrated K_x values and aquifer thickness of 100 m for Calhoun Site, respectively

[b] The value of S_1 and S_2 for both the Ward & Lough (2011) solution and the WWAT are constant and consistent with reported values for leaky aquifers (Reeves et al., 2009); The value of S_1 and S_2 for MODFLOW are typical values for unconfined and confined aquifer, respectively (Morris and Johnson, 1967).

[c] The values for recharge are from the Michigan Groundwater Inventory and Mapping (GWIM) Project database (Michigan Department of Environmental Quality et al., 2006a; Reeves et al., 2009)

[d] The values of B' are from the GWIM Project database (Michigan Department of Environmental Quality et al., 2006a; Reeves et al., 2009). For Ward & Lough (2011) analytical solution, the B' were assumed to be 1 meter to represent the thinnest possible clay layer as used in MODFLOW

[e] The values of b for both the Ward & Lough (2011) solution and the WWAT are the vertical distance from the stream to the top of the well screen (Reeves et al., 2009) whereas that for MODFLOW is based on typical values of streambed thickness.(Toran et al., 2013)

[f] The values of w for both the Ward & Lough (2011) solution and the WWAT were calculated using Equation 2.5 whereas that for MODFLOW was set equal to 1 m based on satellite images

[g] The values of Q_i for both the Ward & Lough (2011) solution and the WWAT are equal to Q_{index} (Michigan Department of Environmental Quality, n.d.), whereas the Q_i for MODFLOW was based on the actual streamflow measurement at the Black Creek site in Kalkaska due to the absence of any additional information at Dickinson Creek (Hyndman, 2013)

[h] The value of K_S for both the Ward & Lough (2011) solution and the WWAT were calculated by assuming that it is equal to 1/10 of the aquifer K whereas that for MODFLOW were based on numerical calibration using measured Qi at Black Creek (Hyndman, 2013)

[i] The values of λ for Ward & Lough (2011) solutions, WWAT, and MODFLOW were calculated using Equation 3.2 with their respective K_S, w, and b parameters.

bedrock aquifer parameters were unknown and having the lower aquifer parameters to be much larger than the actual calibrated values simulated a more conservative scenario where the aquifer was assumed to be more conductive than the calibrated values. The stream parameters for the Ward and Lough (2011) solution were the same as the one used by the WWAT with modified Hunt (1999) solution, i.e., the stream width was 6 m, the streambed thickness was assumed to be the vertical distance to the well's screen of 31 m, the streambed K was set to 1/10 of the aquifer K (K_S = 1.74 m/d). All the parameters used to calculate Q_s using Ward and Lough (2011), modified Hunt (1999) and the MODFLOW numerical model are listed in Table 3.2. The principle of superposition was used to simulate the five cycles of pumping, similar to the method used to evaluate LQWs in Michigan (Hamilton and Seelbach, 2011; Reeves et al., 2009).

3.2.2 Estimating K_S using K_{soil} of the Soils in the Watershed Areas

In this approach, it was assumed that the streambed parameters would be correlated to the parameter of the soil in the watershed since the streambed sediment came from the soil erosion in the watershed areas. In total there are three different approaches used to derive the K_S from K_{soil} of the watershed areas: (1) based on the area-weighted average of the K_{soil}; (2) based on the area-weighted average of the K_{soil} and land cover; and (3) based on the area-weighted average of K_{soil} with upstream distance weighted contribution. ArcMap 10.4 (ESRI, Redlands, CA) was used to delineate all the hydrographs and watershed boundaries. The watershed and stream boundary lines were acquired from the National Hydrography Dataset (NHD) and Watershed Boundary Dataset (WBD). The K_{soil} values were derived from the Soil Survey Geographic (SSURGO) database hosted by the U.S. Department of Agriculture (USDA). The land cover data were acquired from the National Land Cover Database (NLCD) 2011. A sensitivity analysis of the stream upstream

This illustration is not to scale

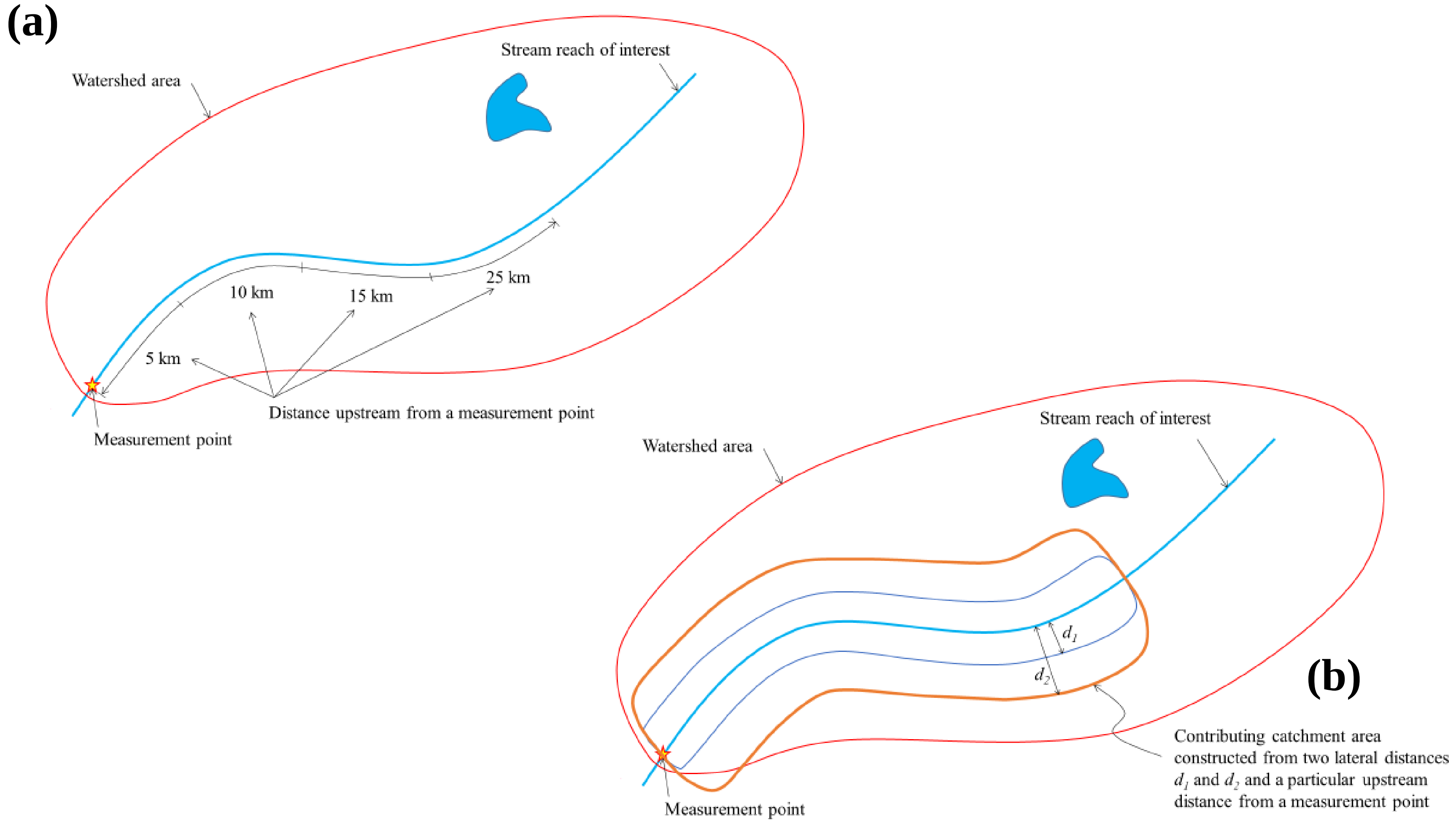


Figure 3.6. Illustrations of **(a)** the delineation of distance upstream from a measurement point and **(b)** contribution catchment area based on the lateral distance.

This illustration is not to scale

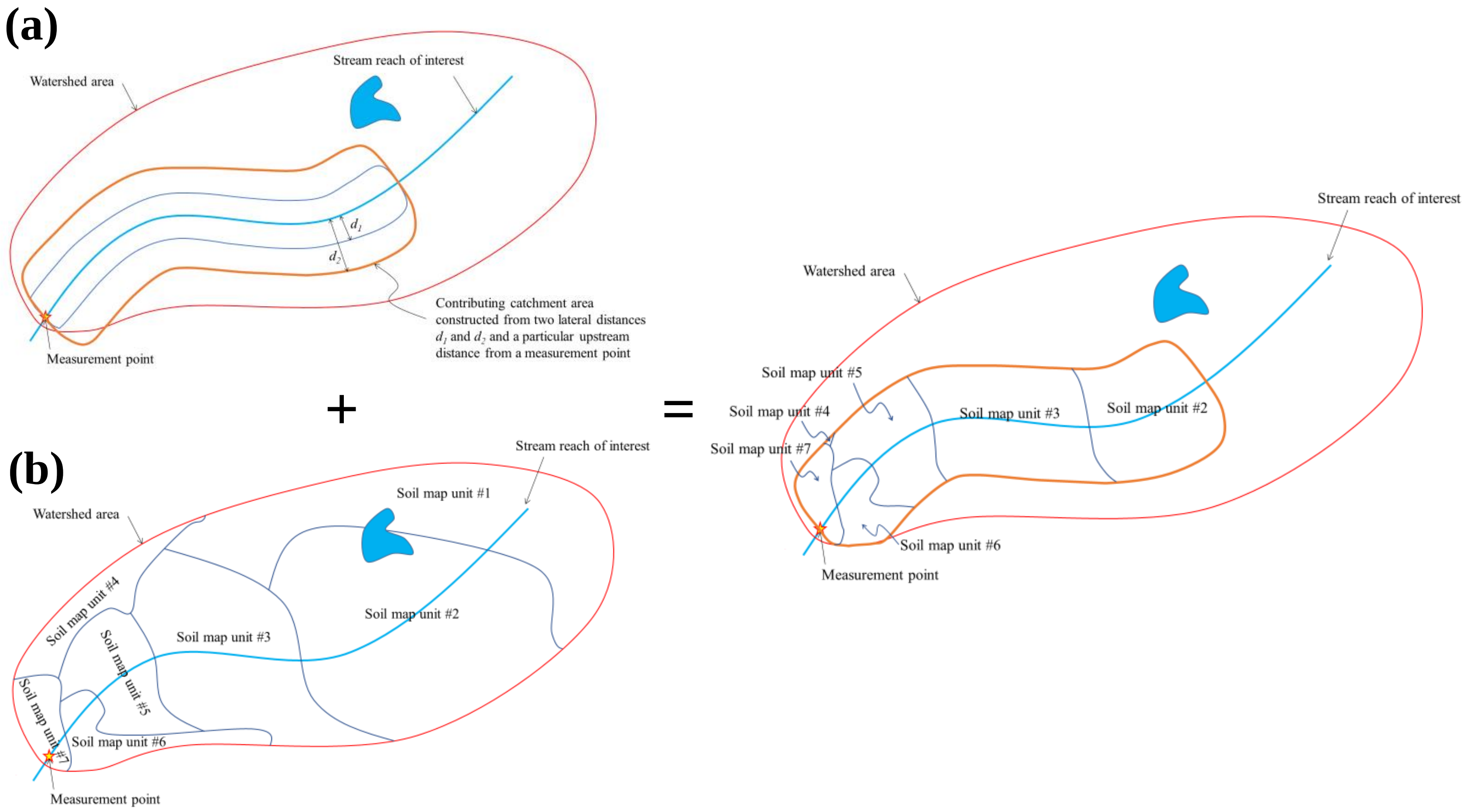


Figure 3.7. Illustration of the catchment soil-derived K_S analysis: **(a)** the catchment study area was overlaid on **(b)** the soil map unit area; the resulting map was used to calculate K_S based on the soil map unit area weighted average of K_{soil} within the contributing catchment area.

This illustration is not to scale

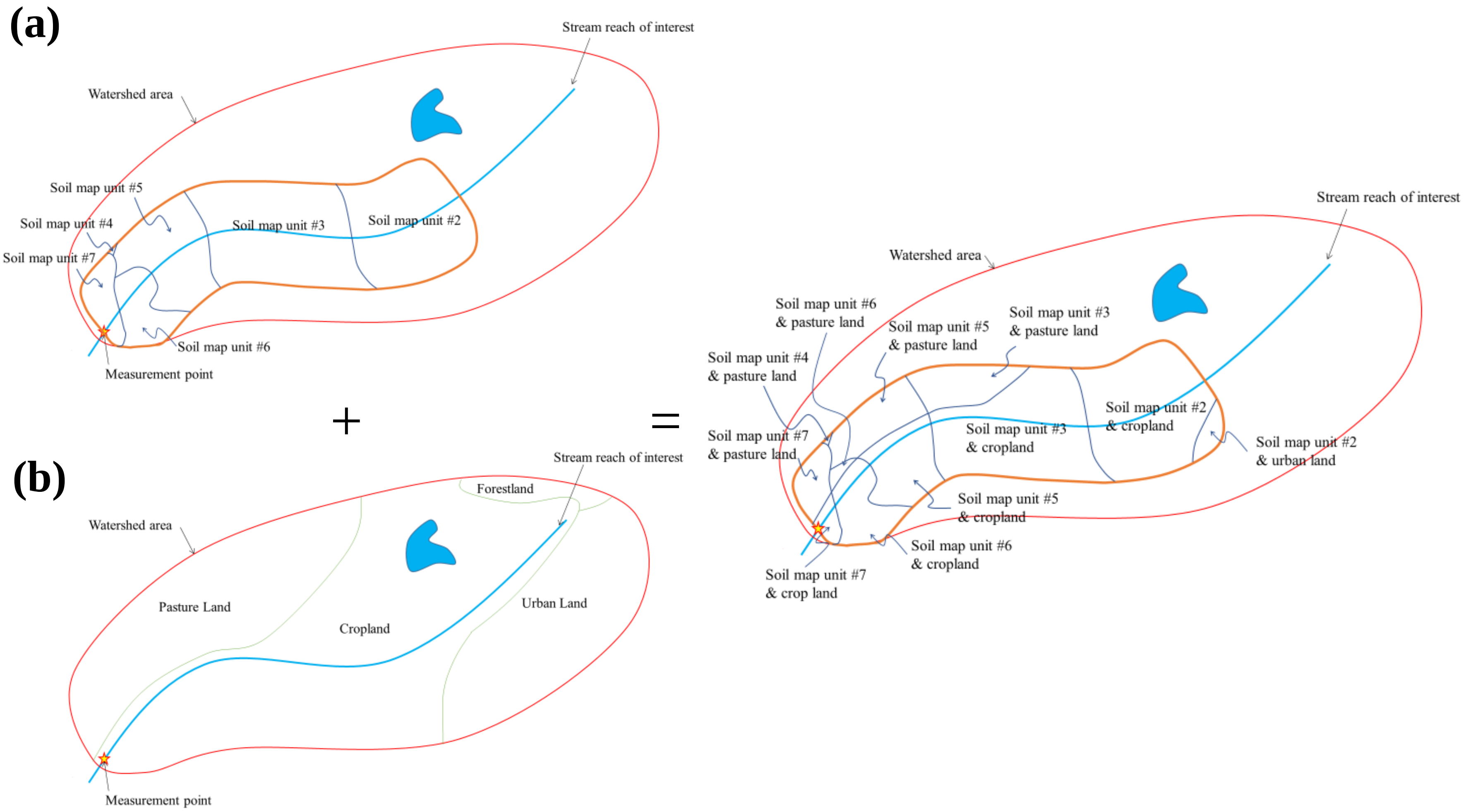


Figure 3.8. Illustration of the land cover-derived K_S analysis: **(a)** soil map unit overlaid with contributing catchment area from Figure 3.7 was overlaid on **(b)** the land cover data area, the K_S was then calculated based on the soil map unit area weighted average of K_{soil} with LCF within the contributing catchment area.

distance was conducted to find out the extent of the upstream contributing catchment areas impact the streambed sediment load (see Figure 3.6a). A contributing catchment area within a watershed of a given stream was defined and it was assumed that most of the streambed sediment would come from this area. This area was defined based on the linear distance lateral to the stream's edge, *d* (see Figure 3.6b).

In the SSURGO database, each unique soil type with their own K_{soil} property was represented as a soil map unit in the watershed of interest (see Figure 3.7b). For the first approach, this soil map unit was then clipped using the contributing catchment area (see Figure 3.7a) and the area-weighted average of the K_{soil} from each soil map unit was used to derive the K_S using the following equation:

$$K_S = \sum_i \frac{A_i}{A_{TOTAL}} \times K_{soil-i} \qquad \text{(Equation 3.9)}$$

where A_i is the area of a soil map unit *i*, A_{TOTAL} is the total area of the contributing catchment area, $K_{soil\text{-}i}$ is the soil saturated hydraulic conductivity for soil map unit *i*, and K_S is the streambed hydraulic conductivity. This approach was defined as the "catchment-soil derived K_S"

For the second approach, a land cover map was added to the clipped map from the first approach, resulting in a combination of all the contributing catchment areas, soil map unit, and land cover data (Figure 3.8). In addition, a separate area called "streambank" area was defined and given a fixed 10% contribution to the area-weighted average calculation of the K_S. This 10% value is based on previous study of streambank contribution on the streambed sediment for stream with slope < 0.02 m/m. The soil erosions from the remaining contributing catchment area were then assumed to contribute to 90% of the streambed sediment. The K_S can then be calculated as the area weighted average of the K_{soil} from each soil map unit with the addition of *LCF* to take into account the different land cover contribution to the soil erosion using the following equation:

Table 3.3. The estimated streambed sediment travel distance contribution based on the study in Allt Dubhaig.

Part	Contribution	Cumulative Contribution
1	37%	37%
2	30%	67%
3	10%	77%
4	5%	82%
5	3%	85%
6	3%	88%
7	3%	91%
8	3%	94%
9	3%	97%
10	3%	100%

$K_S =$ area-weighted avg, of the contributing catchment + area-weighted avg. of the streambank

$$K_S = \left(90\% \times \sum_i \frac{A_i}{A_{TOTAL}} \times K_{soil-i} \times LCF_i \right) + \left(10\% \times \sum_i \frac{A_{strbk-i}}{A_{TOTAL-strbk}} \times K_{soil-i} \times LCF_i \right)$$

(Equation 3.10)

where A_i and $A_{strbk-i}$ are the area of a soil map unit *i* in the contributing catchment area and in the streambank area, respectively; A_{TOTAL} and $A_{TOTAL-strbk}$ are the total area of the contributing catchment area and streambank area, respectively; K_{soil-i} is the soil saturated hydraulic conductivity for soil map unit *i*, *LCF* is the Land Cover Factor, and K_S is the streambed hydraulic conductivity. This approach was defined as the "land-cover derived K_S"

For the third approach, K_S was estimated as the area-weighted average of the soil map unit similar to the first approach, but the portion of the catchment area closer to the measurement point were given a larger weight in the area-weighted average calculation. The weight distribution of these distances was based on the normalized sediment transport distribution of Allt Dubhaig (Figure 3.5) to the upstream distance considered in this study, i.e., the sediment transport distance in Allt Dubhaig was first divided into 10 equal parts and the amount of the sediment transported within this distance part was evaluated (see Table 3.3). The stream of our interest was also divided into 10 equal parts and the weight distribution for each of this contributing catchment area corresponds to Table 3.3. The following equations described the approach:

$$
\begin{aligned}
K_{S-1} &= 37\% \times \frac{A_{i-1}}{A_{TOTAL-1}} \times K_{soil-i} \\
K_{S-2} &= 30\% \times \frac{A_{i-2}}{A_{TOTAL-2}} \times K_{soil-i} \\
K_{S-3} &= 10\% \times \frac{A_{i-3}}{A_{TOTAL-3}} \times K_{soil-i} \\
&\vdots \\
&\vdots \\
K_{S-10} &= 3\% \times \frac{A_{i-10}}{A_{TOTAL-10}} \times K_{soil-i} \\
K_S &= K_{S-1} + K_{S-2} + \ldots + K_{S-10}
\end{aligned}
\qquad \text{(Equation 3.11)}
$$

where K_{S-1}, K_{S-2}, …, K_{S-10} is the streambed hydraulic conductivity derived from the area-weighted average of the corresponding distance, A_{i-1}, A_{i-2}, …, A_{i-10} is the area of soil map unit in the contributing catchment area for the corresponding distance, $A_{TOTAL-1}$, $A_{TOTAL-2}$, …, $A_{TOTAL-10}$ is the total area of the contributing catchment areas for corresponding distance, and K_{soil-i} is the is the soil saturated hydraulic conductivity for soil map unit i, and K_S is the streambed hydraulic conductivity. This approach was defined as the “distance-derived K_S”.

3.2.3 *Comparison of K_{soil}-derived K_S with the Measured and Aquifer-derived K_S*

The K_S values from all of the three approaches discussed above were used to estimate the measured K_S at the 23 locations listed in Table 3.1 and the results were compared with that of the WWAT using the “aquifer-derived K_S” approach. Due to the absence of any additional supporting data to perform a meta statistical analysis (e.g., the population and the distribution data of both the measured K_S and the aquifer-derived K_S), the root mean squared error (RMSE) and the average linear distance between the two K_S values were used to quantify the validity of aquifer-derived K_S

in estimating the streambed measured K_S. The RMSE and the average linear distance can be calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(K_{S,estimated-i} - K_{S,measured-i}\right)^2}{n}} \qquad \text{(Equation 3.12)}$$

$$\text{Average Linear distance} = \frac{\sum_{i=1}^{n}\left(K_{S,estimated-i} - K_{S,measured-i}\right)}{n} \qquad \text{(Equation 3.13)}$$

where n is the number of measurement; and $K_{S,measured}$ is the actual measured K_S values from Table 3.1. In both the RMSE and the average linear distance analysis (hereafter referred to as simply 'linear distance'), the maximum (upper bound), minimum (lower bound) and the mean values (or the mid-point values depending if the mean values were reported) were considered. The maximum RMSE and linear distance are the upper bound or the largest possible discrepancies between the two K_S values of interest. The minimum RMSE and linear distance are the smallest possible discrepancy between the two K_S values. If the two K_S values overlapped, the minimum RMSE or linear distance was assigned a value of 0. The mean (or median) RMSE and linear distance are the distances between the two mean K_S values.

3.2.4 Application of the Improved Estimated K_S Values at the Kalkaska and Calhoun Sites

The approach with the smallest RMSE and average linear distance was subsequently used to estimate the K_S values in the study presented in the previous chapter, i.e., Black Creek in Kalkaska County, MI and Dickinson Creek in Calhoun County, MI. As discussed in the previous chapter, the geologic settings at both sites were simplified into three layers. For the Kalkaska site, the lithologic setting consists of a glacial aquifer (Layer #1), a thin aquitard (Layer #2) and a semi-confined glacial aquifer (Layer #3). For the Calhoun site, the lithologic setting consists of a glacial aquifer (Layer #1), a thin aquitard (Layer #2), and a semi-confined bedrock aquifer (Layer #3).

Table 3.4. Summary of the aquifer, stream, and pumping parameters for both the Kalkaska and Calhoun site. W&L denotes the Ward and Lough (2011) analytical solution.

<table>
<tr><th colspan="2"></th><th>Kalkaska Site</th><th>Calhoun Site</th></tr>
<tr><td colspan="4">***Surficial Aquifer parameters (Layer #1)***</td></tr>
<tr><td rowspan="3">Aquifer transmissivity ^{a}, T_1 [m^2/d]</td><td>WWAT</td><td>718</td><td rowspan="2">435</td></tr>
<tr><td>W&L</td><td>n/a</td></tr>
<tr><td>MODFLOW</td><td>521</td><td>6650 – 38000</td></tr>
<tr><td rowspan="3">Storage coefficient ^{b}, S_1 [-]</td><td>WWAT</td><td colspan="2">0.01</td></tr>
<tr><td>W&L</td><td>n/a</td><td>0.01</td></tr>
<tr><td>MODFLOW</td><td colspan="2">0.16</td></tr>
<tr><td rowspan="3">Average glacial formation thickness ^{c}, B [m]</td><td>WWAT</td><td>180</td><td rowspan="2">25</td></tr>
<tr><td>W&L</td><td>n/a</td></tr>
<tr><td>MODFLOW</td><td>20 – 120</td><td>7 – 40</td></tr>
<tr><td>Surficial aquifer recharge rate ^{d} [cm/year]</td><td>MODFLOW</td><td>22.9</td><td>28.0</td></tr>
<tr><td colspan="4">***Aquitard Parameters (Layer #2)***</td></tr>
<tr><td rowspan="3">Aquitard hydraulic conductivity, K' [m/d]</td><td>WWAT</td><td rowspan="6">n/a</td><td>n/a</td></tr>
<tr><td>W&L</td><td rowspan="2">8.64×10^{-7}</td></tr>
<tr><td>MODFLOW</td></tr>
<tr><td rowspan="3">Aquitard thickness ^{c}, B' [m]</td><td>WWAT</td><td>n/a</td></tr>
<tr><td>W&L</td><td>1</td></tr>
<tr><td>MODFLOW</td><td>1 – 5</td></tr>
<tr><td colspan="4">***Aquifer underlying the aquitard Parameters (Layer #3)***</td></tr>
<tr><td rowspan="3">Aquifer transmissivity ^{a}, T_2 [m^2/d]</td><td>WWAT</td><td rowspan="2">n/a</td><td>n/a</td></tr>
<tr><td>W&L</td><td>435</td></tr>
<tr><td>MODFLOW</td><td>2.2 – 2.53</td><td>0.432</td></tr>
<tr><td rowspan="3">Storage coefficient ^{b}, S_2 [-]</td><td>WWAT</td><td rowspan="2">n/a</td><td>n/a</td></tr>
<tr><td>W&L</td><td>0.01</td></tr>
<tr><td>MODFLOW</td><td>10^{-3}</td><td>10^{-3}</td></tr>
<tr><td colspan="4">***Stream parameters***</td></tr>
<tr><td rowspan="3">Streambed thickness ^{e}, b [m]</td><td>WWAT</td><td rowspan="2">37</td><td rowspan="2">31</td></tr>
<tr><td>W&L</td></tr>
<tr><td>MODFLOW</td><td colspan="2">1.0</td></tr>
<tr><td rowspan="3">Streambed width ^{f}, w [m]</td><td>WWAT</td><td rowspan="2">6.8</td><td rowspan="2">6.0</td></tr>
<tr><td>W&L</td></tr>
<tr><td>MODFLOW</td><td colspan="2">1.0</td></tr>
<tr><td rowspan="3">Streamflow rate ^{g}, Q_i [m^3/d]</td><td>WWAT</td><td rowspan="2">15750</td><td rowspan="2">5870</td></tr>
<tr><td>W&L</td></tr>
<tr><td>MODFLOW</td><td>4155</td><td>488</td></tr>
<tr><td colspan="4">***Streambed hydraulic conductivity, K_S [m/d]***</td></tr>
<tr><td colspan="2">From MODFLOW ^{h}</td><td>0.026</td><td>0.026</td></tr>
<tr><td colspan="2">From WWAT ^{i}</td><td>0.289</td><td>1.74</td></tr>
<tr><td colspan="2">From Land Cover Analysis ^{j}</td><td>6.73 ± 2.94</td><td>6.49 ± 2.70</td></tr>
<tr><td colspan="4">***Streambed conductance ^{k}, λ [m/d]***</td></tr>
<tr><td colspan="2">From MODFLOW</td><td>0.026</td><td>0.026</td></tr>
<tr><td colspan="2">From WWAT</td><td>0.053</td><td>0.274</td></tr>
<tr><td colspan="2">From Land Cover Analysis</td><td>1.24 ± 0.54</td><td>1.26 ± 0.52</td></tr>
<tr><td colspan="4">***Pumping parameters***</td></tr>
<tr><td colspan="2">Distance between well and stream, d [m]</td><td colspan="2">1000</td></tr>
<tr><td colspan="2">Pumping rate, Q_w [m^3/d]</td><td>2530</td><td>6540</td></tr>
<tr><td colspan="2">Pumping schedule</td><td colspan="2">3 months pumping followed by 9 months shutoff annually for 5 years</td></tr>
</table>

[a] The values for T_1 and T_2 for both the Ward & Lough (2011) solution and the WWAT are from the Michigan Groundwater Inventory and Mapping (GWIM) Project database (Michigan Department of Environmental Quality et al., 2006a; Reeves et al., 2009) whereas those for MODFLOW are based on calibrated K_x values and aquifer thickness of 180 m and 100 m for Kalkaska and Calhoun Site, respectively

[b] The value of S_1 and S_2 for both the Ward & Lough (2011) solution and the WWAT are constant and consistent with reported values for leaky aquifers (Reeves et al., 2009); The value of S_1 and S_2 for MODFLOW are typical values for unconfined and confined aquifer, respectively (Morris and Johnson, 1967).

[c] The values of B are from the observed well logs from the DEQ Wellogic database (Michigan Department of Environmental Quality, 2000), whereas B' are from the GWIM Project database (Michigan Department of Environmental Quality et al., 2006a; Reeves et al., 2009). For Ward & Lough (2011) solution, the B' were assumed to be 1 meter to represent the thinnest possible clay layer as used in MODFLOW

[d] The values for recharge are from the Michigan Groundwater Inventory and Mapping (GWIM) Project database (Michigan Department of Environmental Quality et al., 2006a; Reeves et al., 2009)

[e] The values of b for both the Ward & Lough (2011) solution and the WWAT are the vertical distance from the stream to the top of the well screen (Reeves et al., 2009) whereas that for MODFLOW are based on typical values of streambed thickness.(Toran et al., 2013)

[f] The value of w for both the Ward & Lough (2011) solution and the WWAT were calculated using Equation 2.5 whereas that for MODFLOW were set equal to 1 m based on satellite images

[g] The values of Q_i for both the Ward & Lough (2011) solution and the WWAT are equal to Q_{index} (Michigan Department of Environmental Quality, n.d.), whereas the Q_i for MODFLOW were based on the actual streamflow measurement at the Black Creek site in Kalkaska due to the absence of any additional information at Dickinson Creek (Hyndman, 2013)

[h] The value of K_S for MODFLOW were based on numerical calibration using measured Q_i at Black Creek (Hyndman, 2013)

[i] The K_S from WWAT values were calculated by assuming that they are equal to 1/10 of the aquifer K

[j] The values of K_S from the Land Cover Analysis were derived from the land-cover derived approach utilizing both the K_{soil} and land cover data as described in the methods above

[k] The values of λ were calculated using Equation 3.2 using the respective K_S values

The glacial aquifer layer at the Kalkaska site is on the order of a couple hundred feet, while at the Calhoun site, the glacial aquifer is on the order of 30 – 50 feet thick At the Kalkaska site, both the pumping well and the stream are located in the glacial aquifer (Layer #1). At the Calhoun Site, on the other hand, the stream is located in the glacial aquifer (Layer #1) while the pumping well is screened in the bedrock aquifer (Layer #3). At the Kalkaska site, the modified Hunt (1999) solution and MODFLOW were used to estimate the Q_s values, whereas at the Calhoun site, the Ward and Lough (2011) solution, the modified Hunt (1999) solution, and MODFLOW numerical model were used to estimate the Q_s values. Table 3.4 shows the summary of the values of the parameters used in this analysis. The aquifer, stream, and pumping parameters at the Kalkaska site are consistent with the parameters listed in Table 2.2, with the addition of K_S values from the one of the three K_{soil}-derived approaches with the smallest error. The parameters used at the Calhoun site are those listed in Table 3.2, also with the addition of K_S values from the one of the three K_{soil}-derived approach with the smallest error.

3.3 Results and Discussion

3.3.1 Ward and Lough (2011) Analytical Solution Applied to the Calhoun Site

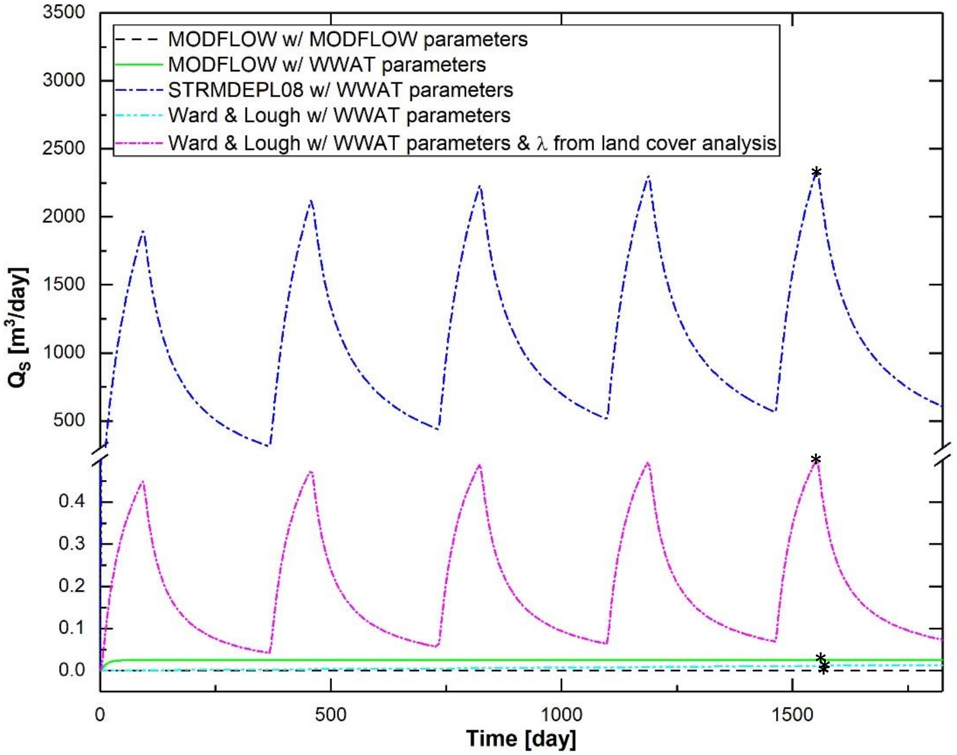


Figure 3.9. Streamflow depletion, Q_S, vs. time, t, calculated using MODFLOW, STRMDEPL08 and the Ward and Lough (2011) analytical solution using parameters derived from MODFLOW calibration, WWAT parameters, and land-cover derived λ. Note the break in the y-axis scale from 0.5 to 300. The asterisks denote the maximum stream depletion, $Q_{s,max}$ over the five-year period.

The maximum streamflow depletion, $Q_{s,max}$, estimated by Ward and Lough (2011) with WWAT parameters is 0.013 m^3/day, whereas MODFLOW with calibrated and WWAT parameter gave estimates of $Q_{s,max}$ are 5×10^{-4} m^3/day and 0.03 m^3/day, respectively. The $Q_{s,max}$ calculated using the modified Hunt (1999) solution was on the order of ~2350 m^3/day, which is larger by about seven and five orders of magnitude, respectively. This actually explain why many LQWs were rejected by the WWAT in the southwestern Lower Peninsula of Michigan, as many areas in this region have similar hydrogeologic settings to that of the Calhoun site. The streamflow depletion calculated using the Ward and Lough (2011) analytical solution is closer to what the numerical model estimated compared to that of the modified Hunt (1999) solution with WWAT parameters (see Figure 3.9). As discussed previously, the hydrogeologic setting in the vicinity of the Calhoun site consists of a relatively thin surficial aquifer made of glacial outwash with an average thickness of about 25 meters overlying a thin layer of clay and a semi-confined bedrock aquifer. As most of the wells in this region are screened in the semi-confined bedrock layer, the clay lenses limit the hydraulic connection between the surficial and the semi-confined bedrock aquifer such that an LQW screened at the bedrock layer would be unlikely to impact the surficial aquifer. The use of the modified Hunt (1999) solution in the WWAT did not capture this clay layer, and as a result, it could potentially over-estimate the Q_s from LQWs, thereby causing proposed LQW permits to be denied. The Ward and Lough (2011) analytical solution capture the presence of these clay lenses and the resulting Q_s is in the same order of magnitude as estimated by the numerical model. The hydrogeological setting considered by the Ward and Lough (2011) solution is actually very common, especially in the southern and northern part of the Lower Peninsula of Michigan because the surficial aquifers were relatively thin at these regions that most LQW wells need to be screened at the aquifer beneath the clay lenses. The use of the Ward and Lough (2011) solution would provide a more accurate estimate of Q_s for these locations and other scenarios where LQWs are screened at an aquifer beneath a clay layer.

3.3.2 Aquifer-derived, Catchment Soil-derived, Land Cover-derived, and Distance-derived K_S

Figure 3.10 shows the aquifer-derived, catchment soil-derived, land cover-derived, and distance-derived K_S at the 23 locations presented in Table 3.1. The mean (or midpoint) RMSE of

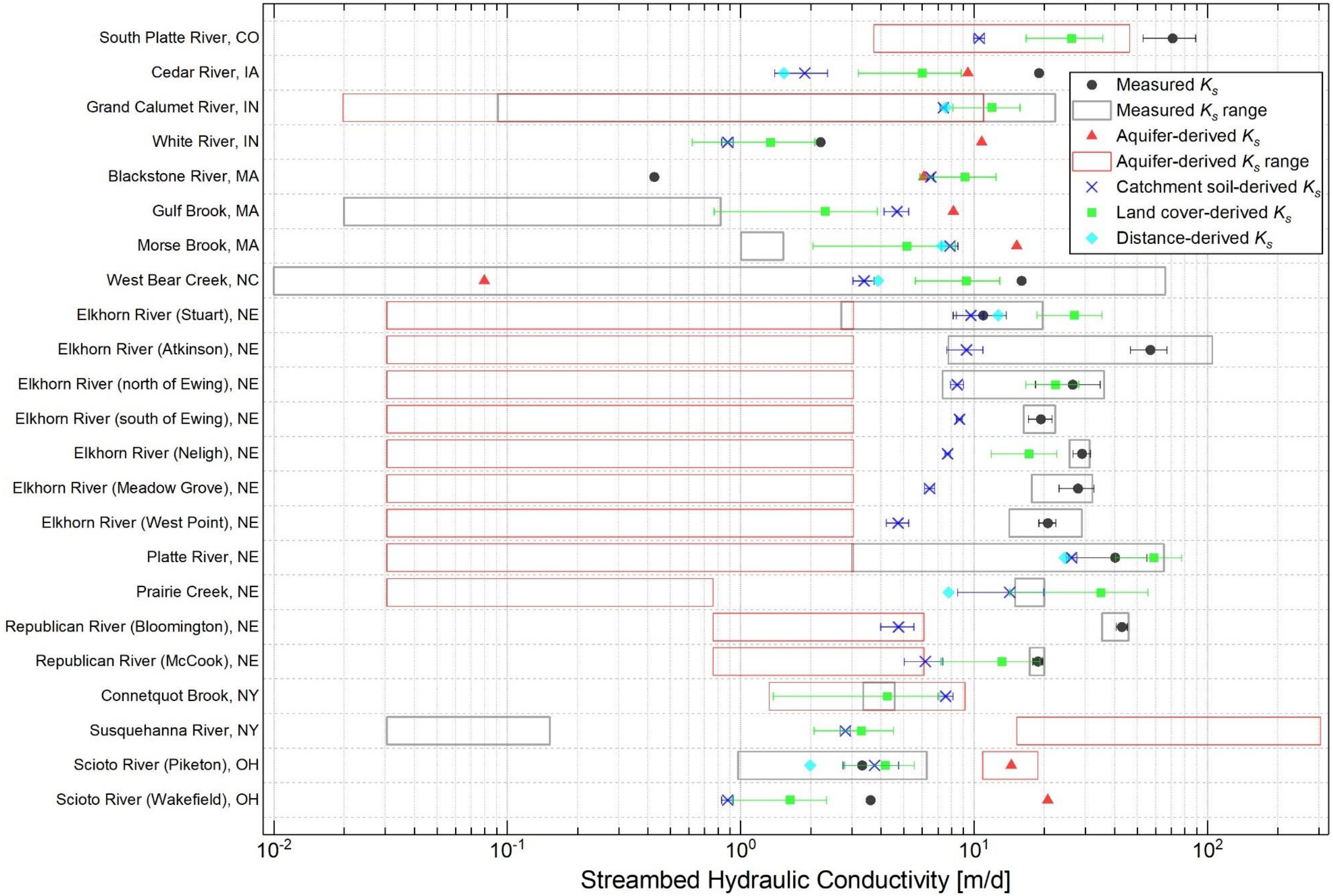


Figure 3.10. Measured (black circles and black boxes) vs. aquifer-derived (red triangles and red boxes) vs. catchment soil-derived (blue crosses) vs. land cover-derived (green squares) vs. distance-derived (light blue diamonds) K_S for the 23 different measurement locations at 15 different streams in the contiguous U.S. used in this study. Note the land cover-derived and the distance-derived K_S analysis only considered 18 and 8 of the 23 measurement locations, respectively.

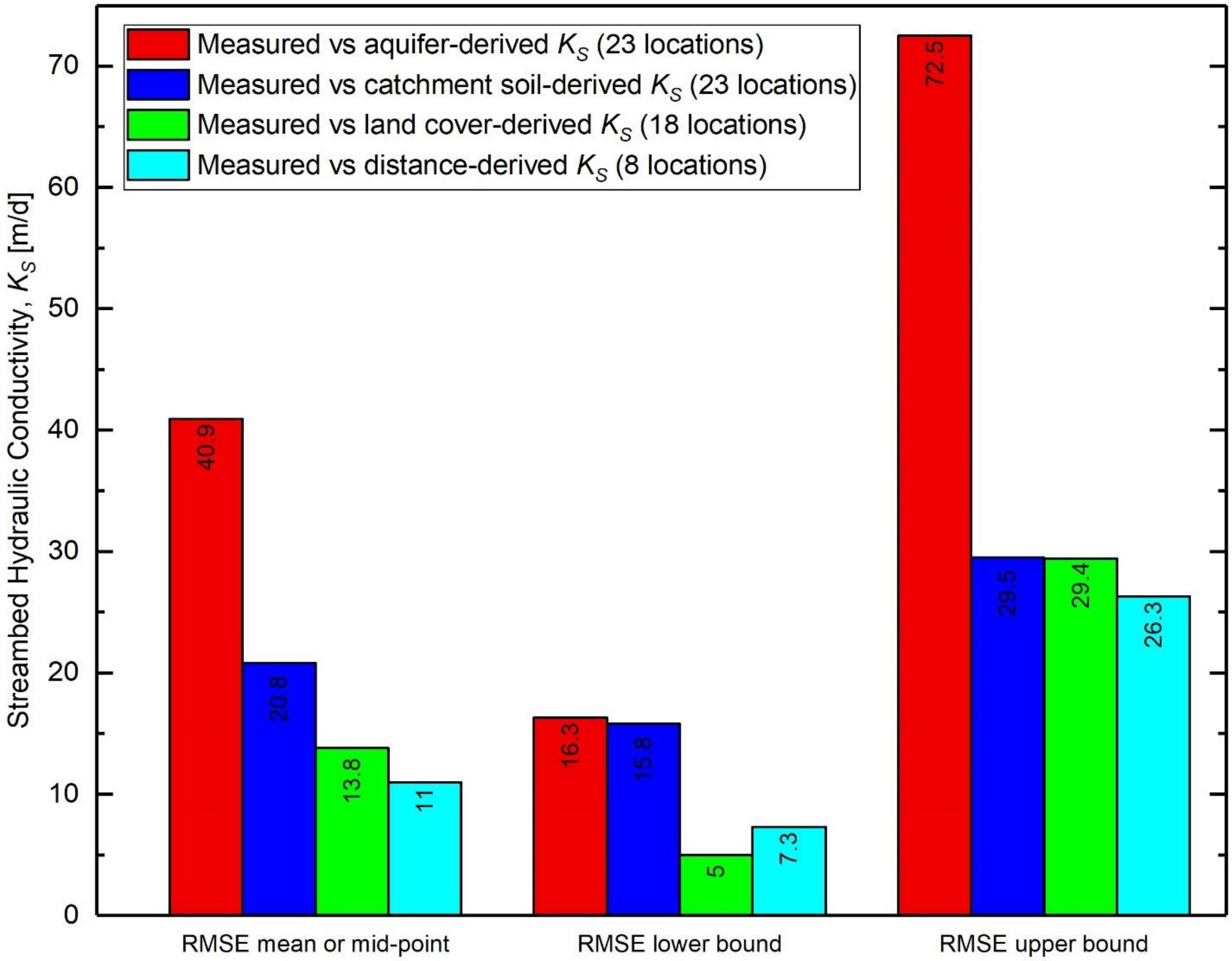


Figure 3.11. The mean (or mid-point), lower bound, and upper bound RMSE of measured K_S with aquifer-derived (red), catchment soil-derived (blue), land cover-derived (green) and distance-derived (light blue) K_S. Note that the number of locations considered in the aquifer-derived and catchment soil-derived were 23 locations, in the land cover-derived were 18 locations, and in the distance-derived were 8 locations.

the aquifer-derived, catchment soil-derived, land cover-derived, and distance-derived K_S were 40.9 m/d, 20.8 m/d, 13.8 m/d, and 11.0 m/d, respectively (Figure 3.11). The lower bound RMSE of the aquifer-derived, catchment soil-derived, land cover-derived, and distance-derived K_S were 16.3 m/d, 15.8 m/d, 5.0 m/d, and 7.3 m/d, respectively (Figure 3.11). The upper bound RMSE of the aquifer-derived, catchment soil-derived, land cover-derived, and distance-derived K_S were 72.5 m/d, 29.5 m/d, 29.4 m/d, and 26.3 m/d, respectively (Figure 3.11). On the other hand, the mean (or midpoint) linear distance of the aquifer-derived, catchment soil-derived, land cover-derived, and distance-derived K_S were -6.2 m/d, -12.0 m/d, -1.0 m/d, and -6.5 m/d, respectively

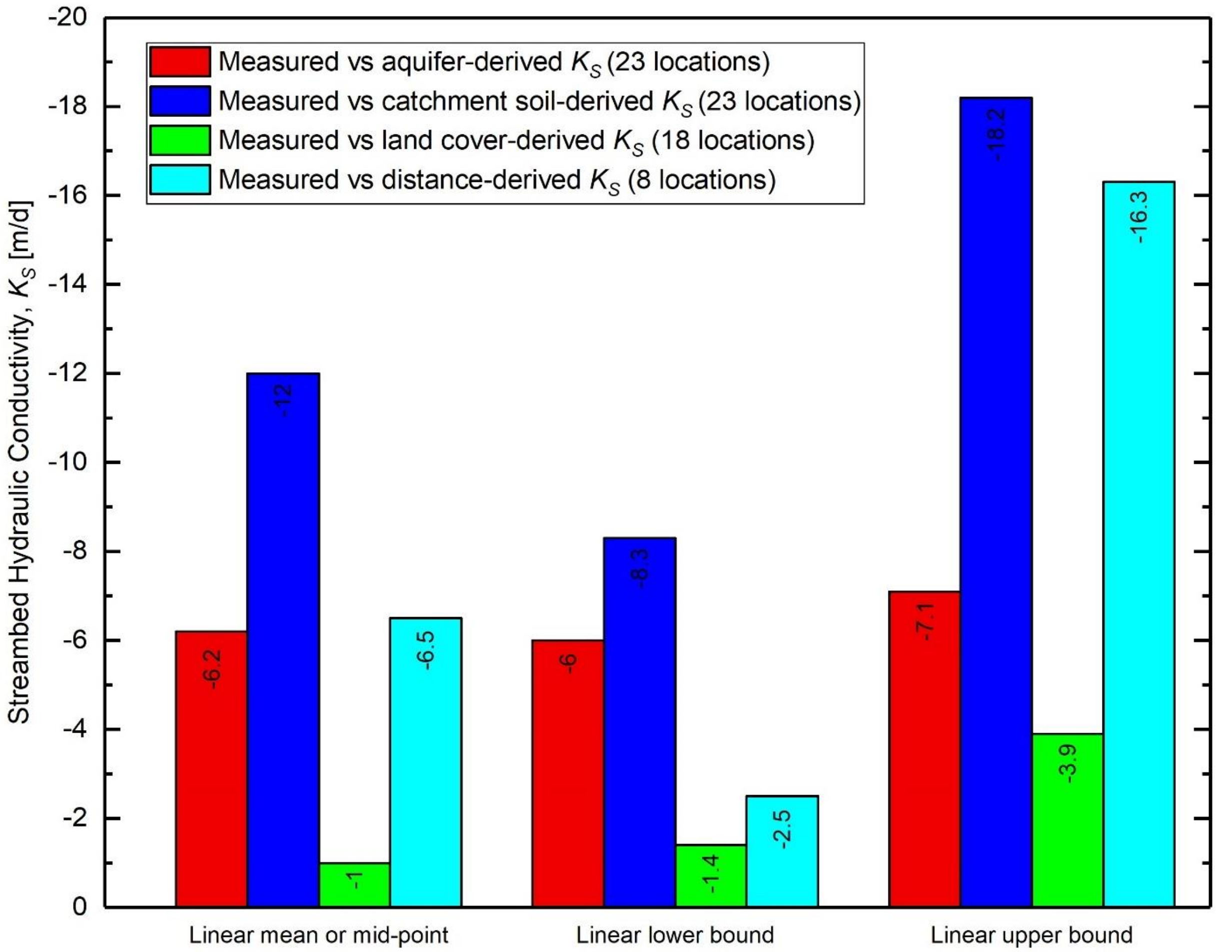


Figure 3.12. The mean (or mid-point), lower bound, and upper bound linear distances of measured K_S with aquifer-derived (red), catchment soil-derived (blue), land cover-derived (green) and distance-derived (light blue) K_S. Note that the number of locations considered in the aquifer-derived and catchment soil-derived were 23 locations, in the land cover-derived were 18 locations, and in the distance-derived were 8 locations.

(Figure 3.12). The lower bound linear distance of the aquifer-derived, catchment soil-derived, land cover-derived, and distance-derived K_S were -6.0 m/d, -6.3 m/d, -1.4 m/d, and -2.5 m/d, respectively (Figure 3.12). The upper bound linear distance of the aquifer-derived, catchment soil-derived, land cover-derived, and distance-derived K_S were -7.1 m/d, -18.2 m/d, -3.9 m/d, and -16.3 m/d, respectively (Figure 3.12). Overall the land cover-derived approach provided the best estimate of measured K_S since both the RMSE and average linear distance were the best overall compared to other methods. The mean (or mid-point) and upper bound RMSE of the land-cover derived K_S were not the smallest but they were on the smaller side. However, the mean (or mid-point), lower, and upper bound linear distance of the land cover-derived K_S were the smallest, compared to other approaches, suggesting that the other approaches may experience from a systematic error, while the error for the land cover analysis may come from a random error.

The aquifer-derived K_S values were larger than the measured K_S at sixteen of the 23 locations, and smaller at the remaining seven locations. The largest discrepancy is at the Susquehanna River, NY with differences of over two orders of magnitude. Measured K_S and aquifer-derived K_S values overlapped at four locations: Grand Calumet River, CO; Elkhorn River (Stuart), NE; Platte River, NE; and Connetquot Brook, NY. However, at both the Elkhorn River (Stuart), NE and Platte River, NE locations, the measured and aquifer-derived K_S values or ranges only overlapped slightly. From visual observation of Figure 3.10 and evaluation of RMSE and linear distance, it can be suggested that the aquifer- derived K_S may not be the most suitable approach to estimate measured K_S.

The catchment soil-derived method performed better than the aquifer-derived method in estimating the measured K_S. The mean (or mid-point), lower, and upper bound RMSE values were smaller than the aquifer-derived K_S, but the mean (or mid-point), lower, and upper bound linear distances were larger, suggesting that it consistently under-estimated the measured K_S reported in Table 3.1. It under-estimated the measured K_S at ten locations, over-estimated the measured K_S at two locations, and was within the range of measured K_S at the remaining 11 locations. It is especially close to the measured K_S values at the Elkhorn River (Stuart), NE, Platte River, NE, and Scioto River (Piketon), OH locations.

The land cover-derived method was only performed at 18 of the 23 locations reported in Table 3.1. (i.e., location number 10, 12, 14, 15, and 18 were excluded). The mean (or mid-point), lower, and upper bound or RMSE were very small compared to the aquifer-derived and the catchment soil-derived methods but were slightly larger than the distance-derived method. Nevertheless, the mean (or mid-point), lower, and upper bound linear distances were the smallest among the three other methods, suggesting that this method did not suffer from a systematic error as opposed to the other methods. The cropland or pasture land cover were relatively higher than the forest land at 13 of the 18 locations. At four locations, forest land cover was relatively larger than the cropland or pasture land. At the remaining one location, the forest land had an approximately equal area with the cropland and pasture land.

The distance-derived K_S method was only performed at 8 of the 23 locations reported in Table 3.1 (i.e., only location number 2, 3, 7, 8, 9, 16, 17, and 22 were included). The mean (or mid-point), lower, and upper bound or RMSE were the smallest compared to the other three methods. However, the mean (or mid-point), lower, and upper bound linear distances were on the larger side compared to the other three methods. Moreover, since this method is actually a modification of the catchment soil-derived method, it suffers from the same systematic error issue. suggesting that there could be a systematic error with this approach. Another thing to be considered regarding the distance-derived K_S is that the sediment present in the streambed is an accumulation of top soil eroded over long time periods and it may be inaccurate to assume the sediment travel distance would follow the distribution shown in Table 3.3 in the first place.

3.3.3 Application of Estimated K_S at the Kalkaska and Calhoun Sites

The land-cover derived K_S appeared to provide the best estimates of measured K_S and therefore, this approach was used to calculate the K_S at the Kalkaska and Calhoun sites. The Kalkaska site is predominant forest land, whereas the Calhoun site is predominantly crop land. Using the land cover analysis approach, the estimated K_S values for Kalkaska and Calhoun site are

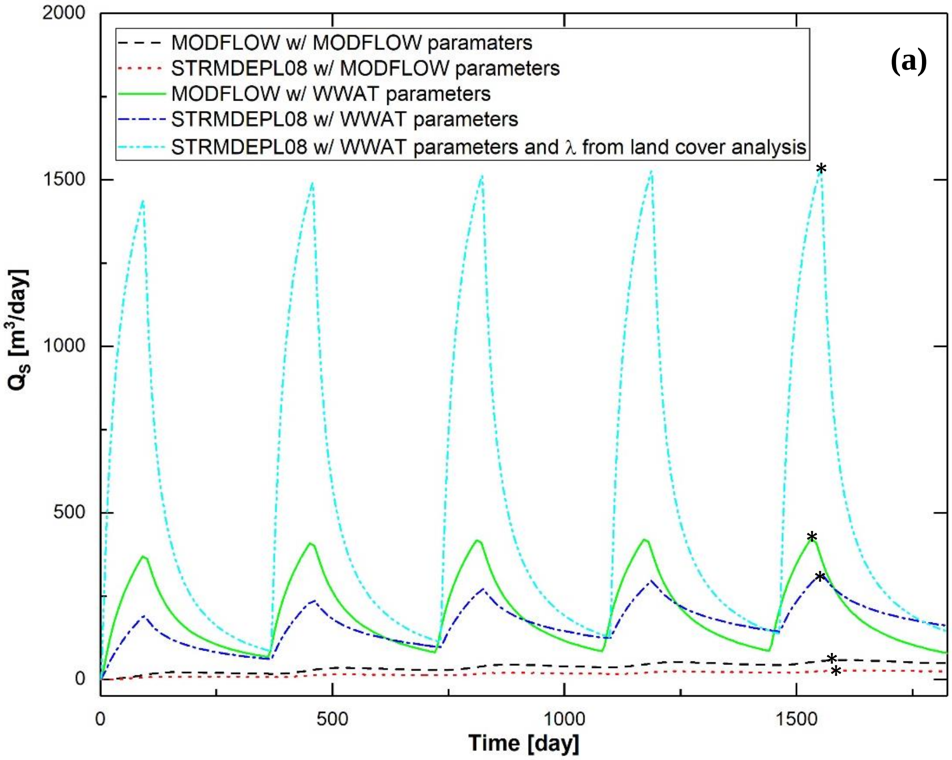


Figure 3.13. Streamflow depletion, Q_S, vs. time, t, calculated by MODFLOW and STRMDEPL08 analytical solution using parameters derived from the calibration of MODFLOW, WWAT parameters, and WWAT parameters with λ from land cover analysis at the Kalkaska site; The asterisks denote the maximum streamflow depletion, $Q_{S,\max}$, over the five-year pumping period.

6.7 ± 2.9 m/d and 6.5 ± 2.7 m/d, respectively. These K_S values were larger than the K_S values used by the WWAT or determined by the calibration of the MODFLOW model (K_S from the WWAT at the Kalkaska and Calhoun sites are 0.289 m/d and 1.74 m/d, respectively; K_S from MODFLOW at Kalkaska and Calhoun are both 0.026 m/d. The K_S for Calhoun site is based on the calibration of the Kalkaska site due to the absence of any streamflow data at Calhoun site). Using the stream parameters shown in Table 3.4, the λ using land cover-derived K_S were 1.2 ± 0.5 m/d and 1.3 ± 0.5 m/d at the Kalkaska site and Calhoun sites, respectively. These streambed conductance values were one to two orders of magnitude larger than those produced by the WWAT and two orders of magnitude larger than that produced by MODFLOW. The K_S values calibrated in MODFLOW was on the lower end of the measured K_S range as reported in Table 3.1.

Figure 3.13 shows the plot of streamflow depletion vs. time at the Kalkaska site and Figure 3.9 shows the plot of streamflow depletion vs. time at the Calhoun site. The Q_s at the Kalkaska site was calculated using two different methods: the modified Hunt (1999) solution (denoted as STRMDEPL08) and MODFLOW using MODFLOW calibrated parameters, WWAT parameters, and WWAT aquifer parameters with λ from land cover analysis. As shown in Figure 3.13, the $Q_{s,max}$ calculated by the modified Hunt (1999) solution with WWAT parameters and λ from land cover analysis was estimated at 1,535 m^3/day, almost four times larger than the next largest estimate of $Q_{s,max}$ of 421 m^3/day calculated using MODFLOW with WWAT aquifer parameters. This is because the land cover analysis K_S used to calculate λ was 23 times larger than the K_S used by the WWAT. The modified Hunt (1999) solution using the WWAT parameters gave estimates of $Q_{s,max}$ of about 317 m^3/day, which is reasonably close to the $Q_{s,max}$ estimates using MODFLOW with WWAT aquifer parameters, but were much smaller than that of WWAT with λ from land cover analysis.

The $Q_{s,max}$ at the Calhoun site was calculated using three different methods: the Ward and Lough (2011) analytical solution, the modified Hunt (1999) analytical solution, and MODFLOW numerical models. For all three methods, MODFLOW calibrated parameters, WWAT parameters, and WWAT aquifer parameters with λ derived from the land cover analysis were used. The difference between $Q_{s,max}$ calculated using the Ward and Lough (2011) solution, the modified Hunt (1999) solution, and the MODFLOW numerical model with either MODFLOW calibrated parameters or WWAT parameters has been discussed previously in section 3.3.1. The addition of λ from land cover analysis, however, changed the estimation by the Ward and Lough (2011) solution where $Q_{s,max}$ was now estimated to be about 0.5 m^3/day, larger than that estimated using the Ward and Lough (2011) solution with only the WWAT parameters, and MODFLOW using

WWAT or MODFLOW calibrated parameters. However, relative to the $Q_{s,max}$ generated using the modified Hunt (1999) solution, this $Q_{s,max}$ value is still much closer to that given by the numerical model.

The large discrepancies in $Q_{s,max}$ estimations as depicted in Figures 3.9 and 3.13 are mainly due to the differences in K_S values estimated using the MODFLOW calibrated parameters, the aquifer-derived approach as used by the WWAT, and the land cover-derived method. The calibrated K_S values for both the Kalkaska and Calhoun sites were based on an actual measured streamflow data at Black Creek in Kalkaska County, MI and it may not be accurate for the Calhoun site. Streamflow measurement at this site maybe under-estimated due to the existence of beaver's dam upstream of the assumed measurement point. There are also a few other factors that may influence the seemingly very low calibrated K_S values. For example, the stream width and streambed thickness in the numerical model were assumed to be constant at 1 meter for the whole stretch of the stream reach, while the actual stream width and streambed thickness could vary. Finally, there will always be some inherent errors and uncertainties associated with the calibrated model due to some simplifying assumptions and limited observed data. The K_S values in the region were also poorly understood due to the lack of field measurements not only in the Midwest region, but also in the U.S. The nearest available K_S measurement from Michigan as reported by Table 3.1 was at the Grand Calumet River, IN and it ranges from 0.1 to 22 m/d.

From Figure 3.12, it was also suggested that the estimated K_S values using the aquifer-derived method were consistently under-estimated. The larger land cover-derived K_S values relative to the MODFLOW calibrated or the aquifer-derived method suggest that there is a greater connectivity between the aquifer and the stream than inferred from the calibration from streamflow measurement or from the reliance of the aquifer K values. As the WWAT was designed to be a conservative screening tool, the utilization of a lower estimated K_S values in the WWAT may have unintended repercussions in that the estimated $Q_{s,max}$ values are not really representative of the maximum possible streamflow depletion. Using K_S, and by extension λ, based on the land cover analysis may result in a more conservative estimate of $Q_{s,max}$. At both the Kalkaska and Calhoun sites, the resulting $Q_{s,max}$ was larger than that originally produced by the WWAT and that using Ward and Lough (2011) solution with aquifer-derived K_S, respectively. Using K_S values based on the land cover analysis may result in more site-specific reviews for future LQW applications but it may provide better protection to sensitive trout streams in this region.

3.4 Conclusion

Water scarcity and prolonged drought periods have forced water resource managers to rely heavily on groundwater to meet the ever-increasing water demand. They typically rely on analytical or numerical models to assess streamflow depletion, a phenomenon where large capacity pumping causes a head depression and shifts the water table enough to divert the water that is recharging the stream. Numerical models generally provide a more accurate assessment of streamflow depletion than analytical models, but they generally require more resources and time to develop. Analytical models, on the other hand, provide a relatively simple and rapid assessment of streamflow depletion but have their own drawbacks in that some of them do not accurately reflect the important features of the hydrogeological settings. For example, the WWAT uses a modified Hunt (1999) analytical solution to evaluate LQWs in Michigan. This analytical solution assumes a single lithologic unit at Dickinson Creek in Calhoun County, MI and the well is screened below an aquitard. Thus, the ability to incorporate a three-layer-system is crucial for accurate estimates of Q_s. The Ward and Lough (2011) analytical solution provides a means to estimate streamflow depletion for the hydrogeologic setting found at Dickinson Creek and hence, this solution was evaluated to see if it provided a similar result to the numerical model discussed in the previous chapter. The Ward and Lough (2011) analytical solution was demonstrated to provide a good estimate of $Q_{s,max}$ value at Dickinson Creek. The Ward and Lough (2011) solution with WWAT parameters estimated the $Q_{s,max}$ to be at 0.013 m3/day, whereas MODFLOW with both calibrated and use of WWAT parameters estimated $Q_{s,max}$ values of 5×10^{-4} m^3/day and 0.03 m^3/day, respectively. The result from utilizing the Ward and Lough (2011) solution is much closer to that of the numerical model compared to that of the modified Hunt (1999) solution which estimated a $Q_{s,max}$ value of 2,530 m^3/day. Given that many parts of Michigan can be described as three layers where the critical part is where the well is screened, the Ward and Lough (2011) solution may be more suitable to provide estimates of streamflow depletion than the modified Hunt (1999) solution.

Based on a sensitivity analysis, streambed conductance was found to be an important parameter that governs the degree of hydraulic connectivity between the stream and the aquifer. Within this parameter, the streambed hydraulic conductivity, K_S, is the most critical given that it has the largest degree of variability compared to the other parameters: streambed thickness and stream width. Historically, there are a limited number of reported streambed hydraulic conductivity values reported in the literature. In addition, K_S varies within a stream reach, thus multiple measurements may be necessary for a given situation. The State of Michigan estimates the K_S for stream reaches across the state as 1/10 of the screened aquifer hydraulic conductivity value (defined as "aquifer-derived K_S"). In this chapter, three new approaches were proposed to quickly and reasonably estimate the K_S values knowing that streambed sediments come from soil erosion inside the watershed area: (1) a "catchment soil-derived" method which uses an area-weighted average of saturated soil hydraulic conductivity, K_{soil}; (2) a "land cover-derived" method which uses an area-weighted average of K_{soil} modified by land cover data; and (3) a "distance-derived" method which uses an area-weighted average of K_{soil} with a distance distribution that placed more weight on soil closer to measurement point. The K_{soil} values were acquired from the SSURGO database, land cover data from the NLCD, and streams and watersheds boundary lines from NHD and WBD. The K_S values from these three approaches were then statistically compared with actual measured K_S values and also with K_S calculated as 1/10 of the aquifer hydraulic conductivity at 23 different measurement location across the U.S.

Relative to the measured K_S, the aquifer-derived and land cover-derived KS have a mean (or mid-point) RMSE of 40.9 m/d and 13.8 m/d, respectively; a lower bound RMSE of 16.3 m/d and 5.0 m/d, respectively; and an upper bound RMSE of 72.5 m/d and 29.4 m/d, respectively. On the other hand, the aquifer-derived and land cover-derived KS relative to the measured KS have a mean (or mid-point) linear distance of -6.2 m/d and -1.0 m/d, respectively; a lower bound linear distance of -6.0 m/d and -1.4 m/d, respectively; and an upper bound linear distance of -7.1 m/d and -3.9 m/d, respectively. Out of the three approaches, the land cover-derived K_S provided the best estimates of measured K_S values. The catchment soil-derived K_S approach consistently underestimated the measured K_S values and both the RMSE and linear distance were much larger than the other two approaches. On the other hand, the distance-derived K_S approach provided the smallest mean (or mid-point) and upper bound RMSE values, however the linear distances were larger than the land cover-derived approach, suggesting that it suffers from a systematic error. The study shows that the consideration of variation in land cover is important to allow the best estimation of K_S.

This land cover-derived K_S approach was then used to estimate the streamflow depletion at both the Kalkaska site and Calhoun sites. The estimated K_S values based on the land cover analysis for the Kalkaska and Calhoun sites are 6.7 ± 2.9 m/d and 6.5 ± 2.7 m/d, respectively. On the other hand, the K_S values from WWAT parameters for the Kalkaska and Calhoun sites are 0.289 m/d and 1.74 m/d, respectively. K_S values from MODFLOW are 0.026 m/d for both the Kalkaska and Calhoun sites. Subsequently, the streambed conductance values for the Kalkaska and Calhoun sites with land cover-derived K_S are 1.2 ± 0.5 m/d and 1.3 ± 0.5 m/d, respectively. These values were larger than the streambed conductance values from the WWAT (the values of λ were 0.053 m/d and 0.274 m/d at the Kalkaska and Calhoun sites, respectively) and from MODFLOW (the values of λ were 0.026 m/d for both the Kalkaska and Calhoun sites). Land cover-derived K_S values were larger than those used by the WWAT and MODFLOW. There are very limited number of K_S reported in the literature and none of these measurements existed in Michigan. The nearest field K_S measurement was in the Grand Calumet River, IN and with a measured K_S range of 0.02 to 11 m/d. The K_S values of 0.026 m/d from MODFLOW calibration is at the lower end of this range and also among other ranges of K_S values shown in Table 3.1. This could be due to some error in the streamflow measurement of which the K_S values were calibrated, error in the assumption of streambed thickness and stream width values, and the inherent error in the calibration process itself. Although the RMSE and linear distance error analysis show that the land cover-derived K_S provided the most reasonable approach to estimate the actual measured KS, a field measurement might be needed to validate this approach.

The discrepancies of K_S values from MODFLOW calibration, the WWAT, and the land cover-derived approach caused variations in the Q_s estimation at both the Kalkaska and Calhoun sites. At the Kalkaska site, the $Q_{s,max}$ calculated with λ from land cover-derived K_S values using the modified Hunt (1999) solution is 1,535 m^3/day, which is larger than those calculated using MODFLOW with WWAT parameters (421 m^3/day) and using modified Hunt (1999) solution with WWAT parameters (317 m^3/day). At the Calhoun site, the $Q_{s,max}$ calculated with λ from land cover-derived K_S values using the Ward and Lough (2011) solution is 0.5 m^3/day. This value is larger than the $Q_{s,max}$ calculated using Ward and Lough (2011) with WWAT parameters ($Q_{s,max}$ is 0.013 m^3/day), $Q_{s,max}$ calculated using MODFLOW with WWAT parameters ($Q_{s,max}$ is 0.03 m^3/day) and with calibrated parameters ($Q_{s,max}$ is 5×10^{-4} m^3/day). These results imply that the streamflow depletion due to LQWs at the Calhoun site will be generally small. However, as discussed previously, $Q_{s,max}$ calculated using the modified Hunt (1999) solution is on the order of ~2,500 m^3/day and it implies that the streamflow depletion were very high.

In this study, the Ward and Lough (2011) analytical solution was demonstrated to provide a better estimate of streamflow depletion at sites with a three-layered hydrogeologic system which is commonly found in many parts of Michigan, including at the Calhoun site and it can be readily included in the WWAT for evaluation of $Q_{s,max}$. This study also shown that the land cover analysis approach may provide an improved estimate of measured K_S at locations without prior K_S measurements. The soil parameter data, land cover data, and stream and watershed data are readily available online and it can be relatively easily included in the WWAT for future improvements.

3.5 Acknowledgement

This work was supported in part by funding from the University of Michigan Water Center and from the National Science Foundation under grant number 1214416. The authors would like to thank you Dr. Manish Verma from the University of Michigan Consulting for Statistics, Computing and Analytics Research (CSCAR) for providing guidance on the statistical analysis methods in this study.

CHAPTER 4

Using a Mental Model Approach to Understand Water Resources Management Perspectives in Michigan

4.1 Introduction

As discussed in Chapter 1, sound groundwater governance and management require not only the active role of federal government, but also participation from local agencies and some form of stakeholder involvement. Understanding the state of mind of ‘experts’ and ‘non-experts’ and how they respond to groundwater management issues could be of a great value in ensuring sustainable groundwater management in Michigan. Potentially combative communication between ‘experts’ and ‘non-experts’ is not limited to water resources management; it arises frequently, perhaps most often in situations involving new technology or in other areas that are complex enough to not be easily understood by most people. For example, a study by Cook et al., (2004) regarding genetically modified foods showed that the ‘experts’ (i.e., scientists) engage with the ‘non-experts’ (i.e., the public) from their own linguistic and social domain. Another study by Swift and Wilson (2009) about the ‘expert’ and ‘non-expert’ views on brain injury show misconceptions on the part of the ‘non-experts’ arising from inaccurate and inadequate knowledge. ‘Experts’ typically view ‘non-experts’ as emotional and vulnerable to manipulation politicians, the press, and non-governmental organizations (NGOs) among others. ‘Non-experts’ were also found to be sometimes inadequately informed about a particular topic of interest despite their genuine feeling that they understand the situation (Thomas et al., 2015). Another study by Gibson et al., (2016) about communication of the subsurface aquifer and hydrogeology also exposed some of the ‘non-experts’ perceptions that were rather unusual that ‘experts’ might hardly consider them.

’Experts’ and ‘non-experts’ responses will depend on how each individual perceives the underlying problem, or his/her mental model (Kaplan and Basu, 2015). A mental model is a conceptual construct of how something works. It is composed by the human mind as a result of different experiences, attitudes, knowledge and comprehension relative to a given problem (Kearney and Kaplan, 1997; World Bank, 2014). Although mental model studies are meant to evaluate the cognition level of people on a particular matter, many of these studies only focus on what people do not know, looking for gaps in their knowledge, while ignoring what they already know about a given topic or how they utilize their existing knowledge (Gamba and Oskamp, 1994; Syme et al., 1993). Identifying knowledge gaps in understanding environmental issues is important, but it does not, by itself, provide sufficient information to understand the overall construct of one’s mental model.

In order to compare the mental models of different individuals or groups, it is helpful to construct a cognitive map as a “graphic description” of the mental model (Langfield-Smith, 1992). The method used to develop a visual representation of this internal thought framework has to meet four different requirements: (1) identification of the relevant concepts that an individual considers important in relation to a particular issue; (2) only those concepts that the individual owns are chosen (i.e., those corresponding to his/her existing understanding); (3) the relationships among concepts as understood by the individual are captured; and (4) the method enables the individual to reveal his/her cognitive structure to him/herself during the process of externalizing it (Kearney and Kaplan, 1997). Among the techniques that fit these requirements is the conceptual, content, and cognitive mapping (3CM) technique. This approach was used by Tikkanen et al. (2006), for example, to study forest owners' objectives about forest management in Northern Finland. It was found that the forest owners' objectives focused more on forest vigor, consistent with the role of "a good tender of the forests", rather than on timber sales income. Upham and Perez (2015) also used the same approach to construct cognitive maps and understand public objections to wind power infrastructure in Galicia, Spain. It was found that the local stakeholders felt that the non-local stakeholders gave little weight to the consequences that they considered negative, while highlighting the perceived positive outcomes anticipated at local, regional, and national levels. The local stakeholders also felt that neither monetary nor in-kind compensation would make the infrastructure project acceptable, whereas the non-local stakeholders considered compensation at market value would be considered acceptable. Basu et al. (2015b) also used 3CM to investigate stakeholder perceptions and government agency credibility in dealing with the beach muck problems in the Bay City State Recreation Area in Michigan. It was found that the 'expert' participants postulate a more systematic set of possible causes of beach muck and recognize the limits of methods for control. The 'non-experts', on the other hand, seem to feel that there is a solution if only there were the governmental will to address it.

Although the evaluation of mental models through cognitive mapping has been considered beneficial in many studies, its utilization in water resources management remains limited (Gibson et al., 2016; Kearney et al., 1999; Thomas et al., 2015; Wolf et al., 2013). The objective of this study is to identify mental model similarities and differences between 'experts' and 'non-experts' regarding groundwater resource management in Michigan. The objective was achieved by utilizing the 3CM method to develop aggregated cognitive maps of 'experts' and 'non-experts'. Elucidating the mental model and cognitive frameworks could aid in the understanding of how groundwater resource management is understood by the public, allowing water resource managers and regulators to take into account a broader purview of relevant issues or concepts for future outreach strategies, conflict mediation, and regulation development that could reflect the values of the community (Morgan et al., 2002; Özesmi and Özesmi, 2004; Pahl-Wostl and Hare, 2004).

4.2 Methods

4.2.1 Study Participants

In this study, the 3CM method was used to construct cognitive maps to provide insight into the mental models of ‘experts’ and ‘non-experts’ regarding to water resource management in Michigan. The ‘experts’ consisted of participants with formal education and/or professional background in the field of water or groundwater resource management and engineering. On the other hand, the ‘non-experts’ study group consisted of participants who did not have any formal education and/or professional background in the field of water or groundwater resource management and engineering, but still had a strong interest in groundwater resource management in Michigan. The participants came from various backgrounds, including, but not limited to, state and federal government officials, academia, farmers, anglers, educators, and members of environmental NGOs. Since the study groups were differentiated based on their prior knowledge, the ‘non-expert’ group could include state or federal government officials, while the ‘expert’ group could include members of the general public. Hence, in this study, the labels of ‘expert’ and ‘non-expert’ do not necessarily represent the dichotomy of regulators vs. the public.

In total, there were 25 participants in this study: 14 ‘experts’ and 11 ‘non-experts’. Initially, the participants were recruited based on the authors’ network of contacts; subsequent participants were contacted based on the initial participants’ recommendations. Since the selection process was not random, the outcome of this study should not be considered as a robust representation of the mental model and cognitive maps of ‘experts’ and ‘non-experts’ in State of Michigan regarding water resource management.

4.2.2 Conceptual, Content, and Cognitive Mapping

In this study, the Conceptual, Content, and Cognitive Mapping (3CM) method was used to externalize the mental models of the participants and to construct the cognitive maps of two groups designated as ‘experts’ and ‘non-experts’ based on whether they had formal training or a professional background in water resources (Kearney et al., 1999; Kearney and Kaplan, 1997). The approach used in this study was similar to that used by Basu et al. (2015) in studying the beach muck issue in the Bay City State Recreational Area in Michigan in which a semi-structured in-person interview that involved a card sorting activity was used to activate the mental model and externalize it as a cognitive map. The approach consisted of the following steps:

1) The following prompt was presented to the interview participant:

   > “I want you to think for a moment about your own perspective on high volume or high capacity water withdrawal in the State of Michigan. Imagine someone you know recently heard about high volume or high capacity water withdrawal in the State of Michigan. Since you are more familiar with the issue, they are interested in getting your perspective. What are the things you would be most likely to mention when discussing this issue?”

2) The participant was then invited to write down any words or phrases that he/she considered as important on individual cards. These words or phrases are here termed as ‘concepts’.
3) When the participant was satisfied and felt that all the important concepts had been written down, he/she was then presented with a list of 60 concepts that had been generated previously by the authors (Table 4.1). The participant was then asked to select additional concepts that he/she considered as important but were not included initially.
4) Once the participant was satisfied with his/her selection of concepts, he/she was then asked to sort these concepts into different groups such that concepts that were considered closely related

to each other were placed into the same group. The participant was then subsequently asked to pick a title for each of the groups he/she created.

5) Finally, the participant was asked to give a brief explanation of how he/she arrived at his or her choice of concepts, how the concepts were grouped, and why he/she thought that the title for each group was appropriate.

Prior to the interview process, all participants signed a consent form informing them that the interview process would be recorded but the interview would remain anonymous and any identifying information would be kept confidential. The recordings was then transcribed for data verification and archival purposes. The final arrangement of cards for each participant was also photographed to supplement the audio recording.

4.2.3 Data Analysis and Development of Cognitive Maps

As participants were asked to generate their own concepts prior to selecting from a set of pre-generated concepts, deviations and variations in the language used to describe the same concepts occurred. A total of 220 concepts (both self-generated and pre-generated) were created in this study, many of them referring to the same idea. To reduce the number of concepts while ensuring that the underlying idea remained, these 220 concepts were sorted into different classes. Each class combined concepts that were worded differently but had overlapping meaning or ideas. Two separate classification exercises were performed, each independent of the other, resulting in a final distillation of 220 concepts into 52 classes, presented in Table 4.2. 46 out of the 52 classes contained more than one concept, with the remaining six concepts being sufficiently distinct to be retained as separate classes. Because of the breadth of some of the concepts, some of them fell into multiple classes.

Table 4.1. The 60 "pre-generated" concepts that were given to the study participants after he/she generated their own concepts sorted by alphabetical order.

1. Additional pressure on water resources
2. Agricultural use
3. Annual water use report
4. Aquatic life habitat
5. Aquifer type
6. Climate change
7. Complexity of the problem
8. Dewatering
9. Drought
10. Dry water wells
11. Drying lake
12. Drying river
13. Education
14. Fish population change
15. Great Lakes Basin
16. Groundwater model
17. Groundwater quality
18. Groundwater recharge
19. Hydraulic fracturing / oil & gas use
20. Impact on ecosystem
21. Impact on other farms
22. Impact on residential housing
23. Increased population
24. Increased water demand
25. Industrial use
26. Irrigation
27. Lack of understanding of the science
28. Land subsidence
29. Less precipitation
30. Lowering water table
31. MI Dept of Environmental Quality (DEQ)
32. Mining use
33. Municipal Water Supply
34. Oil / gas regulation exemption
35. Outreach / communication effort
36. Prior appropriation water law
37. Public meeting
38. Riparian vegetation
39. Riparian water law
40. Site specific review for each HV/HC WW application
41. Stream depletion
42. Stream temperature
43. Stricter regulation
44. The Great Lakes
45. Thermoelectric power plant use
46. U.S. Environmental Protection Agency (EPA)
47. U.S. Geological Survey (USGS)
48. Water policy
49. Water priority
50. Water quality deterioration
51. Water rights
52. Water table drawdown
53. Water table monitoring well
54. Water use audit
55. Water use dispute
56. Water use restrictions
57. Water Withdrawal Assessment Tool (WWAT)
58. Water withdrawal permit
59. Wetland protection
60. Wildlife habitat

Table 4.2. The 52 classes that encompassed all 220 concepts used in the study sorted by alphabetical order. ^ Denotes the pre-generated concepts.

1. Additional regulation
- stricter regulation^
- wetland protection^

2. Agricultural & irrigation water usage
- agricultural use^
- agricultural use is a higher use than fracking
- agricultural use not subject to FOIA
- irrigation^

3. Basic rights
- property rights
- water rights^

4. Beneficial use of our large water supplies
- big supply of water
- water quantity
- we have plenty of water and are positioned to use it

5. Climate change associated water problems
- climate change^
- drought^
- less precipitation^
- protection against impact of climate change

6. Community education, outreach and involvement
- community involvement
- education^
- outreach or communication effort^
- public meeting^

7. Complex problem and lack of understanding
- complexity of the problem^
- lack of understanding of the science^
- low community understanding of water resources

8. Context of the problem
- context
- holistic point of view
- old vs. recent groundwater withdrawal
- required need for survival
- transportation
- why high-volume water withdrawals are regulated
- why it matters

9. Dispute and conflict management
- conflict management
- legal remedies
- water use dispute^

10. Equal access to water resources
- maintaining access
- water justice
- water priority^

11. Farmers' response
- farmers assuring response management
- Michigan agricultural environmental assurance program

12. Fracking water usage
- DEQ education related to hydraulic fracturing to citizens
- hydraulic fracturing or oil and gas use^
- oil or gas regulation exemption^
- reasons for use related to fracking cause concern to citizens
- secondary recovery
- talk about withdrawal for fracking

13. Impact of aquatic life habitat
- aquatic life habitat^
- aquatic life
- fish population change^
- mechanism for fish impacts

14. Impact on aquifer
- dry water wells
- impacts of groundwater withdrawal
- lowering water table
- water table drawdown

15. Impact on small water users
- impact on other farm^
- impact on residential housing^
- impact on small water withdrawal users

16. Impact on stream
- drying lake^
- drying river^
- stream depletion^
- stream impacts
- stream-aquifer connection

17. Impact on the ecosystem and environment
- adverse resource impact
- degree of ecosystem protection is a choice
- impact on ecosystem^
- impact to the environment
- invasive species
- land subsidence^
- riparian septic issue
- some water needed for ecosystem health
- water ecosystem supports overall quality of life
- withdrawal impacts in source watershed

18. Impact on wildlife habitat
- animal use
- wildlife habitat^
- wildlife use

19. Important for agriculture
- crop health
- crop insurance
- crop use
- help us keep farm land in our farm
- important for agriculture and food production
- more kind of crops
- they don’t make more ground so need to get more out of it

20. Increased water demand
- additional pressure on water resources^
- increased population^
- increased water demand^
- global demand

21. Industrial and municipal water users
- dewatering^
- industrial use^
- industries that withdraw high volume groundwater
- mining use^
- municipal water supply^
- residential, private and city
- thermoelectric power plant use^
- use category
- water user comparisons
- water user groups

22. Little impact on Michigan water resources
- little impact on water resources in Michigan
- low environmental impact

23. MI Dept of Environmental Quality (DEQ)

24. Michigan Water Withdrawal Legislation
- Great Lakes Basin Compact
- legal parameters
- Michigan Water Use Law
- part 327 policy and procedures
- policy and regulation
- regulatory requirements
- water policy

25. Politics and regulation
- collaborative
- governance structures
- science to policy to politics
- some role for regulatory, some role for local governance

26. Potential economic impact
- burden of government regulation
- economic impact

27. Prior appropriation water law

28. Problems with water regulation
- discontinuation of water law
- no environmental damage present
- permitting issues
- present laws allows destruction of environment

29. Quantity of water withdrawal
- amount of water that leaves the watershed
- examples of amount of water withdrawn
- specific examples of amount by industry

30. Regional aquifer characteristics
- aquifer type^
- groundwater distribution is lumpy
- regional aquifer characteristics
- unique geology

31. Regional water resource studies
- Hyndman study
- limited to Au Sable and Manistee area
- Water Use Advisory Council, Graham Study and water strategy

32. Responsible use of water in Michigan
- it matters for Michigan future
- local responsibility
- others should be doing it
- unusual to be proactive in water rich region
- water sustainability issue is significant even for a state surrounded by water
- water withdrawal assessment represents an important step forward

33. Riparian water law

34. Science based
- groundwater model
- model based
- model integration
- scientific based
- use of best available science

35. Stream characteristics
- intermittent stream
- perennial stream
- riparian vegetation^

36. Surface water use
- it's about the surface use
- method of groundwater withdrawal (surface effects)

37. Sustainable use of resources
- common pool resources
- conservation
- need to make wise and sustainable choices
- reasonable use and sharing of resources
- reduce, reuse, recycle
- resource stewardship and use
- sustainability of resources
- sustainable use
- use of best available conservation practices

38. The Great Lakes Basin
- Great Lakes Basin^
- Great Lakes level
- Great Lakes water diversion
- The Great Lakes^

39. Transparency and ethics in water use decision
- decision makers and society need strong water ethics
- informed and transparent water use decisions
- transparent water use data

40. US Environmental Protection Agency (EPA)

41. US Fish and Wildlife Services

42. US Geological Survey (USGS)

43. Water Quality Aspects
- groundwater quality^
- water quality
- water quality deterioration^

44. Water recharge
- annually renewable
- groundwater recharge^
- groundwater recharge (industrial) as part of withdrawal process
- groundwater recharge rates
- increased rainfall over last 3 decades
- water budgets per land unit

45. Water use audit and reporting
- annual water use report^
- water use audit^

46. Water use monitoring
- lack of monitoring
- need digital monitoring with cut off
- water table monitoring well^

47. Water use restrictions
- government restriction
- water use restrictions^

48. Water withdrawal permit
- aquifer pumping test
- water withdrawal permit^

49. Water withdrawal and stream biology
- connects groundwater withdrawal to biology
- stream temperature^

50. Water Withdrawal Assessment Tool
- 10 years in the making
- built from core principles
- ecological models embedded in law
- generalized but not specific
- near anonymous consensus
- online
- state wide
- Water Withdrawal Assessment Tool^

51. WWAT problems
- analysis as to whether or not water tool is effective for high volume withdrawals
- consumptive use factor not stated
- current WWAT has major flaws
- index flow and stream depletion model are problematic
- WWAT extrapolation of inaccurate index flow
- WWAT weaknesses and lack of data

52. WWAT site specific review
- site specific review for each high volume or high capacity water withdrawal application
- WWAT site specific review not on site

This information was then used to create two matrices, matrix $\boldsymbol{A}$ (size 52 × 14) representing the 'experts' and matrix $\boldsymbol{B}$ (size 52 × 11) representing the 'non-experts'. The matrices' rows represented the classes, the columns represented the participants, and a cell contains the list of groups where the classes were categorized. For example, a participant chose the "Great Lakes Basin" and "Great Lakes water diversion" concepts and have each of the concept on a separate group. However, these two concepts were included in the same "The Great Lakes Basin" class, thus the cell in matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ would contain these two different groups. The 'experts' created 76 groups, while the 'non-experts' created 50 groups. As a result, two additional matrices were subsequently created to represent these numbers of groups into which the participants had sorted these concepts into, i.e., matrix $\boldsymbol{A_m}$ (size 52 × 76) and $\boldsymbol{B_m}$ (size 52 × 50). In matrices $\boldsymbol{A_m}$ and $\boldsymbol{B_m}$, the rows represented the 52 classes, and the columns represented the groups in which these classes appeared. This study also used the endorsement analysis approach used by Tikkanen et al. (2006) where the frequency to which a particular class was calculated as a measure of that particular class' importance. In addition, Ward's Hierarchical Clustering Analysis (Ward's HCA) was used to analyze these matrices into cognitive maps using RStudio 1.0.136 (RStudio, Inc., Boston, MA) (Basu et al., 2015b; Kaplan and Basu, 2015). In the Ward's HCA, the rows in matrices $\boldsymbol{A_m}$ and $\boldsymbol{B_m}$ were treated as vectors and the Euclidean distance between two vectors was calculated as the root mean squared difference (Aldenderfer and Blashfield, 1984; Basu et al., 2015b; Kaplan and Basu, 2015; Kearney and Kaplan, 1997; Murtagh and Legendre, 2014).

4.3 Results and Discussion

4.3.1 Analysis of the 3CM Card Sorting Exercise

Overall, the study participants generated 160 concepts and chose all the 60 pre-generated concepts. The 'experts' generated between 2 and 17 concepts with an average of 7.5. They selected between 13 and 53 of the pre-generated concepts with an average of 25.4. Thus, the 'experts' selected 16 to 67 concepts with an average of 32.9 concepts. On average, the 'experts' selected 6.6 more concepts than the 'non-experts'. An analysis of the titles produced some common themes, which could be classified into four overarching themes: 'Policy, Law and Regulation', 'Knowledge and Science', 'Environmental Impacts', and 'Water Uses' (see Table 4.3). Some of the titles used by the 'experts' were very specific, e.g., 'policy and management tools', 'riparian rights', 'groundwater and surface water are one connected system', 'developing an effective tool requires cutting-edge science and technology', 'biological effects and outcomes to habitat', and 'must track water use within catchment budget'.

On the other hand, the 'non-experts' generated between 0 and 8 concepts with an average of 5.2. They selected between 7 and 39 pre-generated concepts with an average of 21.1. Overall, the 'non-experts' selected 10 to 47 concepts with an average of 26.3. Only a handful of the 'non-experts' showed a high level of understanding like that of experts with most of them coming up with more general titles, e.g., 'regulation', 'law', 'public policy', 'groundwater science', 'the big picture', 'water quality concerns', 'impacts', 'agricultural use', 'farms', and 'industry use'. In one case, a 'non-expert' participant used 'the most important', 'second most important', 'third most important', and 'fourth most important', as titles. All 'experts' group were able to come with specific, diverse titles for their group of concepts, whereas 'non-experts' tend to come up with broader titles for their group of concepts. Thus, the complexity of the titles many indirectly describe the participants' extent of knowledge.

Table 4.3. Common themes with several examples of actual group titles from the 3CM exercise. # denotes examples of titles used by 'experts', and * denotes examples of titles used by 'non-experts'.

Theme 1 **Policy, Law and Regulation**	**Theme 2** **Knowledge and Science**
- Policy and regulation#	- Groundwater and surface water are one connected system#
- Policy and management tools#	- Developing an effective tool requires cutting-edge science and technology#
- Riparian rights#	- Groundwater science*
- Legal underpinnings#	- Science*
- Regulation*	- The big picture*
- Law*	
- Public policy*	
Theme 3 **Environmental Impacts**	**Theme 4** **Water Uses**
- Environmental impacts#	- Must track water use within catchment budget#
- Ecosystem effects#	- Balancing water use and water protection#
- Biological effects and outcomes to habitat#	- Water use context and comparisons#
- Surface water effects#	- Agricultural use*
- Effects of water withdrawal*	- Farms*
- Water quality concerns*	- Industry use*
- Impacts*	

4.3.2 Concept Classes and Endorsement Frequencies Analysis

Figure 4.1 shows the top 17 most endorsed classes by both the 'experts' and the 'non-experts', sorted by theme. This was defined as classes that were selected by more than 50% of either one of the two sets of study participants. Both 'experts' and 'non-experts' consider the Michigan Water Withdrawal Legislation as very important and relevant to the Policy, Law and Regulation theme. Dispute and conflict management were also important for both study groups, although the 'non-experts' put slightly more emphasis on this class than the 'experts'. All of the 'expert' participants and the majority of the 'non-expert' participants were concerned about the impact on aquifers. However, with regard to water use in Michigan, more of the 'non-expert' participants were concerned about fracking water usage than the 'expert' participants. Overall, it

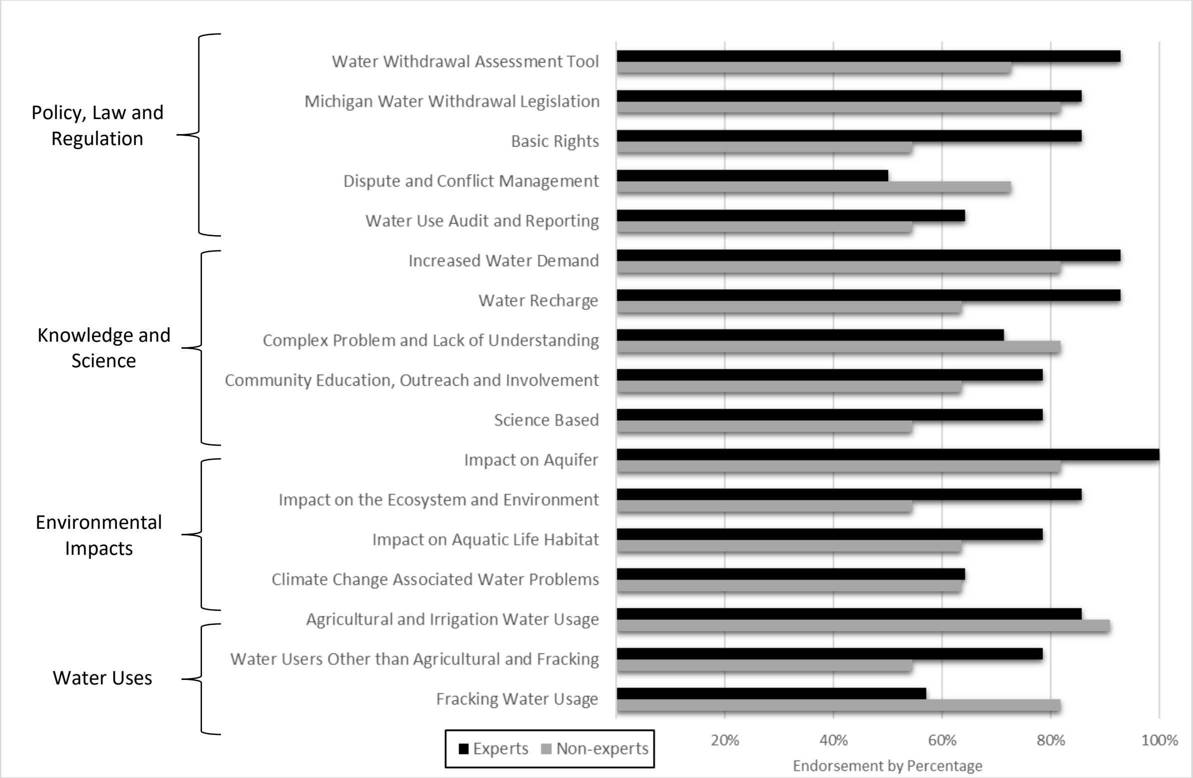


Figure 4.1. The top 17 most endorsed classes with more than 50% endorsement from both 'experts' and 'non-experts'.

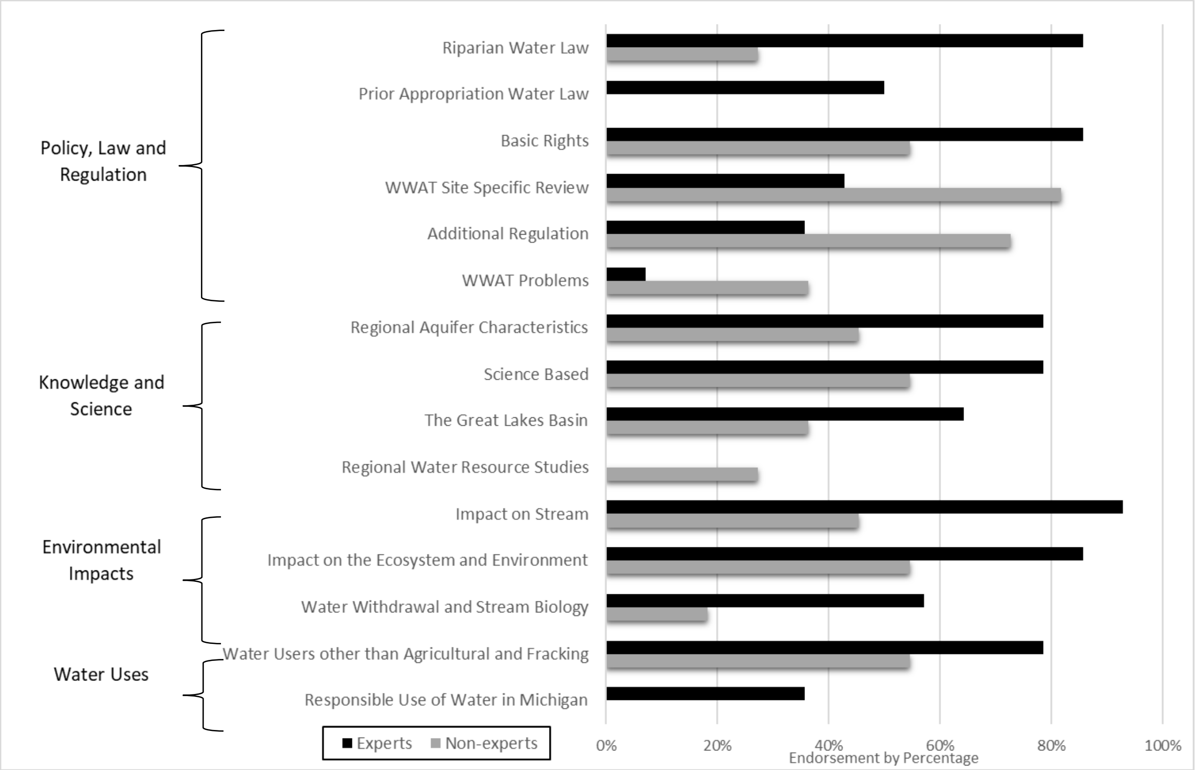


Figure 4.2. The 15 classes with the largest endorsement discrepancies (> 24%) between 'experts' and 'non-experts'.

was observed that both the ‘experts’ and the ‘non-experts’ exhibit fundamental knowledge related to water resource management in Michigan.

Figure 4.2 shows the 15 classes with discrepancies ≥ 24% in endorsement frequencies between the ‘experts’ and the ‘non-experts’, symptomatic of a significant mismatch in viewpoint between the ‘experts’ and the ‘non-experts’. It can be seen that that only a handful of the ’non-experts’ have a knowledge of the basis for water rights in the U.S. as less than 40% of them chose ‘Riparian Water Law’ and none chose ‘Prior Appropriation Water Law’. On the other hand, the majority of the ‘experts’ included both water laws in their selection. It appears that the ‘experts’ have a broader knowledge scope, but the ‘non-experts’ are more critical in some of the areas where there may be opportunities for improvement. For example, only a few or none of the ‘non-experts’ chose ‘water withdrawal and stream biology’, ‘impact on stream’, ‘the Great Lakes Basin’, or ‘responsible use of water in Michigan’. These classes were comprised of very specific issues regarding water resource management in Michigan (Table 4.2). On the other hand, only a few of the ‘experts’ chose ‘WWAT problems’, ‘additional regulations’, and ‘regional water resource studies’. These classes comprised of concepts pertaining to opportunities for improvement with the WWAT (Table 4.2). The ‘experts’ seemed to be confident with the science behind the WWAT and the tool itself while the ‘non-experts’, despite their non-familiarity with some of the specific terms, felt the tools and the approach used to regulate LQWs in Michigan were inadequate in many ways. Interestingly, prior, during, and after the interview process, many of the ‘experts’ actually discussed the drawbacks of the WWAT. However, these concerns were not externalized as part of their mental model, suggesting that they recognized it but accepted it or felt that other issues had greater weight. The results reported here are consistent with previous studies involving ‘experts’ and ‘non-experts’ where ‘experts’ were found to have a broader scope of knowledge than the ‘non-experts' and the 'non-experts' were observed to have incomplete information about specific concepts, especially when they are technically complex (Cook et al., 2004; Swift and Wilson, 2009).

4.3.3 Hierarchical Clustering Analysis and Cognitive Maps

Figure 4.3 shows the cognitive maps as dendrograms for the 'experts' and the 'non-experts'. These maps were developed based on the Ward's HCA from matrix $\boldsymbol{A_m}$ and $\boldsymbol{B_m}$. The classes were clustered together depending on how the concepts within the classes were originally assembled by the participants. The number of clusters were determined by sensitivity analysis in which the number were varied from 2 to 15 to ensure that related classes were clustered together, and unrelated classes were not clustered together. From this evaluation, it was found that 9 clusters and 10 clusters were the most suitable for the 'experts' and 'non-experts' cognitive maps, respectively. A qualitative analysis of the clusters and classes for each dendrogram showed that there are four discernable themes, each of them consisting of one or more clusters. These four themes are (1) 'Knowledge or context of the problem'; (2) 'Legal, policy, and regulation'; (3) 'Potential impacts'; and (4) 'Large water users'; these themes are very similar to those previously distilled from the group titles from the 3CM exercise. Table 4.4 summarizes the themes and the respective classes within each theme for both 'experts' and 'non-experts'.

4.3.3.1 Knowledge or Context of Problem

The first theme, 'Knowledge or context of the problem' is described by the classes in clusters k_4, k_8 and k_9 from the 'experts' dendrogram and clusters k_3, k_9 and k_{10} from the 'non-experts' dendrogram. For the 'experts', this theme is comprised of classes including, but not limited to, 'complex problems', 'increased water demand', 'WWAT', 'little impact in Michigan',

Figure 4.3. The cognitive maps shown as dendrogram of the 'experts' (left) and the 'non-experts' (right), respectively. The scale at the top shows the Euclidian distance of the data in matrix $\boldsymbol{A_m}$ and $\boldsymbol{B_m}$. $k_1 - k_{10}$ and the red boxes correspond the clusters of these classes based on their groups' distance in the Ward's HCA.

Table 4.4. Summary of the four different themes and the respective classes within each theme for the ‘experts’ and the ‘non-experts’.

	Experts	**Non-experts**
Knowledge and context of the problem	• Complex problems • Community education & public outreach • Increased water demand • Aquifer’s recharge • Impact on aquifer • Water Withdrawal Assessment Tool • Water use monitoring • Little impact in Michigan water resources • WWAT site specific review • Politics & regulation • Responsible water use	• Aquifer’s recharge • Regional aquifer characteristics • Science based • Complex problems • MI water withdrawal legislation • Citizens’ rights • Community education & public outreach • Additional regulation • Sustainable water use • Impact on wildlife habitat • Important for agriculture • Context of the problem • Farmer’s response
Legal, policy and regulation	• Michigan water withdrawal legislation • Riparian water law • Citizens’ rights • The Great Lakes Basin • EPA, MI-DEQ, USGS • Water use restrictions • Water withdrawal permit • Water use audit & reporting • Additional regulation	• EPA, MI-DEQ • Water withdrawal permit • Water Withdrawal Assessment Tool (WWAT) • WWAT site specific review • Water use restrictions
Potential impacts	• Impact on the ecosystem & environment • Impact on stream • Impact on aquatic life habitat • Water withdrawal & stream biology • Science based • Aquifer’s regional characteristics • Climate change associated problems • Impact on small water users • Dispute/conflict management • Sustainable water use • Water quality	• Impact on ecosystem & environment • Impact on aquatic life habitat • Water quality • Impact on streams • The Great Lakes Basin • Impact on the aquifer • Impact on small water users • Water use monitoring • Dispute/conflict management
Large water users	• Agricultural & irrigation water use • Hydraulic fracturing water use • Industrial, municipal and other water use	• Agricultural & irrigation water use • Increased water demand • Climate change associated water problems • Hydraulic fracturing water use • Industrial, municipal and other water use

‘WWAT site specific review’, ‘politics and regulation’, and ‘responsible water use’. On the other hand, for the ‘non-experts’, this theme is comprised of classes including, but not limited to, ‘regional aquifer characteristics’, ‘science based’, ‘complex problem’, ‘water withdrawal legislation’, ‘additional regulation’, ‘context’, and ‘sustainable water use'. The class ‘complex problems’ was included in the dendrograms of both ‘experts’ and ‘non-experts’, suggesting that both sets of participants recognized this issue as a complex problem. Both sets of participants also agreed that more outreach and education efforts about the Great Lakes Preservation legislation were necessary.

The ‘experts’ overall cognitive map is more structured and organized compared to that of the ‘non-experts’. The ‘expert’ participants were able to recognize that although science is important, it is not possible to remove politics from the policy equation. In contrast, these were absent from the ‘non-experts’ cognitive map. To quote one of the ‘expert’ participants:

> *“You have to do science, but the science has to be informing the policy, but the policy has to be cognizant of the political environment.”*

The ‘experts’ also considered science more as the basis upon which to evaluate the potential impacts of LQWs and incorporate this into the regulation. They also voiced the opinion that despite of the increased water demand, Michigan is actually managing its water resources fairly well and any problems were usually isolated. However, ‘non-experts’ seem to disagree with this in that they felt that the current regulations were inadequate in many ways. On the other hand, the non-experts’ overall cognitive map was broad but less structured and less organized. For example, the ‘non-experts’ included ‘Michigan water withdrawal legislation’, suggesting that they view the legislation more generally and as part of the background context of the issue. In contrast, ‘experts’ included any legislation related concepts in the ‘Legal, Policy and Regulation’ theme.

4.3.3.2 Legal, Policy, and Regulation

The second theme ‘Legal, Policy, and Regulation’ is associated with clusters k_5 and k_6 from the ‘experts’ dendrogram and cluster k_5 from the ‘non-experts’ dendrogram. For experts’, this theme included classes such as ‘water withdrawal legislation’, ‘riparian water law’, ‘citizens’ rights’, ‘water use restrictions’, ‘EPA’, ‘MI-DEQ’, ‘USGS’, ‘water withdrawal permit’, ‘water use audit and reporting’, and ‘additional regulation’. On the other hand, for ‘non-experts’, it included classes such as ‘water withdrawal permit’, ‘WWAT’, ‘WWAT site specific review’, ‘water use restrictions’, ‘EPA’, and ‘MI-DEQ’. Both sets of the study participants considered restrictions and permits, but ‘experts’ also included more specific, additional measures, such as possibility of water use audits and reports.

It appeared that the classes found in the ‘experts’ cognitive maps were more detailed than that of the ‘non-experts’. The ‘experts’ recognized the riparian water law doctrine as the basis of water allocation regulation in Michigan. The experts also included all the relevant federal and state government organizations (e.g., EPA, USGS, MI-DEQ) that are responsible in the regulation of water resource management. simpler than that of ‘experts’. For experts, the ‘MI water withdrawal legislation’ class was included in this theme, whereas it was included in another theme for the non-experts. From the non-experts’ perspectives, it can be observed that their cognitive map was much simpler than that of experts. Only a handful of the ‘non-experts’ included riparian water law in their selection of concepts and none selected prior appropriation water law. In contrast, the ‘experts’ knew that riparian doctrine is the basis of water legislation and regulation in Michigan. Unlike the ‘experts’, ‘non-experts’ did not include the USGS in their cognitive map for this theme, instead it was closer to the class ‘regional water resource studies’ suggesting that non-experts consider the USGS more as an organization responsible for water resource studies.

4.3.3.3 Potential Impacts

The third theme is ‘Potential Impacts’ which describes all the potential adverse impacts of LQWs on the water resources in Michigan. This theme is associated with clusters k_2 and k_3 from the ‘experts’ cognitive map, and clusters k_2 and k_6 from the ‘non-experts’ cognitive map. Both sets of participants used many concepts that fell into classes that describe impacts, including, but not limited to, ‘impact on the ecosystem and the environment’, ‘impact on aquatic life habitat’, ‘impact on streams’, ‘water quality’, ‘impact on small water users’, and ‘dispute or conflict management’. Both sets of participants also associated potential adverse impacts on the ecosystem, on the environment, on the streams, on the aquatic life habitat, on small water users, and on the water quality with water resource management. Lastly, both groups also described that prolonged drought and other potential extreme weather due to climate change have caused more reliance on groundwater that potentially results in LQWs and adverse impacts on the environment.

The main differences between ‘experts’ and ‘non-experts’ in this theme were ‘experts’ also considered other concepts that fell into the other classes related to the impact on the environment such as ‘water withdrawal and stream biology’, ‘science based’, ‘aquifer’s regional characteristics’, ‘climate change associated problems’, and ‘sustainable water use’. These other impact classes were not considered by the ‘non-experts’. On the other hand, ‘non-experts’ included concepts that fell into classes that were not considered by ‘experts’ such as ‘The Great Lakes Basin’. The ‘experts’ viewed this class more related to the other themes instead of the potential impact theme.

4.3.3.4 Large Water Users

The fourth and the last theme is ‘Large water users’ which is associated with the ‘non-experts’ clusters k_7 and k_8 and clusters k_1 of the ‘experts’. For the ‘non-experts’, cluster k_8 also included ‘increased water demand’ and ‘climate change associated problems’. It appeared that the ‘experts’ were only concerned about the potential adverse impacts on the aquifer as a result of LQWs regardless of the use of the water. However, it became apparent that many of ‘non-experts’ were more concerned about the impact of water withdrawals associated with fracking or industrial activities. They were less concerned about agricultural water withdrawals, even of the same magnitude. Although this study did not explicitly address the differentiation, it appeared that a segregation of water users depending on the end use of the water existed in their mental model. Additional conversations suggested that farmers were seen as “locals” who were more willing to come to a resolution with their neighbors should a dispute about water allocation arise. In addition, the concepts that fell into ‘increased water demands’ and ‘climate change associated problems’ were seen more closely related to agricultural and irrigation water use.

4.4 Conclusions

As water resources are expected to become even more important in the future, contentious communication between the regulator and the public is anticipated to intensify. In many environmental related problems, public and regulator responses depends on how well they understand the underlying problem, i.e. their mental model. Understanding this mental model would allow water resource managers to assess the issues that were more important and relevant to be addressed and improve communication for conflict mediation and future regulation development. Our objectives here were to use the conceptual, content and cognitive mapping

(3CM) approach to evaluate and externalize the mental model of the ‘experts’ and the ‘non-experts’ in understanding water resource management in Michigan.

The participants of this study included 14 ‘experts’ and 11 ‘non-experts’ based on their prior knowledge about water resource management. Our study shows that despite of some similarities, there are some structural mental model differences between the ‘experts’ and the ‘non-experts’. It was observed that the ‘experts’ mental model encompassed a more diverse spectrum of ideas relative to that of the ‘non-experts’ as shown by the average number of concepts chosen. A qualitative evaluation of the groups’ titles resulted in four fundamental themes: (1) policy, law, and regulation; (2) knowledge and science; (3) environmental impacts; and (4) water uses. An examination of the frequency of endorsement showed that the ‘non-experts’ were unfamiliar with the water law concepts in the U.S. Only a handful of the ‘non-experts’ knew about riparian water rights and understood that this doctrine allows for an ‘unlimited’ use of water by a property owner as long as it is withdrawn within the property boundary. It was also observed that the ‘non-experts’ understanding on the possible adverse impact of water resource management was more general and they seemed to be less familiar with more specific impacts, especially related to how LQWs may cause streamflow depletion that may adversely impact the ecosystem within the riparian zone. On the other hand, it was observed that the majority of the ‘experts’ tend to put less emphasis on the potential shortcomings of the WWAT. Interestingly, prior, during, and after the interview process, almost all of the ‘experts’ recognized and discussed, to a certain extent, that the WWAT needed improvements. However, during the card sorting activity, they somehow decided to dismiss this concept all together which suggested that this probably does not belong in their internal representations (Kearney and Kaplan, 1997).

The cognitive maps developed using the hierarchical clustering analysis yielded four themes: (1) Knowledge and context of the problem; (2) Legal, policy, and regulation; (3) Potential impacts; and (4) Large water users. These themes are very similar to the theme from the 3CM group titles analysis, suggesting that the Ward's HCA supported the qualitative results from another analysis. These four themes represent the essence of the cognitive maps for both sets of the study participants. From the two different cognitive maps, it can be concluded that the 'non-experts' has a more general views and understanding compared to those of the 'experts'. The 'experts' also have both more specific yet broader views regarding many of the issues pertaining to groundwater resource management in Michigan. For example, the 'experts' recognized the importance of politics in shaping the regulation, while the 'non-experts' did not. The 'experts' also viewed the WWAT simply as a tool that can be tweaked and improved, but not the regulation, while the 'non-experts' confound the WWAT with the regulation itself. The 'non-experts' were also more subjective in viewing large water users as they viewed agricultural water users separately from industrial and mining water users. They see the farmers as locals that were more willing to come to a resolution should a dispute occur. On the other hand, the 'experts' were less interested in the actual users itself and were more interested at the impact these large water users may bring to the environment.

All these results are consistent with previous studies that involved the comparison of 'experts' vs. 'non-experts' views (Gibson et al., 2016; Swift and Wilson, 2009; Thomas et al., 2015). The 'non-experts' were often incompletely informed, even though they thought they had an in-depth understanding. For example, they considered the users of LQWs as important, while the LQW users actually have no relationship with regards to the impact of LQWs to the environment. The 'non-experts' also demonstrated difficulties in clearly describing some concepts and many of them were very generalized, whereas experts had little struggle in explaining things and they could be very specific or broad, showing a very high level of understanding regarding the issue.

Understanding someone's existing mental model is required to determine and predict their response to new information and effective communication can be achieved if new information can be framed in a way that encourages people to integrate it into their mental model. One common denominator from this study is the need of more education, outreach and two-way communications, both formally and informally, from both the 'experts' and the 'non-experts' in addressing the discrepancies in their mental model. This outreach effort can benefit the public as they can be more informed about the importance of the fundamental of water laws, the role of politics and science in shaping the regulation, and they can also be more informed about the consequences of LQWs, not only on the aquifer, but also on the stream biology and the riparian ecosystem. This study could also provide water resource managers, regulators and relevant stakeholders with priorities from the 'non-experts' on what they think are more crucial and what they thought as the underlying problems in managing water resources in Michigan.

4.5 Acknowledgement

This work was supported in part by funding from the University of Michigan Water Center and from the National Science Foundation under grant number 1214416. The authors would like to thank Jason Duvall for providing a guidance and review in setting up the 3CM exercise access and Avik Basu for providing the Hierarchical Clustering Analysis.

CHAPTER 5

Evaluation of Knowledge-based Water Management Perspectives in Michigan using a Co-orientation Approach

5.1 Introduction

In natural resource management, public participation is desired; however, it is often viewed as antithetical. The public want the best scientific and technical approaches to guide water resource management decisions, but they also want their opinions to be considered. On the other hand, managers want some useful participation from the public, but they also want the public to have confidence in their expertise. Natural resource managers, including water resource managers, have strived to enhance their knowledge about the public's diverse views and opinions, as well as seek ways to encourage more public involvement in developing the broader goals and objectives in guiding and managing natural resources (Jacobson et al., 2007). In the previous chapter, the knowledge and comprehension of 'experts' and 'non-experts' pertaining to groundwater resource management in Michigan were elucidated through mental model studies. However, the studies only demonstrated what each study group knew, while disregarding the degree of understanding between them. In facing water resource related issues, both the water resource managers and the public expressed their own concerns, views, and opinions. However, their own concerns, views, and opinions may differ from what the other parties perceived.

Water resource managers, like other natural resource managers, often rely on their own perceptions about the citizens the serve when making relevant decisions on regulations (Leuschner et al., 1989). Nevertheless, studies have shown that the public's views and opinions were often different from what the resource managers perceived (Absher et al., 1988; Bradley and Kearney, 2007; Kearney et al., 1999). When facing complex issues like this, two-way symmetrical communication that foster mutual understanding is preferable than asymmetrical one-way communication that involves persuasion and influence (Kelly et al., 2006). In a one-way asymmetrical communication, one party continuously communicate their concerns, views, and opinions to the other party while disregarding what the other party's concerns, views, and opinions are. In contrast, in a two-way symmetrical communication between two parties (e.g., the 'experts' and the 'non-experts'), the 'experts' communicate their concerns, views, and opinions to the 'non-experts' while also actively listens to the 'non-experts' concerns, views, and opinions and vice-versa. Symmetrical two-way communication allows both parties to collaborate and work together towards implementing policies and regulations that balance the needs and desires of everyone (Dozier et al., 2013; Grunig, 2001).

To achieve two-way symmetrical communication and perceptions between two parties of interest, co-orientation models may be used (Cutlip et al., 2012). Such models have been used in many types of study, including, but not limited to the fields of journalism, marketing, international relations, organizational studies, tourism, public relations, and natural resource management (Avery et al., 2010; Cho and Kelly, 2014; Eisenberg et al., 1984; Kelly et al., 2006; Lubbers, 2005; Musca, 2014; Verčič et al., 2006; Walden et al., 2015). To understand the degree of understanding between 'experts' and 'non-experts', each party's view is first categorized into two: their own views and opinion, and their perceived views and opinion relative to the other party (see Figure 5.1). The co-orientation model organizes the measurement of these two different views and opinions into three dimensions: (1) agreement, (2) accuracy; and (3) congruency (see Figure 5.1).

Agreement is a measure of the degree of similarity between ‘experts’ and ‘non-experts’ self-views and opinion. A high level of agreement means that both ‘experts’ and ‘non-experts’ share similar views and opinion. Accuracy is a measure of the degree of similarity between one party’s perceived views and opinions on the other party and the other party’s actual views and opinions. For example, a high level of accuracy for ‘experts’ means that the ‘experts’ have a good grasp of what the ‘non-experts’ views and opinions are.

The co-orientation states from each study group explain the quality of communication from that particular group (McLeod and Chaffee, 1973). Collectively, the co-orientation model uses the agreement and accuracy dimensions to come up with four different co-orientation states: (1) true consensus, (2) dissensus, (3) false conflict, and (4) false consensus (see Table 5.1). A true consensus state occurs when the level of agreement and accuracy are both high. This means both ‘experts’ and ‘non-experts’ share the same views and both parties recognize this (i.e., they agree, and they know they agree). A dissensus state occurs when the agreement level is low, but the accuracy level is high. The ‘experts’ and ‘non-experts’ have different views and opinions, but they recognize the disagreement between them (i.e., they do NOT agree, and they know they do NOT agree). A false conflict state occurs when the agreement level is high, but accuracy level is low. This means that both ‘experts’ and ‘non-experts’ share the same views and opinions, however they fail to recognize this (i.e., they agree, but they do NOT know they agree). Lastly, the false consensus state occurs when both agreement and accuracy levels are low. This means that neither ‘experts’ nor ‘non-experts’ have similar views and opinions, and they fail to recognize the disagreement (i.e., they disagree, and they do NOT know that they disagree).

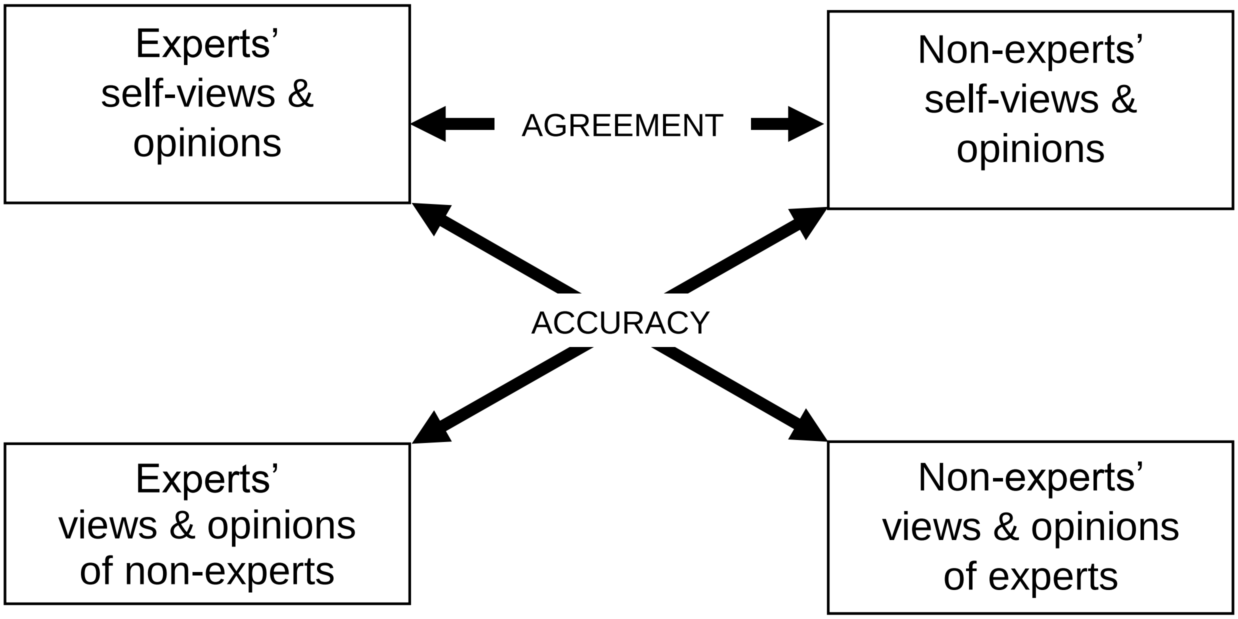


Figure 5.1. Agreement and accuracy between 'experts' and 'non-experts' in a co-orientation model framework.

Table 5.1. The four different co-orientation states and their respective agreement and accuracy levels.

		Agreement	
		High	Low
Accuracy	High	True Consensus	Dissensus
	Low	False Conflict	False Consensus

Many studies have benefited from the application of a co-orientation framework in improving the understanding between two or more groups of stakeholders (Basu et al., 2015b; Carrozzino-Lyon et al., 2014; Connelly and Knuth, 2002; Leong et al., 2008; Twight and Paterson, 1979; von Kutzschenbach and Brønn, 2006). Von Kutzschenbach and Brønn (2006) used co-orientation to examine the perception of sustainable forest development between forest owners and forest product consumers in Norway, suggesting different approaches for improving communication according to the co-orientation states. Connelly and Knuth (2002) used a co-orientation framework to compare local residents' and three local community groups' views regarding restoration of the Hudson River estuary in New York. The study found that the local residents and the three local community groups did not agree completely on the importance of specific restoration actions. Two of the three community groups shared some common views with the residents but the other group placed more importance on restoration actions than the local residents. Carrozzino-Lyon et al. (2014) used co-orientation to study wildlife habitat management activities between the State Wildlife Agency personnel and recreational users in VA. They found that both the managers and the users expressed support for many of the same land management practices, however, the managers generally expressed stronger support. In contrast, the managers did not support timber harvesting to remove undesirable or diseased trees due to certain logistic and economics challenges, but this view was not shared by the users. This kind of differences required a greater effort to communicate. Basu et al. (2015a) also used a co-orientation approach to study the perceptions of both natural resource agencies and citizens regarding the causes and impacts of beach muck in the Bay City State Recreation Area in Michigan. They found that the citizens were actually more knowledgeable than they were given credit for by the agencies and the experts were more concerned than what they were given credit for by the citizens. These studies show that it is hard to predict the state of communication between relevant parties on a particular issue since it may differ according to the exact focus of each party. Co-orientation approach is useful in pinpointing the areas where more time should be invested to ensure the understanding and communication states between the relevant parties.

The study presented in Chapter 4 showed that ‘experts’ have more detailed knowledge than the ‘non-experts’ with respect to groundwater resource management in Michigan. In contrast, ‘non-experts’ clearly showed dissatisfaction with the tool. As water resource managers face ever-increasing pressures from the public, communities, and constituencies, co-orientation studies could be useful in understanding how to communicate the delicate balance that successful management of water resources entails. Water resource managers can proactively understand and engage with stakeholders and partners before controversial issues reach the boiling point. The mental models of ‘experts’ and ‘non-experts’ regarding groundwater resource management in Michigan has been outlined in the previous chapter but the degree of understanding between them remains unclear. The objective of this work was to use a co-orientation approach to evaluate the degree of understanding between ‘experts’ and ‘non-experts’ pertaining to water resource management in Michigan. The results of this co-orientation study would provide more details of the level of understanding between the two groups, complementing the results from the previous chapter and provided beneficial information for water resource managers or other decision makers who seek to improve communication and encourage more collaboration with their stakeholders about water resource management in Michigan.

5.2 Methods

5.2.1 Study participants

Similar to the approach in Chapter 4, the participants for this study were divided into two groups: the ‘experts’ and the ‘non-experts’. Participants with formal education and/or professional background in the field of water or groundwater resource management and engineering were classified as ‘experts’, whereas those who did not have any formal education and/or professional background in the field of water or groundwater resource management and engineering, but nevertheless had a strong interest in groundwater resource management in Michigan were placed in the ‘non-experts’ group. Since the study groups were differentiated based on their prior knowledge, the ‘non-expert’ group included members of state or federal government officials, while the ‘expert’ group included members of the general public. Some participants were recruited from the study reported in Chapter 4. Additional participants were recruited in conjunction with the Michigan State University Extension Office through their website (Day, 2017).

5.2.2 Co-orientation Survey Questions

Participants who were also part of the study discussed in Chapter 4 were given hard-copy co-orientation survey forms. All other participants took on-line surveys using a Qualtrics website (Qualtrics, Provo, UT). Two different co-orientation survey forms were used: one for ‘experts’ and another one for ‘non-experts’. In the survey form, the term ‘agencies’ were used to represent ‘experts’ and the term ‘local community member’ was used to represent ‘non-experts’ and this information was communicated to all the participants beforehand. The survey forms were designed based on the co-orientation study performed by Basu et al. (2015b) about beach muck issues in Michigan. Before completing the survey forms, all participants were provided a consent form where they were informed that the survey data would be anonymous. Table 5.2 shows the type of co-orientation dimensions (i.e., agreement and/or accuracy) evaluated, topics and the corresponding prompts asked for both sets of study groups. The complete survey forms for ‘experts’ and ‘non-experts’ can be found Appendices B.1 and B.2, respectively. Several demographic questions (e.g., gender, age, employment status) were included in the survey forms to understand where each participant fits in the general population’s demographic. In addition to these basic demographic questions, ‘experts’ were also asked about their professional affiliations, whereas, the ‘non-experts’ participants were asked: (1) if they were born in the Great Lakes States, (2) if they were involved in any organizations related to sustainable water resource management, and (3) if they owned a pumping well(s) and what the pumping well(s) were used for if they had one.

Some questions were designed to evaluate the co-orientation states from each study group's perspective by assessing both the agreement level and the accuracy level, while some other questions were designed to measure either the level of agreement or accuracy, but not both. There were three questions that evaluated the co-orientation states of both sets of the study groups: (1) the importance of several issues related to sustainable water resource management, (2) whether some of the issues would cause unsustainable water resource management, and (3) how much they were concerned about the issue. Additionally, there were two questions that only assessed the level of co-orientation agreement of both study groups: (1) agreement/disagreement regarding several statements about a particular topic and (2) the effectiveness and practicality of several strategies to ensure sustainable water resource management. Finally, there were two questions that only measured the level of accuracy of 'experts' prediction of 'non-experts' views and opinions: (1) efforts of natural resource management agencies in ensuring sustainable water resource management and (2) the source of information used to learn about the research topic. A five-point Likert scale was used to measure the responses, ranging from (1) 'very not important' or 'never' or 'strongly disagree' or 'not at all' to (5) 'very important' or 'very often' or 'strongly agree' or 'extremely' depending on the specific question. An additional category of 'don't know' was also included as an option for some of the questions. The selection of this option by a study participant was treated as a 'null' or missing value in the analysis.

Table 5.2. The co-orientation dimension, topics, and survey prompts on 'experts' and 'non-experts' forms, respectively.

Co-orientation Dimension or State	Topics	Survey prompt for expert participant	Survey prompt for 'non-expert' participant
Agreement level of both 'experts' and 'non-experts'	Agreement/disagreement on several statements about water resource management	"How much do you agree with the following statements?"	"How much do you agree with the following statements?"
	Effectiveness and practicality of several strategies to ensure sustainable water resource management	"How effective do you think these strategies would be?" "How practical do you think these strategies would be to implement?"	"How effective do you think these strategies would be?" "How practical do you think these strategies would be to implement?"
Accuracy level of 'experts' in predicting 'non-experts' views	Efforts of agencies in ensuring sustainable water resource management	"How much do you agree about how the public feels regarding efforts of agencies in the following statements?"	"How much do you agree with the efforts of agencies in the following statements?"
	Source of information about sustainable water resource management	"How often do you think the local community members gets information from these sources?"	"How often do you information from these sources?"
Agreement and accuracy of both 'experts' and 'non-experts' and subsequently the co-orientation states	Importance of issues related to sustainable water resource management	"How important is each issue to local community members?" "How important is each issue to agencies?"	"How important is each issue to local community members?" "How important is each issue to agencies?"
	How much these issues would cause unsustainable water resource management	"How much do local community members think each issue would cause unsustainable water resource management?" "How much do agencies think each issue would cause unsustainable water resource management?"	"How much do local community members think each issue would cause unsustainable water resource management?" "How much do agencies think each issue would cause unsustainable water resource management?"
	Level of concern from issues that would cause unsustainable water resource management	"How much does it concern the local community members?" "How much does it concern agencies?"	"How much does it concern the local community members?" "How much does it concern agencies?"

5.2.3 Data Analysis

The results of the co-orientation survey were quantified on a scale of 1 to 5 or ‘don’t know’. These data were then evaluated using a combination of one-way Analysis of Variance (ANOVA) and one-way Multivariate Analysis of Variance (MANOVA) from the ‘experts’ and the ‘non-experts’ point of view, respectively, similar to the approach used by Von Kutzschenbach and Brønn (2006) in their co-orientation study of forest management certification in Norway. The statistical analyses were performed using SPSS Statistics 25 (IBM Corporation, Armonk, NY). Both ANOVA and MANOVA measured the differences in the survey responses based on dependent variables and independent variables. For example, ANOVA was used for questions where only the agreement or accuracy level measurement was measured, whereas MANOVA was used for questions where both agreement and accuracies were measured. For both analyses, the dependent variables were the survey responses, while the independent variables were the experts’ self-views, experts’ prediction on non-experts’ views, non-experts’ self-views, and non-experts’ prediction on experts’ views. The null hypothesis, H_0, was that both the ‘experts’ and the ‘non-experts’ have the same views and opinions (i.e.: high agreement) and they recognized that they were in agreement (i.e.: high accuracy). H_0 was rejected if the resulting p-value was < 0.05, meaning that the difference between the two values was significant. The failure to reject H_0 for both agreement and accuracy indicated that the co-orientation state was true consensus. The rejection of only H_0 for agreement indicated that the agreement was low, but the accuracy remained high. A rejection of the H_0 for accuracy indicated that the accuracy was low, but the agreement remained high. Based on which hypotheses were rejected, the corresponding co-orientation state could then be inferred on the basis of the information in Table 5.1.

5.3 Results

5.3.1 *Participants' Demographic Data*

In total, 90 people participated in this co-orientation study. 65 of them completed the survey online whereas the remaining 25 completed the survey after participating in the previous mental model study discussed in Chapter 4. Out of the 65 survey forms submitted online, only 45 were complete. The remaining 20 incomplete surveys were discarded. 39% of the total 70 completed survey forms (*n* = 27) were from 'experts' and the remaining 61% (*n* = 43) were from 'non-experts'. The study participants came from various backgrounds, including, but not limited to, state and federal government officials, academia, farmers, anglers, teachers, and members of environmental NGOs. 44% (*n* = 30) of the 70 participants who completed the survey were male, and the remaining 56% (*n* = 40) of the participants were female. 7% (*n* = 5) of the participants were between 70-79 years old, 30% (*n* = 21) were between 60-69 years old, 23% (*n* = 16) were between 50-59 years old, 16% (*n* = 11) were between 40-49 years old, 16% (*n* = 11) were between 30-39 years old and the remaining 8% (*n* = 6) were between 18-29 years old. About 90% (*n* = 81) of the survey respondents were born or grew up in the Great Lakes States and 33% of them (*n* = 30) have groundwater pumping wells. All study participants were residents of the State of Michigan.

5.3.2 *Agreement/disagreement on Several Statements about Water Resource Management*

Table 5.3 shows the arithmetic means and the *p*-value of the participants' responses on their self-views and opinions regarding 19 statements about water resource management in Michigan. Here, the 'experts' and 'non-experts' were asked on how much do they agree with the statements given to them and the survey only measure the agreement level. The 'experts' and

Table 5.3. Arithmetic means of participants' responses to statements regarding sustainable water resource management and practices in Michigan. * denotes *p*-value < 0.05 which indicates that the mean values of 'experts' and 'non-experts' survey responses were statistically significant (i.e., different). The statements below are sorted by *p*-value.

"How much do you agree with the following statements?"	Experts $\bar{X}$	Non-experts $\bar{X}$	*p*-value
High agreement			
Regulation ensuring sustainable water management can possibly restrict economic growth.	3.37	3.26	0.693
Sustainable water resource management regulation shall not limit access to freshwater resources.	2.96	2.84	0.669
More research needs to be done on sustainable water resource management programs.	4.41	4.33	0.657
Agricultural related water consumptions are NOT sustainable in the long run.	3.11	3.37	0.386
Water resources related problems have increased in the last 10-15 years.	4.15	4.35	0.376
Sustainable water resource management will maintain and/or improve water quality and stream ecology.	4.26	4.44	0.281
The community has the right to participate in sustainably managing water resources in their area.	4.70	4.49	0.131
High volume groundwater withdrawal is a serious issue in Michigan.	3.89	3.33	0.119
Agricultural activities (e.g.: irrigation, etc.) consume the most amount of water and/or groundwater.	3.96	3.53	0.103
Residential home owners water wells consumptions are NOT sustainable in the long run.	2.00	2.37	0.070
Combined, residential home owners water wells consume the most amount of groundwater.	2.04	2.44	0.063
Water resource diversion from the Great Lakes Basin is a serious issue.	3.89	4.42	0.052
Low agreement			
High volume hydraulic fracturing activities will adversely impact the environment, specifically water quality.	3.54	4.23	0.008*
Hydraulic fracturing related water consumptions are NOT sustainable in the long run.	2.89	3.88	0.001*
High volume hydraulic fracturing activities will adversely impact the environment, specifically water quantity.	2.96	3.91	0.001*
The local community care about water resources for current & future generation.	2.33	3.19	0.000*
Industrial activities consume the most amounts of water and/or groundwater.	2.67	3.60	0.000*
Industrial related water consumptions are NOT sustainable in the long run.	1.96	3.02	0.000*
Hydraulic fracturing activities consume the most amounts of water and/or groundwater.	3.93	4.86	0.000*

‘non-experts’ shared the same views (i.e., high agreement level, p-value > 0.05) on 12 of the 19 statements and didn’t share the same views (i.e., low agreement level, p-value < 0.05) on the remaining seven statements. For these seven statements, the survey results showed that the non-experts picked ‘strongly agree’ more frequently than the ‘experts’. These seven statements were related to hydraulic fracturing associated water withdrawals, industrial activities associated water withdrawals, and whether the local community cared about water resources for current and future generations. The ‘experts’ and ‘non-experts’ picked the same level of agreement regarding the remaining 12 issues, such as the possibility that regulation can possibly restrict economic growth, that regulation shall not limit access to freshwater resources, and if more research is needed on water resource management program.

5.3.3 Effectiveness and Practicality of Strategies to Ensure Sustainable Water Management

Table 5.4 shows the arithmetic means of the participants’ responses to their own views and opinions regarding the effectiveness and practicality of nine different strategies to ensure sustainable water resource management and practices. Here, the ‘experts’ and ‘non-experts’ were asked if some strategies were effective or practical in ensuring sustainable water resource management and the survey only measure the agreement level. With respect to effectiveness of the strategies, ‘experts’ and ‘non-experts’ shared similar views on three different strategies and different views on the remaining six strategies. With respect to practicality of the strategies, ‘experts’ and ‘non-experts’ shared similar views on five strategies and different views on the remaining four strategies. Both sets of participants shared similar views of the effectiveness and practicality of strategies such as more outreach and education, and more rigorous water regulations for agricultural and industrial activities. In contrast, both sets of study groups shared different

Table 5.4. Arithmetic means of participants' responses to statements regarding the effectiveness and practicality of different strategies for ensuring sustainable water resource management and practices. * denotes p-value < 0.05 which indicates that the mean values of 'experts' and 'non-experts' survey responses were statistically significant (i.e., different). The statements below are sorted by p-value.

"… is effective in ensuring sustainable water resources management."	Experts $\bar{X}$	Non-experts $\bar{X}$	*p-value*	"… is practical to be implemented in ensuring sustainable water resources management."	Experts $\bar{X}$	Non-experts $\bar{X}$	*p-value*
High agreement							
More outreach and education about sustainable water management practices for the public, especially for stakeholders	4.19	4.20	0.967	More outreach and education about sustainable water management practices for the public, especially for stakeholders	4.00	4.02	0.919
More rigorous water regulations for industrial activities	3.65	3.95	0.304	More rigorous water regulations for agricultural activities	2.85	3.28	0.145
More rigorous water regulations for agricultural activities	4.04	3.59	0.122	More rigorous water regulations for industrial activities	3.08	3.54	0.115
				Water use audits	3.15	3.66	0.068
				More rigorous water regulations for fracking and energy industry	3.20	3.77	0.064
Low agreement							
More rigorous water regulation for residential water withdrawals	2.23	2.82	0.048*	Strictly prohibit water diversions from the Great Lakes Basin (e.g., Great Lakes Compact)	3.26	3.95	0.026*
Water use audits	3.70	4.26	0.046*	More rigorous water regulations for residential water withdrawal	1.81	2.55	0.013*
Strict review for all individual high volume / high capacity water withdrawal proposals	3.59	4.32	0.025*	Strict review for all individual high volume / high capacity water withdrawal proposals	2.96	3.90	0.004*
Strict prohibition of any water withdrawals at locations with sensitive stream ecology	3.63	4.37	0.017*	Strict prohibition of any water withdrawals at locations with sensitive stream ecology	2.52	3.78	0.000*
More rigorous water regulations for fracking and energy industry	3.52	4.29	0.012*				
Strictly prohibit water diversions from the Great Lakes Basin (e.g., Great Lakes Compact)	3.31	4.36	0.001*				

effectiveness and practicality views for strategies such as strict prohibition of the Great Lakes water diversions and water withdrawals near sensitive streams, strict reviews on all LQWs, and more rigorous regulations on residential water withdrawals were neither effective nor practical. Generally, ‘non-experts’ viewed all these strategies as more effective and practical than the ‘experts’. Finally, both ‘experts’ and ‘non-experts’ shared a similar view in terms of practicality but different view in terms of effectiveness regarding water use audits and more rigorous regulations on fracking industries.

5.3.4 Efforts of Agencies in Ensuring Sustainable Water Resource Management

Here, the ‘experts’ were asked to predict the ‘non-experts’ views, while the ‘non-experts’ were asked to give their own views on 15 statements regarding the efforts done by the water resource management agencies in ensuring sustainable water resource management in Michigan and the survey measured the accuracy level of experts in predicting the non-experts by comparing the prediction against the actual answers. The ‘experts’ accurately predicted ‘non-experts’ views and opinions on 13 of the 15 statements asked (see Table 5.5). The accuracy levels were particularly high on questions such as whether the agencies are making reasonable effort to ensure sustainable water resources, the agencies have tried to enforce sustainable water resource regulations, the agencies treat community members fairly, and the agencies want to preserve water resources in Michigan. However, the ‘experts’ failed to accurately predict the ‘non-experts’ views regarding whether the agencies want to minimize problems on economic development due to regulations and the agencies know what are causing potential unsustainable water resource management.

Table 5.5. Arithmetic means of participants' responses to 15 statements regarding the efforts by water resource management agencies to ensure sustainable water resource management in Michigan. * denotes *p*-value < 0.05 which indicates that the mean values of experts on non-experts and 'non-experts' survey responses were statistically significant (i.e., different). The statements below are sorted by *p*-value.

Experts: "The local communities believe that the agencies …" Non-experts: "The agencies … "	Experts on non-experts $\bar{X}$	Non-experts $\bar{X}$	*p*-value
High accuracy			
… are making a reasonable effort to ensure a sustainable use of water resources.	3.07	3.07	0.985
… have tried to enforce sustainable water resource regulations.	2.70	2.72	0.941
… treat community members fairly.	2.78	2.70	0.761
… want to preserve water resources in Michigan.	3.82	3.74	0.739
… are trying to provide the public with useful information about sustainable water resource management and practices.	2.41	2.57	0.529
… are not interested in ensuring sustainable water resources management.	3.22	3.07	0.531
… know what to do to improve sustainable water resource management and practices.	3.11	3.26	0.521
… have the right people working on sustainable water resources issues.	2.81	2.63	0.405
… understand the concerns of the local community.	2.41	2.65	0.303
… don't care about the feelings of the community.	3.19	2.91	0.246
… communicate effectively with the public.	2.21	1.82	0.149
… try to actively engage the community about sustainable use of water resources.	2.26	2.67	0.087
… want to improve the local economy.	2.89	3.37	0.072
Low accuracy			
… want to minimize problems on economic development due to regulations.	2.96	3.65	0.008*
… know what are causing potential unsustainable water resource management.	2.78	3.60	0.001*

5.3.5 Sources of Information

Here, the 'experts' were asked to predict the source of information of which the 'non-experts' get their information about sustainable water resource management from, while the 'experts' were asked where they get this information from and the survey was designed to measure the experts' accuracy level by comparing the prediction against the actual answer. The results suggested that the ‘experts’ were able to accurately predict social media, local media, local community members, and four other outlets as the sources of information where the public often get their sustainable water resource management information from (Table 5.6). However, the study also showed that the ‘experts’ were inaccurate in predicting that commercial well drillers and business groups were hardly used as sources of information about water resource management by the public (Table 5.6).

Table 5.6. Arithmetic means of participants’ responses regarding the sources of information about sustainable water resource management. * denotes *p*-value < 0.05 which indicates that the mean values of ‘experts’ and ‘non-experts’ survey responses were statistically significant (i.e., different). Statements are sorted by *p*-value.

Experts: “The public usually get information about sustainable water resource management from… “ Non-experts: “I usually get information about sustainable water resources management from …”	Experts on non-experts $\bar{X}$	Non-experts $\bar{X}$	*p*-value
High accuracy			
Social media	2.83	2.79	0.899
Local media	2.78	2.72	0.798
Local community members	2.67	2.79	0.623
Michigan DEQ website	2.52	2.19	0.202
National media	2.26	2.53	0.167
Public meetings	2.56	2.16	0.089
Environmental conservation groups	3.44	2.91	0.059
Low accuracy			
Commercial well drillers	2.04	1.51	0.019*
Business groups	2.22	1.74	0.017*

5.3.6 Importance of Issues Related to Sustainable Water Resource Management

Here, the survey question was about the importance of some issues related to sustainable water resource management in Michigan. Both sets of participants were asked to evaluate their own views as well as gave prediction on the other party’s view. The survey question measured both the agreement and accuracy from both sets of participants’ perspectives. It can be observed that most of the issues were viewed as generally important by both sets of study groups. Although statistically some statements had a low co-orientation agreement level, both sets of study groups acknowledge that all the statements given to them were important and the differences were that the ‘non-experts’ had stronger views than the ‘experts’. The arithmetic mean values were between 3.52 to 4.52 and 4.38 to 4.81 for ‘experts’ and ‘non-experts’, respectively (Table 5.7). Interestingly, however, both ‘experts’ and ‘non-experts’ under-estimated the other party’s views and opinions. The arithmetic mean values of experts’ prediction of the opinion of non-experts were between 2.93 to 4.33, while the non-experts’ prediction of experts yielded arithmetic mean values of between 3.45 to 3.83. From the ‘experts’ perspective, there were one issue with dissensus, five issues with false conflict, and five issues with false consensus. From the ‘non-experts’ perspective, there were one issue with true consensus, four issues with dissensus, four issues with false conflict, and two issues with false consensus. From these co-orientation states, it was observed that the ‘experts’ generally performed poorly in predicting the ‘non-experts’ views and opinions (only one out of 11 statements had a high level of accuracy, the remaining 10 had low level of accuracy). On the other hand, the ‘non-experts’ generally performed better than the ‘experts’ in predicting the other party’s views and opinions (one statement with true consensus and four statements with dissensus).

Table 5.7. Arithmetic means of the participants' answers to the questions of the importance of different water resource management issues. * denotes *p*-value < 0.05 which indicates that the mean values of 'experts' vs. 'non-experts' responses, experts' prediction on non-experts' vs. non-experts' actual responses, and non-experts' prediction on experts vs. experts' actual responses were statistically significant (i.e., different).

"How important is/are … ?"	Agreement			Accuracy			
	Experts $\bar{X}$	Non-experts $\bar{X}$	*p*-value	Experts on non-experts $\bar{X}$	*p*-value	Non-experts on experts $\bar{X}$	*p*-value
				False conflict		***True consensus***	
… high capacity surface water withdrawals in MI	4.15	4.50	0.171	3.04	0.000*	3.67	0.062
				False conflict		***False conflict***	
… preserving & improving river/stream ecology and the environment	4.37	4.64	0.177	3.26	0.000*	3.83	0.008*
… preserving & improving surface water resources in MI	4.52	4.69	0.361	3.78	0.000*	3.79	0.000*
… users that withdraw large amounts of water in MI	4.26	4.38	0.633	3.26	0.000*	3.52	0.005*
… high capacity groundwater withdrawals in MI	4.19	4.64	0.054	2.93	0.000*	3.57	0.010*
				False consensus		***False consensus***	
… Great Lakes Basin water resources diversions	4.33	4.81	0.040*	3.44	0.000*	3.81	0.024*
				Dissensus		***False consensus***	
… right to access clean freshwater resources	4.22	4.76	0.024*	4.33	0.072	3.69	0.026*
				False consensus		***Dissensus***	
… sustainable water resource management and practices	4.19	4.67	0.023*	3.52	0.000*	3.81	0.075
… preserving & improving groundwater resources in MI	4.04	4.71	0.006*	3.04	0.000*	3.62	0.086
… water related outdoor & recreational activities	3.96	4.52	0.008*	3.93	0.000*	3.69	0.195
… the impact of hydraulic fracturing on water resources in Michigan	3.52	4.45	0.001*	3.52	0.001*	3.45	0.811

5.3.7 *Causes of Unsustainable Water Resource Management*

Here, both sets of participants were asked about issues that would cause unsustainable water resource consumption. Both sets of participants were asked to express their own views and

Table 5.8. Arithmetic means of the participants' answers to the questions regarding the importance of different issues that would cause unsustainable water resource consumption. * denotes p-value < 0.05 which indicates that the mean values of 'experts' vs. 'non-experts' responses, experts' prediction on non-experts' vs. non-experts' actual responses, and non-experts' prediction on experts vs. experts' actual responses were statistically significant (i.e., different).

	Agreement			Accuracy			
"… would cause unsustainable water resources consumption."	Experts $\bar{X}$	Non-experts $\bar{X}$	p-value	Experts on non-experts $\bar{X}$	p-value	Non-experts on experts $\bar{X}$	p-value
				True consensus		***True consensus***	
Residential related water withdrawals …	2.38	2.59	0.479	2.07	0.072	2.60	0.451
Extreme weather events …	3.11	3.35	0.409	2.81	0.068	3.09	0.938
				False conflict		***True consensus***	
Agricultural related water withdrawals …	3.81	3.55	0.328	2.85	0.010*	3.41	0.097
Global climate change …	3.70	3.78	0.757	3.26	0.044*	3.40	0.231
				Dissensus		***Dissensus***	
Hydraulic fracturing related water withdrawals …	2.70	4.16	0.000*	4.26	0.726	3.00	0.279
				False consensus		***Dissensus***	
Industrial activity related water withdrawals …	2.93	3.90	0.000*	3.30	0.018*	3.26	0.190
Water resource diversions from the Great Lakes Basin …	3.04	4.24	0.000*	3.57	0.018*	3.36	0.263
Lack of regulations …	3.08	4.00	0.003*	3.12	0.005*	3.28	0.516
Lack of regulation enforcement …	3.04	3.91	0.005*	3.19	0.020*	3.05	0.956

also predict the other party's views and their agreement and accuracy level were then subsequently measured. The 'experts' and the 'non-experts' did not entirely agree on whether some of the issues would cause unsustainable water resource management. For example, the 'experts' did not see hydraulic fracturing as an issue (experts' $\bar{X}$ = 2.7), whereas the 'non-experts' saw it as important issue (non-experts' $\bar{X}$ = 4.16) (see Table 5.8). This relationship also applies to other issues such as industrial activity related water withdrawals, Great Lakes water diversions, lack of regulations, and lack of enforcement of the regulations. However, both sets of study groups agreed, and they know the other group agreed that residential related water withdrawals were not impactful. From the ‘experts’ view point, it can be observed that there were two statements with true consensus, one statement with dissensus, two statements with false conflict, and four statements with false consensus. On the other hand, from the ‘non-experts’ view point, there were four statements with true consensus and five statements with dissensus. From these co-orientation states, it can be observed that the ‘non-experts’ had high agreement levels on all statements with the ‘experts’, but some of the accuracy levels were low. In contrast, there were some statements with low accuracy and low agreement from the experts’ perspective.

5.3.8 Level of Concern on Issues as a Result of Unsustainable Water Resource Management

Here, the survey question was about the level of concern regarding issues as a result of unsustainable water resource management in Michigan. Both sets of participants were asked to evaluate their own views as well as gave prediction on the other party’s view. The survey question measured both the agreement and accuracy from both sets of participants’ perspectives. both sets of study groups were asked about their own views and opinions and also what the other parties’ views and opinions would be on the level of concerns from the seven issues that would cause unsustainable water resource management. Table 5.9 shows the arithmetic means of participants’ responses to this question. From the experts’ perspectives, there were four statements with true consensus, two statements with false conflict, and one statement with false consensus. On the other hand, from the non-experts’ perspectives, there were three statements with true consensus, one statement with dissensus, and three statements with false conflict. These data suggest that both sets of participants had a decent understanding of each other as the agreement level between them was

Table 5.9. Arithmetic means of the participants’ answers to questions of different issues regarding sustainable water resource management. . * denotes p-value < 0.05 which indicates that the mean values of ‘experts’ vs. ‘non-experts’ responses, experts’ prediction on non-experts’ vs. non-experts’ actual responses, and non-experts’ prediction on experts vs. experts’ actual responses were statistically significant (i.e., different).

“I am concerned with … “	Agreement			Accuracy			
	Experts $\bar{X}$	Non-experts $\bar{X}$	p-value	Experts on non-experts $\bar{X}$	p-value	Non-experts on experts $\bar{X}$	p-value
				True consensus		***True consensus***	
… drop in groundwater levels and/or wells going dry.	4.07	4.24	0.546*	3.74	0.069	3.68	0.147
… extreme weather events that may impact water resources.	3.44	3.47	0.945*	3.44	0.945	3.88	0.151
				True consensus		***False conflict***	
… drop in surface water levels and/or surface water going dry.	4.48	4.07	0.131*	3.81	0.349	3.59	0.001*
… health risks related to water resources.	4.16	4.23	0.803*	4.12	0.699	3.43	0.014*
				False conflict		***True consensus***	
… deterioration in water quality.	4.11	4.44	0.212*	3.81	0.019*	3.85	0.335
				False conflict		***False conflict***	
… negative impacts and damages to stream ecology.	4.44	4.35	0.701*	3.07	0.000*	3.66	0.002*
				False consensus		***Dissensus***	
… competition in access to fresh water resources.	3.67	4.23	0.020	3.41	0.001*	3.55	0.634

high. However, in terms of accuracy, the ‘experts’ were only able to predict the ‘non-experts’ views on four of the seven statements, whereas, the ‘non-experts’ were only able to predict the ‘experts’ views on three of the seven statements.

5.4 Discussion

The objective of this study was to assess the degree of understanding and differences in perspective between ‘experts’ and ‘non-experts’ about water resource management in Michigan using a co-orientation approach. The study results suggest that ‘experts’ and ‘non-experts’ had different degree of understandings of the perspectives of the other party. Issues with false conflict, false consensus, or dissensus co-orientation states seemed to be correlated with more controversial water resource topics such as the Great Lakes water diversions and LQWs associated with agricultural, industrial, and hydraulic fracturing activities. For example, when both sets of participants were asked to express their agreement or disagreement level on 19 statements about sustainable water resource in Michigan, the issues with low agreement levels were largely about hydraulic fracturing and industrial water withdrawals. On these two particular issues, the ‘non-experts’ picked ‘strongly agree’ more than the ‘non-experts’ on their survey responses. In terms of the effectiveness and practicality of strategies for sustainable water resource management, the ‘experts’ knew which strategies are more feasible. The ‘non-experts’, on the other hand, tended to view most strategies as both practical and effective, without considering their feasibility. For example, the ‘experts’ agreed that regulating water withdrawals for hydraulic fracturing activities and auditing water use would be practical but ineffective. It would waste too much of the agencies’ limited resources to do them and there are alternative strategies that can achieve the same objectives. The non-experts, on the other hand, did not share this view.

Both sets of participants were found to have high agreement levels on many issues, but they also have both a reasonable and poor understanding of the other party’s perspectives depending on the survey questions. Both ‘experts’ and ‘non-experts’ agreed on many topics other than Great Lakes water diversions, water withdrawal associated with industrial activities, and also those associated with hydraulic fracturing activities. For these controversial topics, the ‘non-experts’ tended to view them as more important than the ‘experts’ and the ‘non-experts’ were able to predict the experts’ views. The ‘experts’, however, were not able to predict the non-experts’ views. The false conflict, false consensus, and dissensus states between ‘experts’ and ‘non-experts’ found support the level of controversies surrounding specific issues in the last couple years. As discussed previously in Chapter 1, communities in the Great Lakes Basin, particularly in Michigan, were concerned that Waukesha’s request for water diversions from the Great Lakes Basin would set the stage and used as a justification for other places that sit just outside the Great Lakes Basin borders to access the water resources from the basin (Ellison, 2016b, 2016a; Martinez, 2016; Mlive.com, 2016b; Samilton, 2016; Wells, 2016). Additionally, water withdrawals associated with hydraulic fracturing activities in Michigan was viewed as one of the most controversial environmental issues in recent years (Abbey-Lambertz, 2014; Burton et al., 2014, 2013; Ernstoff and Ellis, 2013b; Gregory et al., 2011; Guest, 2013; Krafcik, 2017; Kuwayama et al., 2015).

Discrepancies in views and opinions often correlate with the trust level between the participants (Cvetkovich and Winter, 2003; Siegrist et al., 2000; Vaske et al., 2007). The ‘experts’ inability to assess the ‘non-experts’ views and opinions could mean that the ‘experts’ might rely more on their personal experiences and values when taking into account the ‘non-experts’ views for decision making. The low level of accuracy and agreement between the two groups could result in potential conflict or unwillingness for future cooperation (Leahy and Anderson, 2008). Priorities for discussion might be given to issues with false consensus and false conflict states. It was found high agreement and high accuracy actually existed despite of the differences in several topics. This agreement could be used as a basic platform for discussion, initiate engagement, and improve communications where mutual interests were evident (Fisher et al., 2011). For example, disagreements about water withdrawal associated with hydraulic fracturing or industrial activities can be approached from the perspective that the main concern for both study groups is a potential drop in groundwater level and wells going dry. This kind of approach may improve the overall communication and understanding between the two parties.

For the regulator, information about areas of disagreement and low accuracy between the ‘experts’ and the ‘non-experts’ would help to (1) clarify necessary educational or outreach efforts to focus on; (2) understand the goals or priorities of the public; and (3) build more trust from the community as they feel more respected and needed when more participation and collaboration are desired. The same information would be beneficial to the public to (1) see the constraints and challenges faced by the ‘experts’; and (2) to identify specific topics that would resonate more strongly with the ‘experts’ for more effective advocacy and involvement in decision making (Basu et al., 2015a). Two-way collaborative cooperation and communication efforts often enhance relationships between different parties involved and improve the perceived legitimacy and trust among different groups (Chase et al., 2002; Lafon et al., 2004). Both groups know that mutual understanding is needed to promote positive collaboration. Open communication and interactions through discussion-based meetings, open houses, community events, and virtual communication through popular social media or internet forums can substantially improve this mutual understanding between the relevant parties. The additional time spent in involving the public on these topics may minimize future unnecessary public relation issues (Force and Forester, 2002; “Reframing public participation,” 2004). Having an improved understanding of the perceptions of the ‘non-experts’, an understanding of the similarities and the differences between the relevant parties, and acknowledgement of the ‘non-experts’ views, would be very beneficial for the ‘experts’ and other relevant agencies to guide community engagement and decision making with the same ultimate objective, i.e., to ensure the sustainable management of Michigan's water resources.

5.5 Acknowledgement

This work was supported in part by funding from the University of Michigan Water Center and from the National Science Foundation under grant number 1214416. The authors wish to thank Dr. Jason Duvall and Dr. Avik Basu of the University of Michigan for the inputs and the analysis of the survey results and Ms. Monica Day of Michigan State University Extension Office for helping to post the online survey form on the MSU Extension Office's website and distributing it to relevant participants.

CHAPTER 6

Conclusions and Future Work

6.1 Conclusions

Groundwater might be one of the most important but also one of the most undervalued natural resources. As the importance of groundwater as a water resource grows, it is essential to ensure that groundwater is utilized, allocated, and managed sustainably. Although surrounded by four of the five largest freshwater bodies in the world and considered as a water rich state, the State of Michigan is not without its own water resource management issues. This dissertation addresses groundwater management issues currently faced by Michigan. Chapters 2 and 3 focused on the groundwater model, one of the three models in the Water Withdrawal Assessment Tool (WWAT) used by the State of Michigan to permit large quantity water withdrawals (LQW). Chapters 4 and 5 addressed the environmental – social aspects of the groundwater management in Michigan, particularly how the ‘experts’ and ‘non-experts’ view the issue and the difference in perspectives between them.

Chapter 2 examined the modified Hunt (1999) analytical solution, utilized by the WWAT to estimate streamflow depletion. This evaluation was conducted by developing 3-D groundwater numerical models for two locations with different geologic settings in Michigan and comparing the resulting streamflow depletion values with those from the modified Hunt (1999) solution. The results showed that the modified Hunt (1999) analytical solution may not provide accurate estimates of streamflow depletion in a three-layered heterogeneous aquifer system (consisting of a glacial surficial aquifer on the top layer, followed by a clay aquitard and a semi-confined bedrock aquifer) when the pumping well is screened below the aquitard. The modified Hunt (1999) solution as utilized by the WWAT predicted an unrealistically large streamflow depletion of over five orders of magnitude larger than that produced by the numerical model. Although the result may be interpreted as conservative as its intent, some community considered that it was probably too conservative as some LQW requests in that area were denied and sent for site specific review. Through an uncertainty analysis, it was found that streambed conductance is the most sensitive parameter in estimating streamflow depletion. The WWAT assumed the streambed hydraulic conductivity of the stream of interest as 1/10 of the adjacent aquifer hydraulic conductivity. Furthermore, the WWAT uses the vertical distance from the stream to the top of the pumping well's screen as the streambed thickness. This approach yields unrealistically and artificially low streambed conductance values, subsequently underestimating streamflow depletion.

Based on the results in Chapter 2, it appeared that an analytical solution that considers three layers to reflect the typical stratigraphy of Michigan would be more suitable in evaluating sites similar to the Calhoun site where the well is screened below the aquitard. Moreover, it also appeared the most sensitive parameter, the streambed conductance, merit more detailed analysis. In Chapter 3, Ward and Lough's (2011) analytical solution was used as an alternative to estimate the streamflow depletion with a three-layered system. The study showed that the streamflow depletion estimated by the Ward and Lough (2011) solution at the site in Calhoun was much smaller and comparable with that estimated by the numerical model in Chapter 2. Streambed conductance depends on streambed hydraulic conductivity (K_S) which the WWAT assumes to be equal to 1/10 of the adjacent screened aquifer hydraulic conductivity. Since there are no available K_S values in Michigan (and there are only very few K_S measurement available in the U.S.) the parameter merit more detailed examination and how more accurate estimates could be generated. The work reported in Chapter 3 proposed using an area-weighted average of K_S values by soil type modified by land cover data from the contributing watershed area to estimate K_S. This approach was based on the principle that streambed sediments come from the soil eroded from the watershed area over long time frames. The estimated K_S values were then compared statistically with previously measured K_S values from 23 locations. It was found that the land cover-derived K_S approach provided better K_S estimates than the approach used by the WWAT. The resulting streamflow depletion at the Kalkaska site calculated using the modified Hunt (1999) solution using the land cover-derived K_S and at Calhoun using the Ward and Lough (2011) solution using the land cover-derived K_S was larger than that calculated based on the K_S from the WWAT. Both of them, however, were larger than the streamflow depletion estimated by the numerical model, mainly because the calibrated K_S from the numerical model was one to two orders of magnitude smaller. However, the calibrated K_S value for Kalkaska site in MODFLOW was at the lower range of the K_S values reported in the literature. This calibrated value was based on several modeling assumptions and limitation in the actual streamflow measurement. A field measurement might be necessary to validate the most accurate K_S values. However, in the absence of any field K_S measurements, K_S derived from soil and land cover maps may provide more accurate K_S values than using the method included in the WWAT.

As a common-pool resource, groundwater resource is expected to become even more important in the future and contentious communication between the relevant parties are anticipated to become more prevalent. Studies have shown that the key for an effective groundwater resource management is the involvement of both the resource managers and stakeholders to reach consensus. However, the general public generally insist that resource managers are more responsible, and as a result, understanding the state of mind and degree of understanding of the relevant stakeholders (i.e., both the regulators and the public) regarding groundwater management would be beneficial. In Chapter 4, the conceptual, content, and cognitive mapping (3CM) approach was used to develop cognitive maps to elucidate the mental models of the 'experts' and the 'non-experts' pertaining to groundwater resource management in Michigan. The 'experts' and the 'non-experts' were categorized based on their prior academic or professional experiences and therefore, 'experts' participant can be a member of the public and 'non-experts' participant can be member of the state government. The work reported in this dissertation found that both groups generally see groundwater resource management from four perspectives: (1) knowledge; (2) policy, laws, and regulations; (3) impacts; and (4) water users. The 'experts' were found to have a broad, yet detailed, knowledge about groundwater management, whereas, the 'non-experts' have a more general understanding and sometimes struggled to find more specific words to describe the phenomena. Furthermore, the 'experts' saw Michigan's regulatory approach as relatively sound, with the WWAT as a tool that could use some improvement. On the other hand, the 'non-experts' consider the WWAT as essentially synonymous with the regulation itself. The 'experts' also highlighted the importance of politics relative to science in enacting water regulations, a perspepctive missing from the 'non-experts' mental model. Finally, the 'non-experts' did not include agricultural water withdrawal as a large water user even though irrigation is the largest groundwater use category in Michigan. The reason behind this seeming contradiction was that farmers were considered as locals who would be more willing to compromise should a dispute occur. On the other hand, the 'experts' were focused more on the impact of large water usage on the environment, without regard to the exact nature of the use or the users, themselves.

In Chapter 5, co-orientation was used to understand the differences in perspectives regarding water resource management in Michigan between the ‘experts’ and the ‘non-experts’. The work reported in this chapter showed that both sets of study participants perceive each other incorrectly when asked about the importance of topics regarding water resource management in Michigan. This finding is particularly true for topics with false consensus and false conflict co-orientation states such as hydraulic fracturing activities, industrial water withdrawals, and Great Lakes water diversions. For these topics, the ‘non-experts’ participants were found to have a stronger response than the ‘experts’, suggesting that these topics were important for the ‘non-experts’ but not as important for the ‘experts’. The ‘experts’ saw water withdrawals associated with fracking and the industry as well regulated and the risks were already properly documented and anticipated. The study also suggested that the ‘non-experts’ tended to view most strategies as both effective and practical without considering the various limitations that might occur in implementation. For example, the ‘non-experts’ considered water use audit and regulating fracking water withdrawals to be both effective and practical. The ‘experts’ agreed that it would be effective, but considered as them as impractical These discrepancies underscore the topics with a potential for misunderstanding that could be addressed in future outreach strategies by regulators as well as by the public.

Collectively, this dissertation contributes to the improvement of groundwater resource management in Michigan from both technical and social aspects. The studies revealed that there is room for improvement in the WWAT as has been pointed out publicly by stakeholders. Chapters 2 and 3 in this dissertation offer some suggestions for improvement in the groundwater portion of the tool. From a technical standpoint, these would be relatively easy to implement in the existing framework, as they are based on an analytical model of groundwater flow, as is the current model, and draws data from publicly accessible databases, as does the current model. Chapters 4 and 5 elucidated and analyzed the similarities and discrepancies between ‘expert’ and ‘non-expert’ viewpoints using cognitive maps and co-orientation studies. This information could be utilized to prioritize issues, and to allocate resources for future outreach efforts or regulation development and implementation to bring both groups of stakeholders closer together regarding water resource management in Michigan.

6.2 Future Work

In the course of this research, several areas were found that merit more evaluation and analysis. These areas could further improve the management of groundwater in Michigan, supplementing the studies presented in this dissertation. In Chapter 2, the index flow measured by the WWAT for smaller streams that are more sensitive and prone to streamflow depletion were based on an extrapolation and regression analysis from 147 streamflow gage data from larger rivers. As discussed in Chapter 2, the measured streamflow at Black Creek in Kalkaska is much smaller than that estimated by the index flow model utilized by the WWAT. As a result, it would be beneficial to go to the field and measure the actual index flow of some of the smaller creeks like Dickinson Creek and possibly develop a separate extrapolation for these smaller creeks. Alternatively, geospatial analyses utilizing precipitation and land cover data could be used to estimate a more accurate index flow instead of using regression analysis based on known streamflow rates from large rivers. The streamflow rate at Dicksinson Creek was unknown and it was assumed to be the same as that measured at Black Creek. The actual value of Dickinson Creek’s streamflow rate may very well be different from that of Black Creek, resulting in a different value of streambed conductance and subsequently different streamflow depletion estimates.

In Chapter 3, after an extensive literature research, only 23 different measurement locations with a previously known or measured K_S values were located in the continental U.S., very few compared to the number of streams and creeks in the U.S. Moreover, none of these 23 locations are located in Michigan. In addition, we do not have actual streamflow depletion measurements as a result of LQW at a site. It would be interesting if field measurements could be conducted at both Black Creek and Dickinson Creek to confirm both the actual streamflow depletion estimated by the analytical as well as numerical models and the actual K_S to validate if the land cover-derived approach would provide accurate estimate of K_S values for streams in Michigan.

In Chapters 4 and 5, a random sampling with larger number of participants would better represent the ‘experts’ and the ‘non-experts’. In addition, it could be interesting to see how participants’ views may have changed given some of the latest events regarding water resource management in Michigan (e.g., the Great Lakes water resource diversion request for the City of Waukesha, WI, has been approved with conditions, Nestlé’s additional groundwater withdrawal request in Evart, MI has also been approved, hydraulic fracturing activities in Michigan has been put on hold due to the low gas prices). It would also be interesting for the regulators or the communities to hold public forums or meetings on some of the issues discussed in this study in order to prevent future communication breakdowns between them.

BIBLIOGRAPHY

Abbey-Lambertz, K., 2014. Not All Michiganders Want To Be A Dumping Ground For America's Radioactive Fracking Waste. Huffington Post.

Absher, J.D., McAvoy, L.H., Burdge, R.J., Gramann, J.H., 1988. Public and commercial managers predicting recreationist opinions. J. Park Recreat. Adm. 6, 66–77.

Aldenderfer, M.S., Blashfield, R.K., 1984. Cluster Analysis. Sage University Paper Series On Quantitative Applications in the Social Sciences 07-044. Sage Publications, Beverly Hills.

Alexander, J., 2013. Bridge : Water, water everywhere in Michigan – but is it enough? Bridge Mag.

Allen, G.H., Pavelsky, T.H., 2015. Patterns of river width and surface area revealed by the satellite-derived North American River Width data set. Geophys. Res. Lett. 42, 395–402.

Anderson, M.P., 2005. Heat as a Ground Water Tracer. Groundwater 43, 951–968. https://doi.org/10.1111/j.1745-6584.2005.00052.x

Arcement, G.J., Schneider, V.R., 1990. Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains (Water Supply Paper No. 2339). U.S. Geological Survey.

Avery, E., Lariscy, R., Sweetser, K.D., 2010. Social Media and Shared—or Divergent—Uses? A Coorientation Analysis of Public Relations Practitioners and Journalists. Int. J. Strateg. Commun. 4, 189–205. https://doi.org/10.1080/1553118X.2010.489501

Baker, M.E., Wiley, M.J., Seelbach, P.W., Carlson, M.L., 2003. A GIS Model of Subsurface Water Potential for Aquatic Resource Inventory, Assessment, and Environmental Management. Environ. Manage. 32, 706–719. https://doi.org/10.1007/s00267-003-0018-1

Barlow, P.M., DeSimone, L.A., Moench, A.F., 2000. Aquifer response to stream-stage and recharge variations. II. Convolution method and applications. J. Hydrol. 230, 211–229. https://doi.org/10.1016/S0022-1694(00)00176-1

Barlow, P.M., Leake, S.A., 2012. Streamflow Depletion by Wells Understanding and Managing the Effects of Groundwater Pumping on Streamflow (Circular No. 1376). U.S. Geological Survey, Reston, Virginia.

Basu, A., Duvall, J., Carman, J., 2015a. Stuck in the Muck: Comparing how experts and local communities see beach muck in the Great Lakes. Presented at the International Symposium on Society and Resource Management, Ann Arbor, MI.

Basu, A., Kaplan, R., Duvall, J., 2015b. Stuck in the Muck: Comparing how experts and local communities see beach muck in the Great Lakes.

Baxter, C., Hauer, F.R., Woessner, W.W., 2011. Measuring Groundwater–Stream Water Exchange: New Techniques for Installing Minipiezometers and Estimating Hydraulic Conductivity. Trans. Am. Fish. Soc. 132, 493–502. https://doi.org/10.1577/1548-8659(2003)132<0493:MGWENT>2.0.CO;2

Best, L.C., Lowry, C.S., 2014. Quantifying the potential effects of high-volume water extractions on water resources during natural gas development: Marcellus Shale, NY. J. Hydrol. Reg. Stud. 1, 1–16. https://doi.org/10.1016/j.ejrh.2014.05.001

Binley, A., Hubbard, S.S., Huisman, J.A., Revil, A., Robinson, D.A., Singha, K., Slater, L.D., 2015. The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. Water Resour. Res. 51, 3837–3866. https://doi.org/10.1002/2015WR017016

Bradley, G.A., Kearney, A.R., 2007. Public and Professional Responses to the Visual Effects of Timber Harvesting: Different Ways of Seeing. West. J. Appl. For. 22, 42–54.

Brunner, P., Therrien, R., Renard, P., Simmons, C.T., Franssen, H.-J.H., 2017. Advances in understanding river-groundwater interactions. Rev. Geophys. 55, 818–854. https://doi.org/10.1002/2017RG000556

Burton, G.A., Basu, N., Ellis, B.R., Kapo, K.E., Entrekin, S., Nadelhoffer, K., 2014. Hydraulic “Fracking”: Are surface water impacts an ecological concern? Environ. Toxicol. Chem. 33, 1679–1689. https://doi.org/10.1002/etc.2619

Burton, G.A., Nadelhoffer, K.J., Presley, K., 2013. Hydraulic Fracturing in The State of Michigan; Environmental/Ecology Technical Report (No. 4), GRAHAM SUSTAINABILITY INSTITUTE INTEGRATED ASSESSMENT REPORT SERIES. University of Michigan Graham Sustainability Institute, Ann Arbor, MI.

Butler, J.J., Zlotnik, V.A., Tsou, M.-S., 2001. Drawdown and Stream Depletion Produced by Pumping in the Vicinity of a Partially Penetrating Stream. Ground Water 39, 651–659. https://doi.org/10.1111/j.1745-6584.2001.tb02354.x

Calver, A., 2001. Riverbed Permeabilities: Information from Pooled Data. Groundwater 39, 546–553. https://doi.org/10.1111/j.1745-6584.2001.tb02343.x

Cardenas, M.B., Zlotnik, V.A., 2005. A Simple Constant-Head Injection Test for Streambed Hydraulic Conductivity Estimation. Groundwater 41, 867–871. https://doi.org/10.1111/j.1745-6584.2003.tb02428.x

Cardenas, M.B., Zlotnik, V.A., 2003. Three-dimensional model of modern channel bend deposits. Water Resour. Res. 39. https://doi.org/10.1029/2002WR001383

Carrozzino-Lyon, A.L., McMullin, S.L., Parkhurst, J.A., 2014. Co-orientation of State Wildlife Agency Personnel and Wildlife Management Area Stakeholders Regarding Wildlife Habitat Management Activities in Virginia. Environ. Commun. 8, 508–528. https://doi.org/10.1080/17524032.2014.955038

Chase, L.C., Siemer, W.F., Decker, D.J., 2002. Designing Stakeholder Involvement Strategies to Resolve Wildlife Management Controversies. Wildl. Soc. Bull. 1973-2006 30, 937–950.

Chen, X., 2005. Statistical and geostatistical features of streambed hydraulic conductivities in the Platte River, Nebraska. Environ. Geol. 48, 693–701. https://doi.org/10.1007/s00254-005-0007-1

Chen, X., 2000. Measurement of streambed hydraulic conductivity and its anisotropy. Environ. Geol. 39, 1317–1324. https://doi.org/10.1007/s002540000172

Chen, X., Yin, Y., 1999. Evaluation of streamflow depletion for vertical anisotropic aquifers. J. Environ. Syst. 27, 55–70.

Cho, M., Kelly, K.S., 2014. Corporate Donor–Charitable Organization Partners: A Coorientation Study of Relationship Types. Nonprofit Volunt. Sect. Q. 43, 693–715. https://doi.org/10.1177/0899764013480566

Christensen, S., 2000. On the estimation of stream flow depletion parameters by drawdown analysis. Groundwater 38, 726–734. https://doi.org/10.1111/j.1745-6584.2000.tb02708.x

Chu, A., 2006. Hydrogeology of the Lloyd Aquifer on Long Island, New York–A Brief Summary of USGS Investigations (Open-File Report No. 2006–1341). U.S. Geological Survey, Coram, NY.

Connelly, N.A., Knuth, B.A., 2002. Using the Coorientation Model to Compare Community Leaders' and Local Residents' Views About Hudson River Ecosystem Restoration. Soc. Nat. Resour. 15, 933–948. https://doi.org/10.1080/08941920290107666

Constantz, J., 2008. Heat as a tracer to determine streambed water exchanges. Water Resour. Res. 44. https://doi.org/10.1029/2008WR006996

Cook, G., Pieri, E., Robbins, P.T., 2004. "The scientists think and the public feels": expert perceptions of the discourse of GM food. Discourse Soc. 15, 433–449.

Cott, P.A., Sibley, P.K., Somers, W.M., Lilly, M.R., Gordon, A.M., 2008. A Review of Water Level Fluctuations on Aquatic Biota With an Emphasis on Fishes in Ice-Covered Lakes1.

JAWRA J. Am. Water Resour. Assoc. 44, 343–359. https://doi.org/10.1111/j.1752-1688.2007.00166.x

Cutlip, S.M., Center, A.H., Broom, G.M., 2012. Effective public relations, 8th ed. Prentice Hall, Upper Saddle River, NJ.

Cvetkovich, G., Winter, P.L., 2003. Trust And Social Representations Of The Management Of Threatened And Endangered Species. Environ. Behav. 35, 286–307. https://doi.org/10.1177/0013916502250139

Day, M., 2017. 15 minutes today to help ensure freshwater for tomorrow [WWW Document]. MSU Ext. URL http://www.canr.msu.edu/news/15_minutes_today_to_help_ensure_freshwater_for_tomorrow

de Lima, V., 1991. Stream-Aquifer Relations and Yield of Stratified Drift Aquifers in the Nashua River Basin, Massachusetts (Water Resources Investigations Report No. 88–4147). U.S. Geological Survey, Boston, MA.

Delinom, R.M., 2017. Groundwater management issues in the Greater Jakarta area, Indonesia. Bull. Terr. Environ. Res. Cent. Univ. Tsukuba Int. Workshop Integr. Watershed Manag. Sustain. Water Use Humid Trop. Reg. Proc. 8, 40–54.

Dennehy, K.F., Litke, D.W., McMahon, P.B., 2002. The High Plains Aquifer, USA: groundwater development and sustainability. Geol. Soc. Lond. Spec. Publ. 193, 99–119. https://doi.org/10.1144/GSL.SP.2002.193.01.09

Dieter, C., Maupin, M.A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Barber, N.L., Linsey, K.S., 2018. Estimated Use of Water in the United States in 2015 (USGS Open-File Report No. 1131), Circular. U.S. Geological Survey, Reston, VA.

Dietz, T., Ostrom, E., Stern, P.C., 2003. The Struggle to Govern the Commons. Science 302, 1907–1912. https://doi.org/10.1126/science.1091015

Dozier, D.M., Grunig, L.A., Grunig, J.E., 2013. Manager's Guide to Excellence in Public Relations and Communication Management. Routledge.

Duwelius, R.F., 1996. Hydraulic conductivity of the streambed, east branch Grand Calumet River, northern Lake County, Indiana (Water Resources Investigations Report No. 96–4218). U.S. Geological Survey, Indianapolis, IN.

Eisenberg, E.M., Monge, P.R., Farace, R.V., 1984. Coorientation on Communication Rules in Managerial Dyads. Hum. Commun. Res. 11, 261–271. https://doi.org/10.1111/j.1468-2958.1984.tb00048.x

Ellison, G., 2017. Reject Nestle water permit, say two Michigan House Democrats [WWW Document]. Mlive.com. URL http://www.mlive.com/news/index.ssf/2017/03/nestle_resolutions_oppose.html

Ellison, G., 2016a. Great Lakes mayors plan legal challenge to Waukesha water approval [WWW Document]. Mlive.com. URL http://www.mlive.com/news/index.ssf/2016/08/great_lakes_mayors_plan_legal.html

Ellison, G., 2016b. Waukesha hasn't proven it needs Lake Michigan water, says Michigan AG [WWW Document]. MLive.com. URL http://www.mlive.com/news/index.ssf/2016/03/michigan_waukesha_diversion.html (accessed 10.17.17).

Ernstoff, A.S., Ellis, B.R., 2013a. Clearing the waters of the fracking debate. Mich. J. Sustain. 1, 109–129.

Ernstoff, A.S., Ellis, B.R., 2013b. Clearing the waters of the fracking debate. Mich. J. Sustain. 1, 109–129.

Feng, W., Zhong, M., Lemoine, J.-M., Biancale, R., Hsu, H.-T., Xia, J., 2013. Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. Water Resour. Res. 49, 2110–2118. https://doi.org/10.1002/wrcr.20192

Ferrand, W.R., Bell, D.L., Wilson, S.E., 1982. Quaternary Geology of Michigan. Geological Survey Division.

Fisher, R., Wingle, W., Patton, B., 2011. Getting to yes: Negotiating agreement without giving in. Penguin Book, New York.

Fleckenstein, J.H., Niswonger, R.G., Fogg, G.E., 2006. River-Aquifer Interactions, Geologic Heterogeneity, and Low-Flow Management. Groundwater 44, 837–852. https://doi.org/10.1111/j.1745-6584.2006.00190.x

Force, J.E., Forester, D.J., 2002. Public involvement in National Park Service land management issues. Soc. Sci. Res. Rev. 3.

Foster, S., Garduño, H., 2012. Groundwater-resource governance: Are governments and stakeholders responding to the challenge? Hydrogeol. J. 21, 317–320. https://doi.org/10.1007/s10040-012-0904-9

Foster, S., Hirata, R., Vidal, A., Schmidt, G., Garduño, H., 2009. The Guarani Aquifer Initiative – Towards Realistic Groundwater Management in a Transboundary Context.

Fox, G.A., 2007. Estimating streambed conductivity: guidelines for stream-aquifer analysis tests. Trans. ASABE 50, 107–113. https://doi.org/10.13031/2013.22416

Fox, G.A., 2003. Estimating streambed and aquifer parameters from a stream/aquifer analysis test. Hydrol. Days 68–79.

Fox, G.A., Heeren, D.M., Kizer, M.A., 2011. Evaluation of Stream-Aquifer Analysis Test for Deriving Reach-Scale Streambed Conductance. Trans. ASABE 54, 473–479. https://doi.org/10.13031/2013.36450

Gamba, R.J., Oskamp, S., 1994. Factors influencing community residents' participation in commingled curbside recycling programs. Environ. Behav. 26, 587–612.

Gellis, A.C., Hupp, C.R., Pavich, M.J., Landwehr, J.M., Banks, W.S.L., Hubbard, B.E., Langland, M.J., Ritchie, J.C., Reuter, J.M., 2009. Sources, Transport, and Storage of Sediment at Selected Sites in the Chesapeake Bay Watershed (Scientific Investigations Report No. 2008–5186). U.S. Geological Survey, Reston, VA.

Gellis, A.C., Noe, G.B., 2013. Sediment source analysis in the Linganore Creek watershed, Maryland, USA, using the sediment fingerprinting approach: 2008 to 2010. J. Soils Sediments 13, 1735–1753. https://doi.org/10.1007/s11368-013-0771-6

Genereux, D.P., Leahy, S., Mitasova, H., Kennedy, C.D., Corbett, D.R., 2008. Spatial and temporal variability of streambed hydraulic conductivity in West Bear Creek, North Carolina, USA. J. Hydrol. 358, 332–353. https://doi.org/10.1016/j.jhydrol.2008.06.017

Gerstein, M., 2017. Nestle's bid for more water withdrawal riles residents [WWW Document]. Detroit News. URL http://www.detroitnews.com/story/news/environment/2017/04/12/nestles-bid-water-withdrawal-riles-residents/100401374/

Getches, D., Zellmer, S., Amos, A., 2015. Water Law in a Nutshell, 5th ed. West Academic.

Gibson, H., Stewart, I.S., Pahl, S., Stokes, A., 2016. A "mental models" approach to the communication of subsurface hydrology and hazards. Hydrol. Earth Syst. Sci. Katlenburg-Lindau 20, 1737–1749. http://dx.doi.org/10.5194/hess-20-1737-2016

Gilchrist, T., 2010. Merrill-area family blames "corporate" farmer's irrigation system after well goes dry [WWW Document]. Saginaw News. URL http://www.mlive.com/news/saginaw/index.ssf/2010/07/merrill-area_family_blames_cor.html

Glover, R.E., Balmer, G.G., 1954. River depletion resulting from pumping a well near a river. Eos Trans. Am. Geophys. Union 35, 468–470. https://doi.org/10.1029/TR035i003p00468

Grannemann, N.G., Hunt, R.J., Nicholas, J.R., Reilly, T.E., Winter, T.C., 2000. The Importance of Ground Water in the Great Lakes Region (Water Resources Investigations Report No. 00–4008). U.S. Geological Survey, Lansing, MI.

Gray, K., 2018. Michigan OKs Nestlé permit for increased water withdrawal for bottled water plant [WWW Document]. Detroit Free Press. URL https://www.freep.com/story/news/2018/04/02/michigan-oks-nestle-permit-increased-water-withdrawal-bottled-water-plant/479896002/ (accessed 7.6.18).

Gregory, K.B., Vidic, R.D., Dzombak, D.A., 2011. Water Management Challenges Associated with the Production of Shale Gas by Hydraulic Fracturing. Elements 7, 181–186. https://doi.org/10.2113/gselements.7.3.181

Grunig, J.E., 2001. Two-way symmetrical public relations: Past, present, and future, Handbook of public relations.

Guest, G., 2013. Fracking brings economic boost, but risks raise concerns [WWW Document]. Univ. Mich. News. URL http://ns.umich.edu/new/releases/21460-fracking-brings-economic-boost-but-risks-raise-concerns (accessed 12.1.17).

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., Weeks, J.B., 1984. Geohydrology of the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (USGS Numbered Series No. 1400- B), Professional Paper.

Hamilton, D.A., Seelbach, P.W., 2011. Michigan's Water Withdrawal Assessment Process and Internet Screening Tool (No. 55), Fisheries Special Report. Michigan Deparment of Natural Resources, Lansing, MI.

Hamilton, D.A., Sorrell, R.C., Holtschlag, D.J., 2008. A Regression Model for Computing Index Flows Describing the Median Flow for the Summer Month of Lowest Flow in Michigan (Scientific Investigations Report No. 5096). U.S. Geological Survey, Reston, Virginia.

Hantush, M.S., 1965. Wells near streams with semipervious beds. J. Geophys. Res. 70, 2829–2838. https://doi.org/10.1029/JZ070i012p02829

Hodge, R.A., Hoey, T.B., Sklar, L.S., 2011. Bed load transport in bedrock rivers: The role of sediment cover in grain entrainment, translation, and deposition. J. Geophys. Res. Earth Surf. 116. https://doi.org/10.1029/2011JF002032

Hunt, B., 2014. Review of Stream Depletion Solutions, Behavior, and Calculations. J. Hydrol. Eng. 19, 167–178. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000768

Hunt, B., 2003. Unsteady Stream Depletion when Pumping from Semiconfined Aquifer. J. Hydrol. Eng. 8, 12–19.

Hunt, B., 1999. Unsteady Stream Depletion from Ground Water Pumping. Ground Water 37, 98–102. https://doi.org/10.1111/j.1745-6584.1999.tb00962.x

Hyndman, D.W., 2013. Preliminary Analysis of Fracking and Flows in Upper Manistee River.

Isiorho, S.A., Meyer, J.H., 1999. The Effects of Bag Type and Meter Size on Seepage Meter Measurements. Groundwater 37, 411–413. https://doi.org/10.1111/j.1745-6584.1999.tb01119.x

Jackson, R.B., Vengosh, A., Carey, J.W., Davies, R.J., Darrah, T.H., O'Sullivan, F., Pétron, G., 2014. The Environmental Costs and Benefits of Fracking. Annu. Rev. Environ. Resour. 39, 327–362.

Jacobson, C.A., Decker, D.J., Carpenter, L., 2007. Securing Alternative Funding for Wildlife Management: Insights from Agency Leaders. J. Wildl. Manag. 71, 2106–2113. https://doi.org/10.2193/2006-442

Jayawan, I.S., Demond, A., Ellis, B., 2016. Emerging investigators series: using an analytical solution approach to permit high volume groundwater withdrawals. Environ. Sci. Water Res. Technol. 2, 942–952. https://doi.org/10.1039/C6EW00108D

Kaffer, N., 2017. Nestle wants more Michigan water [WWW Document]. Detroit Free Press. URL http://www.freep.com/story/opinion/columnists/nancy-kaffer/2017/03/07/nestle-michigan-water/98696462/

Kalbus, E., Reinstorf, F., Schirmer, M., 2006. Measuring methods for groundwater ? surface water interactions: a review. Hydrol. Earth Syst. Sci. Discuss. 10, 873–887.

Kaplan, R., Basu, A., 2015. 3CM: A Tool for Knowing "Where They're At," in: Fostering Reasonableness: Supportive Environments for Bringing Out Our Best. Michigan Publishing, University of Michigan Library, Ann Arbor, MI.

Kearney, A.R., Bradley, G., Kaplan, R., Kaplan, S., 1999. Stakeholder Perspectives on Appropriate Forest Management in the Pacific Northwest. For. Sci. 45, 62–73.

Kearney, A.R., Kaplan, S., 1997. Toward a Methodology for the Measurement of Knowledge Structures of Ordinary People The Conceptual Content Cognitive Map (3CM). Environ. Behav. 29, 579–617. https://doi.org/10.1177/0013916597295001

Kelly, K.S., Thompson, M.F., Waters, R.D., 2006. Improving the Way We Die: A Coorientation Study Assessing Agreement/Disagreement in the Organization–Public Relationship of Hospices and Physicians. J. Health Commun. 11, 607–627. https://doi.org/10.1080/10810730600830047

Kennedy, C.D., Murdoch, L.C., Genereux, D.P., Corbett, D.R., Stone, K., Pham, P., Mitasova, H., 2010. Comparison of Darcian flux calculations and seepage meter measurements in a sandy streambed in North Carolina, United States. Water Resour. Res. 46. https://doi.org/10.1029/2009WR008342

Kollet, S.J., Zlotnik, V.A., 2007. Evaluation of the streambed leakage concept in analytical models using data from three pumping tests. Hydrogeol. J. 15, 1051–1062. https://doi.org/10.1007/s10040-006-0156-7

Krafcik, M., 2017. Environmental activists raise concern over fracking proposal in Barry County [WWW Document]. WWMT. URL http://wwmt.com/news/local/environmental-activists-raise-concern-over-fracking-proposal-in-barry-county (accessed 12.1.17).

Kukla, M., 2012. Huge glacial aquifer under Ottawa County shrinking from overuse, water study finds [WWW Document]. Mlive.com. URL http://www.mlive.com/news/grand-rapids/index.ssf/2012/12/huge_glacial_aquifer_under_ott.html

Kuwayama, Y., Olmstead, S., Krupnick, A., 2015. Water Quality and Quantity Impacts of Hydraulic Fracturing. Curr. Sustain. Energy Rep. 2, 17–24. https://doi.org/10.1007/s40518-014-0023-4

Lackey, G., Neupauer, R.M., Pitlick, J., 2015a. Effects of Streambed Conductance on Stream Depletion. Water 7, 271–287. https://doi.org/10.3390/w7010271

Lackey, G., Neupauer, R.M., Pitlick, J., 2015b. Effects of Streambed Conductance on Stream Depletion. Water 7, 271–287. https://doi.org/10.3390/w7010271

Lafon, N.W., McMullin, S.L., Steffen, D.E., Schulman, R.S., 2004. Improving stakeholder knowledge and agency image through collaborative planning. Wildl. Soc. Bull. 32, 220–231. https://doi.org/10.2193/0091-7648(2004)32[220:ISKAAI]2.0.CO;2

LaFond, K., 2014. Waukesha Presses First Test of Great Lakes Water Compact [WWW Document]. Circ. Blue. URL http://www.circleofblue.org/2014/world/waukesha-presses-first-test-great-lakes-water-compact/ (accessed 3.14.17).

Lamba, J., Thompson, A.M., Karthikeyan, K.G., Fitzpatrick, F.A., 2015. Sources of fine sediment stored in agricultural lowland streams, Midwest, USA. Geomorphology 236, 44–53. https://doi.org/10.1016/j.geomorph.2015.02.001

Landon, M.K., Rus, D.L., Harvey, F.E., 2001. Comparison of Instream Methods for Measuring Hydraulic Conductivity in Sandy Streambeds. Groundwater 39, 870–885. https://doi.org/10.1111/j.1745-6584.2001.tb02475.x

Langfield-Smith, K., 1992. Exploring the Need for a Shared Cognitive Map. J. Manag. Stud. 29, 349–368. https://doi.org/10.1111/j.1467-6486.1992.tb00669.x

Leahy, J.E., Anderson, D.H., 2008. Trust factors in community–water resource management agency relationships. Landsc. Urban Plan. 87, 100–107. https://doi.org/10.1016/j.landurbplan.2008.05.004

Leong, K.M., McComas, K.A., Decker, D.J., 2008. Formative Coorientation Research: A Tool to Assist with Environmental Decision Making. Environ. Commun. 2, 257–273. https://doi.org/10.1080/17524030802389922

Leuschner, W.A., Ritchie, V.P., Stauffer, D.F., 1989. Opinions on Wildlife: Responses of Resource Managers and Wildlife Users in the Southeastern United States. Wildl. Soc. Bull. 1973-2006 17, 24–29.

Lichtenberg, E., Lessley, B.V., 1992. Water quality, cost-sharing, and technical assistance: Perceptions of Maryland farmers. J. Soil Water Conserv. 47, 260–264.

Lu, C., Chen, X., Cheng, C., Ou, G., Shu, L., 2011. Horizontal hydraulic conductivity of shallow streambed sediments and comparison with the grain-size analysis results. Hydrol. Process. 26, 454–466. https://doi.org/10.1002/hyp.8143

Lubbers, C.A., 2005. Media Relations in the Travel and Tourism Industry: A Coorientation Analysis. J. Hosp. Leis. Mark. 12, 41–55. https://doi.org/10.1300/J150v12n01_04

Lui, E., 2013. Kalkaska County: The centre of fracking in the Great Lakes Basin [WWW Document]. FLOW Love Water. URL http://flowforwater.org/kalkaska-county-the-centre-of-fracking-in-the-great-lakes-basin/ (accessed 9.26.18).

Luukkonen, C.L., Blumer, S.P., Weaver, T.L., Jean, J., 2004. Simulation of the ground-water-flow system in the Kalamazoo County area, Michigan (USGS Numbered Series No. 2004–5054), Scientific Investigations Report. U.S. Geological Survey, Reston, VA.

Mahler, R.L., Simmons, R., Sorensen, F., 2006. Public Perceptions and Actions towards Sustainable Groundwater Management in the Pacific Northwest Region, USA. Int. J. Water Resour. Dev. 21, 465–472. https://doi.org/10.1080/07900620500036604

Margat, J., Van der Gun, J., 2013. Groundwater around the world: a geographic synopsis. CRC Press.

Martinez, S., 2016. Great Lakes group challenges Waukesha's water diversion [WWW Document]. Waukesha Now. URL http://www.waukeshanow.com/story/news/local/2016/08/29/group-challenges-waukesha-water-diversion/89546068/

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., Linsey, K.S., 2014. Estimated Use of Water in the United States in 2010 (USGS Open-File Report No. 1405), Circular. U.S. Geological Survey, Reston, VA.

McClymonds, N.E., Franke, O.L., 1972. Water-Transmiting Properties of Aquifers on Long Island, New York (Geological Survey Professional Paper No. 627- E). U.S. Geological Survey, Washington, D.C.

McGuire, V.L., Johnson, M.R., Schieffer, R.L., Stanton, J.S., Sebree, S.K., Verstraeten, I.M., 2003. Water in storage and approaches to ground-water management, High Plains aquifer, 2000 (Circular No. 1243). U.S. Geological Survey, Reston, VA.

McLeod, J.M., Chaffee, S.H., 1973. Interpersonal Approaches to Communication Research. Am. Behav. Sci. 16, 469–499. https://doi.org/10.1177/000276427301600402

McMahon, P.B., Plummer, L.N., Böhlke, J.K., Shapiro, S.D., Hinkle, S.R., 2011. A comparison of recharge rates in aquifers of the United States based on groundwater-age data. Hydrogeol. J. 19, 779–800. https://doi.org/10.1007/s10040-011-0722-5

Megdal, S.B., Gerlak, A.K., Varady, R.G., Huang, L.Y., 2014. Groundwater Governance in the United States: Common Priorities and Challenges. Groundwater 53, 677–684. https://doi.org/10.1111/gwat.12294

Meyer, W., 1978. Hydraulic Characteristics of the White River Streambed and Glacial Outwash Deposits at a Site Near Indianapolis, Indiana. J. Res. US Geol. Surv. 6, 273–283.

Michigan Department of Environmental Quality, 2000. Wellogic. Lansing, MI.

Michigan Department of Environmental Quality, n.d. Accessing the Watershed Accounting Table [WWW Document]. Mich. Water Withdrawal Assess. Tool. URL http://www.deq.state.mi.us/wwat/(S(5ogaomj0m5hxoehw1jbhu5fe))/xmldata.aspx (accessed 7.9.18a).

Michigan Department of Environmental Quality, n.d. Michigan WWAT Watershed Accounting Table. Lansing, MI.

Michigan Department of Environmental Quality, U.S. Geological Survey, Michigan State University, 2006a. Groundwater Inventory and Map Project (Technical Report).

Michigan Department of Environmental Quality, U.S. Geological Survey, Michigan State University, 2006b. Groundwater Inventory and Map Project (Technical Report).

Michigan Legislature, 2008.

Min, L., Yu, J., Liu, C., Zhu, J., Wang, P., 2013. The spatial variability of streambed vertical hydraulic conductivity in an intermittent river, northwestern China. Environ. Earth Sci. 69, 873–883. https://doi.org/10.1007/s12665-012-1973-8

Mlive.com, 2016a. 8 cities that could apply for Great Lakes water [WWW Document]. MLive.com. URL http://www.mlive.com/news/index.ssf/2016/08/waukesha_other_straddling_comm.html (accessed 10.17.17).

Mlive.com, 2016b. Reaction to Wisconsin city's OK for Great Lakes water [WWW Document]. MLive.com. URL http://www.mlive.com/news/index.ssf/2016/06/waukesha_diversion_reaction.html

Morgan, M.G., Fischhoff, B., Bostrom, A., Atman, C.J., 2002. Risk communication: a mental models approach. Cambridge University Press, Cambridge, United Kingdom.

Morris, D.A., Johnson, A.I., 1967. Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geological Survey, 1948-60 (USGS Numbered Series No. 1839- D), Water Supply Paper. U.S. Govt. Print. Off.,.

Mukundan, R., Radcliffe, D.E., Ritchie, J.C., Risse, L.M., McKinley, R.A., 2010. Sediment Fingerprinting to Determine the Source of Suspended Sediment in a Southern Piedmont Stream. J. Environ. Qual. 39, 1328–1337. https://doi.org/10.2134/jeq2009.0405

Murtagh, F., Legendre, P., 2014. Ward's Hierarchical Clustering Method: Clustering Criterion and Agglomerative Algorithm. J. Classif. 31, 274–295. https://doi.org/10.1007/s00357-014-9161-z

Musca, C., 2014. Coorientation Through Written Communication: A case study from the print industry.

National Park Service, n.d. Mississippi River Facts [WWW Document]. Miss. River Facts. URL https://www.nps.gov/miss/riverfacts.htm (accessed 9.11.18).

Norris, S.E., 1983. Aquifer Tests and Well Field Performance, Scioto River Valley, Ohio: Part IIa. Groundwater 21, 438–444. https://doi.org/10.1111/j.1745-6584.1983.tb00745.x

North Carolina Department of Environmental Quality, 2000. Aquifer Characteristics Database Detail for Moss Hill. North Carolina Department of Environmental Quality.

Ostrom, E., 1990. Governing the commons: the evolution of institutions for collective action. Cambridge University Press, Cambridge, United Kingdom.

Özesmi, U., Özesmi, S.L., 2004. Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. Ecol. Model. 176, 43–64. https://doi.org/10.1016/j.ecolmodel.2003.10.027

Pahl-Wostl, C., Hare, M., 2004. Processes of social learning in integrated resources management. J. Community Appl. Soc. Psychol. 14, 193–206. https://doi.org/10.1002/casp.774

Polizzotto, M.L., Kocar, B.D., Benner, S.G., Sampson, M., Fendorf, S., 2008. Near-surface wetland sediments as a source of arsenic release to ground water in Asia. Nature 454, 505–508. https://doi.org/10.1038/nature07093

Post, V.E.., 2005. Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead? Hydrogeol. J. 13, 120–123. https://doi.org/10.1007/s10040-004-0417-2

Prince, K.H., Franke, O.L., Reilly, T.E., 1988. Quantitative Assessment of the Shallow Ground-Water Flow System Associated with Connetquot Brook, Long Island, New York (Water Supply Paper No. 2309). U.S. Geological Survey.

Prudic, D.E., Konikow, L.F., Banta, E.R., 2004. A New Streamflow-Routing (SFR1) Package to Simulate Stream-Aquifer Interaction with MODFLOW-2000 (USGS Numbered Series No. 2004–1042), Open-File Report.

Purwoarminta, A., Moosdorf, N., Delinom, R.M., 2018. Investigation of groundwater-seawater interactions: a review, in: IOP Conf. Series: Earth and Environmental Science. Presented at the Global Colloquium on GeoSciences and Engineering 2017, IOP Publishing Ltd, Bandung, Indonesia. https://doi.org/10.1088/1755-1315/118/1/012017

Rahm, B.G., Riha, S.J., 2014. Evolving shale gas management: water resource risks, impacts, and lessons learned. Env. Sci Process. Impacts 16, 1400–1412.

Reed, R.C., Daniels, J., 1987. Bedrock geology of northern Michigan: Michigan Department of Natural Resources. Geol. Surv. Div. Scale 1.

Reeves, H.W., 2008. STRMDEPL08—An Extended Version of STRMDEPL with Additional Analytical Solutions to Calculate Streamflow Depletion by Nearby Pumping Wells (Open-File Report No. 1166). U.S. Geological Survey, Reston, Virginia.

Reeves, H.W., Hamilton, D.A., Seelbach, P.W., Asher, A.J., 2009. Ground-Water-Withdrawal Component of the Michigan Water-Withdrawal Screen Tool (Scientific Investigations Report No. 5003). U.S. Geological Survey, Reston, Virginia.

Reframing public participation: strategies for the 21st century, 2004. . Plan. Theory Pract. 5, 419–436. https://doi.org/10.1080/1464935042000293170

Reilly, T.E., Dennehy, K.F., Alley, W.M., Cunningham, W.L., 2008. Ground-Water Availability in the United States (USGS Numbered Series No. 1323), Circular. Geological Survey (U.S.).

Richter, B.D., Mathews, R., Harrison, D.L., Wigington, R., 2003. Ecologically sustainable water management: managing river flows for ecological integrity. Ecol. Appl. 13, 206–224. https://doi.org/10.1890/1051-0761(2003)013[0206:ESWMMR]2.0.CO;2

Robelia, B., Murphy, T., 2011. What do people know about key environmental issues? A review of environmental knowledge surveys: : Vol 18, No 3. Environ. Educ. Res. 18, 299–321.

Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460, 999–1002. https://doi.org/10.1038/nature08238

Rosenberry, D.O., Pitlick, J., 2009. Local-scale variability of seepage and hydraulic conductivity in a shallow gravel-bed river. Hydrol. Process. 23, 3306–3318. https://doi.org/10.1002/hyp.7433

Samilton, T., 2016. Mayors appeal Waukesha water diversion [WWW Document]. michiganradio.org. URL http://michiganradio.org/post/mayors-appeal-waukesha-water-diversion (accessed 12.1.17).

Scanlon, B.R., Faunt, C.C., Longuevergne, L., Reedy, R.C., Alley, W.M., McGuire, V.L., McMahon, P.B., 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proc. Natl. Acad. Sci. 109, 9320–9325. https://doi.org/10.1073/pnas.1200311109

Sebok, E., Duque, C., Engesgaard, P., Boegh, E., 2014. Spatial variability in streambed hydraulic conductivity of contrasting stream morphologies: channel bend and straight channel. Hydrol. Process. 29, 458–472. https://doi.org/10.1002/hyp.10170

Seelbach, P.W., Wiley, M.J., Baker, M.E., Wehrly, K.E., 2006. Initial Classification of River Valley Segments across Michigan's Lower Peninsula. Am. Fish. Soc. Symp. 48, 25–48.

Shekell, E., Cameron, L., 2010. Michigan Water Withdrawal Assessment Tool Honored With Awards [WWW Document]. MSU Today. URL https://msutoday.msu.edu/news/2010/michigan-water-withdrawal-assessment-tool-honored-with-awards/

Siddiqui, A., Robert, A., 2010. Thresholds of erosion and sediment movement in bedrock channels. Geomorphology 118, 301–313. https://doi.org/10.1016/j.geomorph.2010.01.011

Siegrist, M., Cvetkovich, G., Roth, C., 2000. Salient Value Similarity, Social Trust, and Risk/Benefit Perception. Risk Anal. 20, 353–362. https://doi.org/10.1111/0272-4332.203034

Song, J., Chen, X., Cheng, C., Wang, D., Lackey, S., Xu, Z., 2009. Feasibility of grain-size analysis methods for determination of vertical hydraulic conductivity of streambeds. J. Hydrol. 375, 428–437. https://doi.org/10.1016/j.jhydrol.2009.06.043

Song, J., Chen, X., Cheng, C., Wang, D., Wang, W., 2010. Variability of streambed vertical hydraulic conductivity with depth along the Elkhorn River, Nebraska, USA. Chin. Sci. Bull. 55, 992–999. https://doi.org/10.1007/s11434-009-0640-2

Sophocleous, M., 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeol. J. 10, 52–67. https://doi.org/10.1007/s10040-001-0170-8

Sophocleous, M., Koussis, A., Martin, J.L., Perkins, S.P., 1995. Evaluation of Simplified Stream-Aquifer Depletion Models for Water Rights Administration. Groundwater 33, 579–588. https://doi.org/10.1111/j.1745-6584.1995.tb00313.x

Sophy, M.J., Toran, L., Fang, A., Nyquist, J., 2010. Effect of Streambed Thickness on Groundwater-Surface Water Interaction Using a Tracer Test at Crabby Creek, Chester County, Pennsylvania.

Southwest Michigan Water Resources Council, 2014. Southwest Michigan Water Resources Council (SWMWRC) Final Report.

Southwestern Michigan College, 2015. Irrigation study proponents meet at SMC [WWW Document]. URL https://www.swmich.edu/news/irrigation-impact-study (accessed 10.17.17).

Steinman, A.D., Nicholas, J.R., Seelbach, P.W., Allan, J.W., Ruswick, F., 2011. Science as a fundamental framework for shaping policy discussions regarding the use of groundwater in the State of Michigan: a case study. Water Policy 13, 69–86.

Strasser, D., Lensing, H.-J., Nuber, T., Richter, D., Frank, S., Goeppert, N., Goldscheider, N., 2015. Improved geohydraulic characterization of river bed sediments based on freeze-core sampling – Development and evaluation of a new measurement approach. J. Hydrol. 527, 133–141. https://doi.org/10.1016/j.jhydrol.2015.04.074

Sun, D., Zhan, H., 2007. Pumping induced depletion from two streams. Adv. Water Resour. 30, 1016–1026. https://doi.org/10.1016/j.advwatres.2006.09.001

Suvedi, M., Krueger, D., Shrestha, A., Bettinghouse, D., 2000. Michigan Citizens' Knowledge and Perceptions About Groundwater. J. Environ. Educ. 31, 16–21. https://doi.org/10.1080/00958960009598634

Swift, T.L., Wilson, S.L., 2009. Misconceptions about brain injury among the general public and non-expert health professionals: an exploratory study. Brain Inj. 15, 149–165. https://doi.org/10.1080/02699050117322

Syme, G.J., Beven, C.E., Sumner, N.R., 1993. Motivation for Reported Involvement in Local Wetland Preservation: The Roles of Knowledge, Disposition, Problem Assessment, and Arousal. Environ. Behav. 25, 586–606. https://doi.org/10.1177/0013916593254003

Tellinghuisen, J., 2001. Statistical Error Propagation. J. Phys. Chem. A 105, 3917–3921. https://doi.org/10.1021/jp003484u

Theis, C.V., 1941. The effect of a well on the flow of a nearby stream. Eos Trans. Am. Geophys. Union 22, 734–738. https://doi.org/10.1029/TR022i003p00734

Thomas, M., Pidgeon, N., Whitmarsh, L., Ballinger, R., 2015. Mental models of sea-level change: A mixed methods analysis on the Severn Estuary, UK. Glob. Environ. Change 33, 71–82. https://doi.org/10.1016/j.gloenvcha.2015.04.009

Tikkanen, J., Isokääntä, T., Pykäläinen, J., Leskinen, P., 2006. Applying cognitive mapping approach to explore the objective–structure of forest owners in a Northern Finnish case area. For. Policy Econ. 9, 139–152. https://doi.org/10.1016/j.forpol.2005.04.001

Toran, L., Nyquist, J.E., Fang, A.C., Ryan, R.J., Rosenberry, D.O., 2013. Observing lingering hyporheic storage using electrical resistivity: variations around stream restoration structures, Crabby Creek, PA. Hydrol. Process. 27, 1411–1425. https://doi.org/10.1002/hyp.9269

Twight, B.W., Paterson, J.J., 1979. Conflict and Public Involvement: Measuring Consensus. J. For. 77, 771–776.

Upham, P., García Pérez, J., 2015. A cognitive mapping approach to understanding public objection to energy infrastructure: The case of wind power in Galicia, Spain. Renew. Energy 83, 587–596. https://doi.org/10.1016/j.renene.2015.05.009

Van der Gun, J., 2012. Groundwater and Global Change: Trends, Opportunities and Challenges, United Nations World Water Assessment Programme. United Nations Educational, Scientific and Cultural Organization, Paris, France.

Vaske, J.J., Absher, J.D., Bright, A.D., 2007. Salient value similarity, social trust, and attitudes toward wildland fire management. Hum. Ecol. Rev. 14, 223–232.

Verčič, D., Verčič, A.T., Laco, K., 2006. Coorientation theory in international relations: The case of Slovenia and Croatia. Public Relat. Rev. 32, 1–9. https://doi.org/10.1016/j.pubrev.2005.10.002

von Kutzschenbach, M., Brønn, C., 2006. Communicating sustainable development initiatives: Applying co-orientation to forest management certification. J. Commun. Manag. 10, 304–322. https://doi.org/10.1108/13632540610681185

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., Bierkens, M.F.P., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37, L20402. https://doi.org/10.1029/2010GL044571

Walden, J.A., Bortree, D., DiStaso, M., 2015. Reconsidering the public relations professional–blogger relationship: A coorientation study. Public Relat. Rev. 41, 526–532. https://doi.org/10.1016/j.pubrev.2015.06.002

Walling, D.E., 2005. Tracing suspended sediment sources in catchments and river systems. Sci. Total Environ., Linking Landscape Sources of Phosphorus and Sediment to Ecological Impacts in Surface Waters 344, 159–184. https://doi.org/10.1016/j.scitotenv.2005.02.011

Ward, N., Lough, H., 2011. Stream Depletion from Pumping a Semiconfined Aquifer in a Two-Layer Leaky Aquifer System. J. Hydrol. Eng. 16, 955–959. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000382

Wehrly, K.E., Wiley, M.J., Seelbach, P.W., 2006. Influence of landscape features on summer water temperatures in lower Michigan streams, in: American Fisheries Society Symposium. pp. 113–127.

Wells, K., 2016. Most Michigan congressional reps want Snyder to deny Great Lakes withdrawal request [WWW Document]. michiganradio.org. URL http://michiganradio.org/post/most-michigan-congressional-reps-want-snyder-deny-great-lakes-withdrawal-request (accessed 12.1.17).

Wilson, G., 2013. Michigan’s groundwater tool: Oversold, overhyped and in question [WWW Document]. Gt. Lakes Echo. URL http://greatlakesecho.org/2013/06/28/michigans-groundwater-tool-oversold-overhyped-and-in-question/ (accessed 10.17.17).

Wojnar, A.J., Mutiti, S., Levy, J., 2013. Assessment of geophysical surveys as a tool to estimate riverbed hydraulic conductivity. J. Hydrol. 482, 40–56. https://doi.org/10.1016/j.jhydrol.2012.12.018

Wolf, K.L., Blahna, D.J., Brinkley, W., Romolini, M., 2013. Environmental stewardship footprint research: linking human agency and ecosystem health in the Puget Sound region. Urban Ecosyst. 16, 13–32. https://doi.org/10.1007/s11252-011-0175-6

World Bank, 2014. Thinking with mental models, in: World Development Report 2015: Mind, Society, and Behavior, World Development Report. The World Bank, pp. 62–75. https://doi.org/10.1596/978-1-4648-0342-0_ch3

Wu, G., Shu, L., Lu, C., Chen, X., Zhang, X., Appiah-Adjei, E.K., Zhu, J., 2015. Variations of streambed vertical hydraulic conductivity before and after a flood season. Hydrogeol. J. 23, 1603–1615. https://doi.org/10.1007/s10040-015-1275-9

Yager, R.M., 1993. Estimation of Hydraulic Conductivity of a Riverbed and Aquifer System on the Susquehanna River in Broome County, New York (Water Supply Paper No. 2387). U.S. Geological Survey.

Zorn, T.G., Seelbach, P.W., Rutherford, E.S., 2012. A Regional-Scale Habitat Suitability Model to Assess the Effects of Flow Reduction on Fish Assemblages in Michigan Streams1. JAWRA J. Am. Water Resour. Assoc. 48, 871–895. https://doi.org/10.1111/j.1752-1688.2012.00656.x

Zorn, T.G., Seelbach, P.W., Wiley, M.J., 2002. Distributions of Stream Fishes and their Relationship to Stream Size and Hydrology in Michigan's Lower Peninsula. Trans. Am. Fish. Soc. 131, 70–85. https://doi.org/10.1577/1548-8659(2002)131<0070:DOSFAT>2.0.CO;2

APPENDIX A

Supplemental Information for

Chapter 3

Improvement of Analytical Solution in Permitting Large Quantity Groundwater Withdrawals

Procedure for K_S estimation from soil map unit's K_{soil} at Platte River, NE.

The Platte River in Nebraska was used in this example. Chen (2005) reported measurements of K_S measured using a permeameter. The protocol is as follows:

1. Download the necessary National Hydrography Dataset (NHD) and Watershed Boundary Dataset (WBD) from the National Map Viewer tools. In this case, the Platte River NHD and the Platte River WBD were used. Figure A.1. shows the Platte River stream line and the Platte River watershed boundary.
2. Identify the location of the field measurement by Chen (2005). Isolate the specific watershed boundary upstream of the measurement point (see Figure A.2).
3. From the measurement point, track an upstream distance of 4 km and 9 km (this is derived after sensitivity analysis from ± 5 – 25 km). Clip these streams and save as separate shapefiles. (see Figure A.3)
4. Because the Platte River is a fairly large river, a polygon shapefile already exists that represents the Platte River. Use this as the boundary for Platte River. (see Figure A.4)
5. Create buffer zones with diameters of 50 m, 100 m, 200 m, 300 m, and 400 m from the Platte River Polygon shapefile for each stream length to represent the catchment areas whose soil erosion contribute to the streambed sediment at the measurement location. If the buffer zones exceed the watershed boundary, clip the buffer zones with the watershed boundary lines. Figure A.4 shows the buffer zones for stream length of 9 km already clipped with the watershed boundary lines.
6. Export these buffer zones into shapefiles.
7. Open Web Soil Survey website (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx) > Click Import AOI (Area of Interest) > Create AOI from Zipped Shapefile > Choose the Shapefile of Interest from the computer directory (e.g., 400 m buffer zone shapefile, see Figure B.5) > Set AOI. (see Figure A.5)

8. Click on “Soil Data Explorer” tab > Click on “Soil Properties and Qualities” sub-tab > Clik on the “Soil Physical Properties” option > Click on the “Saturated Hydraulic Conductivity (K_{soil}).
9. Check the “Detailed Description” box and choose “All Layers (Weighted Average)” on the Layer Options (Horizon Aggregation Method). Leave everything as default. Click “View Rating”.
10. Copy the information in the resulting Saturated Hydraulic Conductivity (K_{soil}) summary table (see Figure B.6) and paste into spreadsheet program (e.g., Microsoft Excel), perform area weighted average calculation to find the K_S. The area weighted average based on soil type is shown in Figure A.7.
11. Repeat the same procedure for the 4 km upstream distance stream and for all respective buffer zones.
12. Calculate the average, maximum, minimum, and the standard deviation for statistical analysis purposes.
13. Repeat the same approach for all 23 locations and perform the RMSE and linear distance to find the error between this method and the field measurement values.

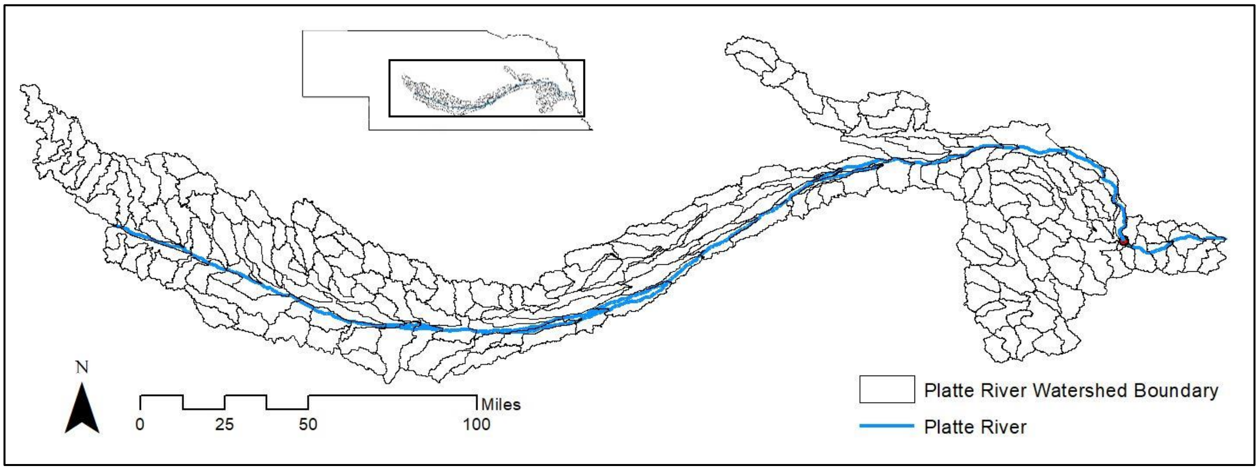


Figure A.1. The Platte River and the Platte River watershed boundaries at the smallest hydrologic unit classification (HUC-12).

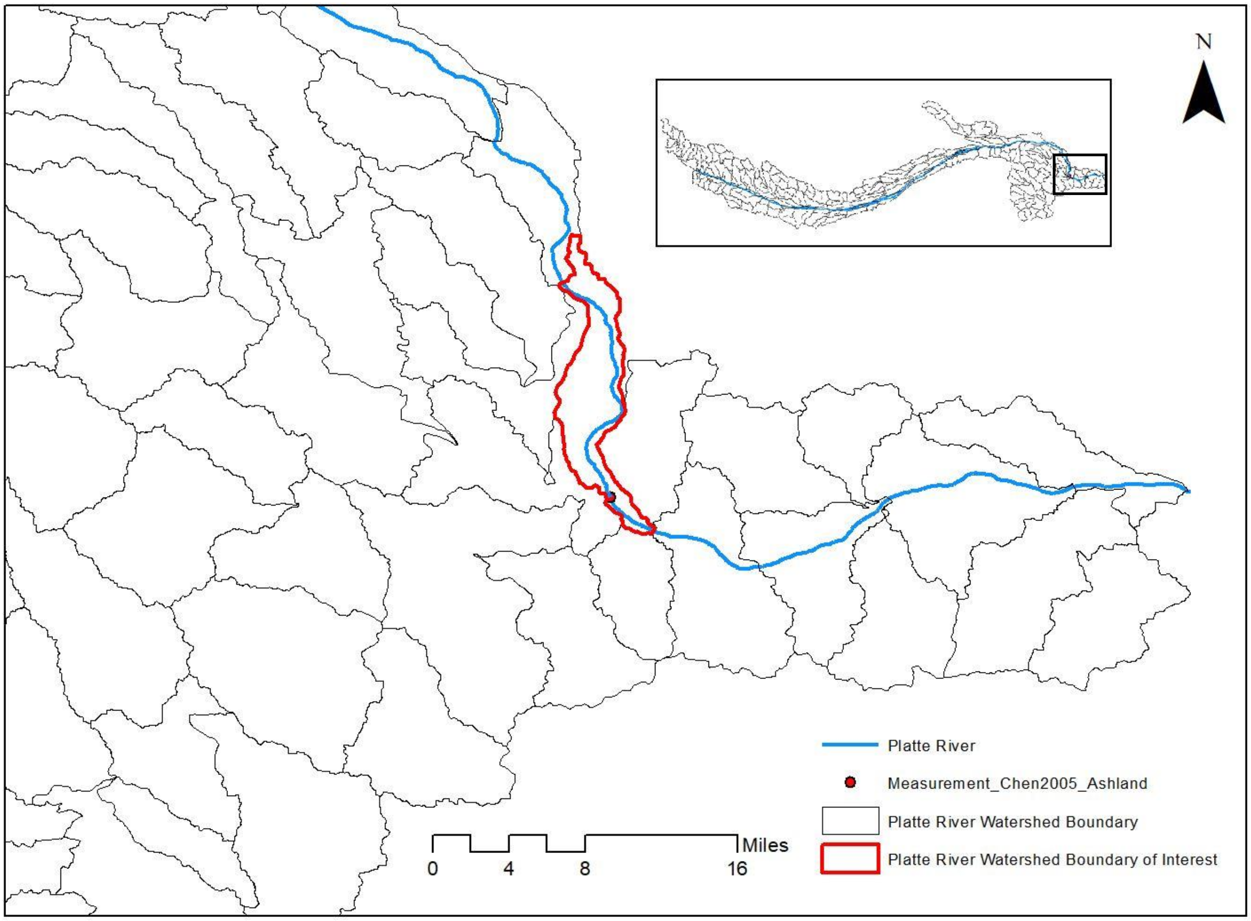


Figure A.2. The measurement point location by Chen (2005) at the Platte River near Ashland. The watershed bounded by red line shows the watershed directly upstream to the measurement location.

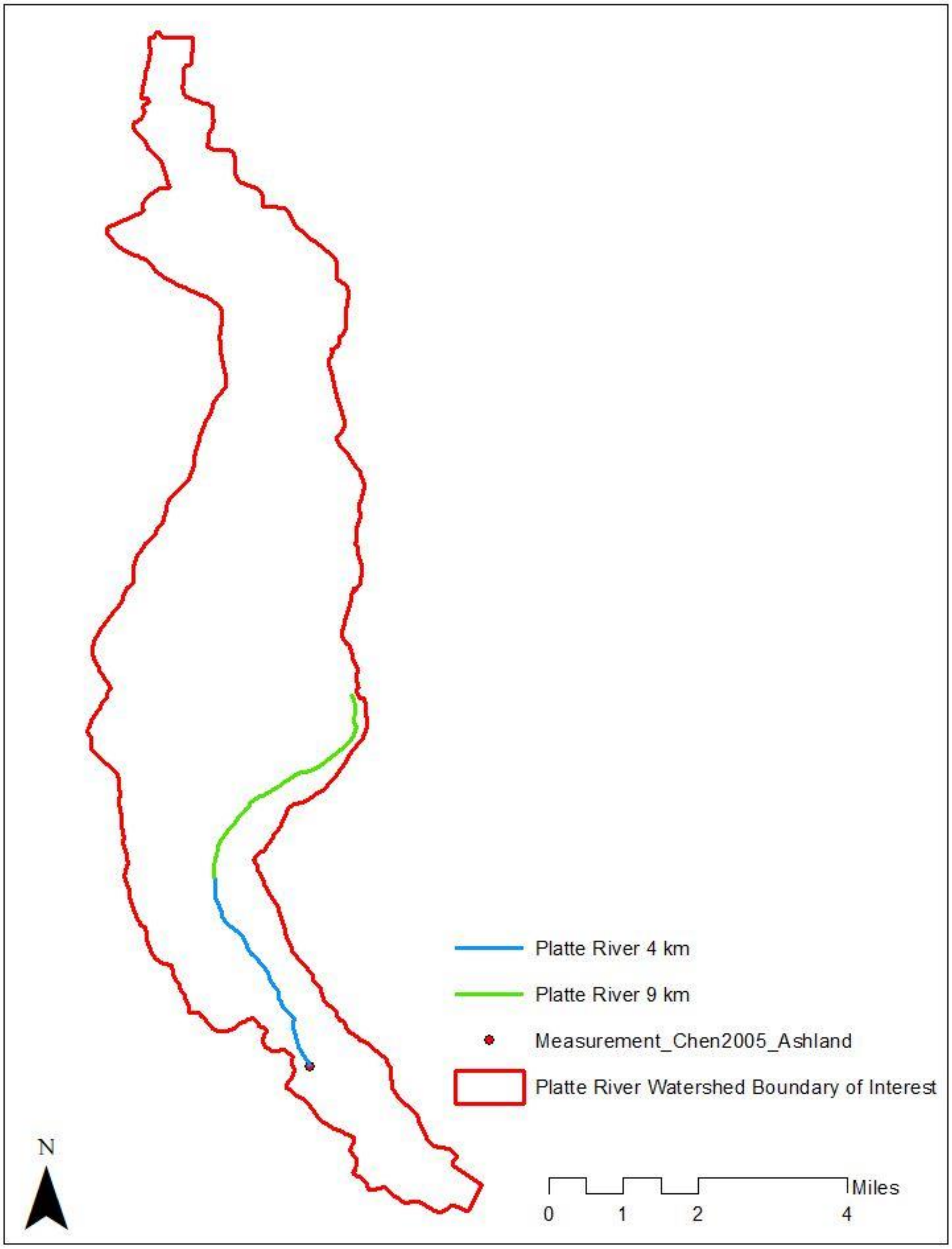


Figure A.3. Platte River 4 km and 9 km upstream distance of the measurement point location as denoted by Chen (2005).

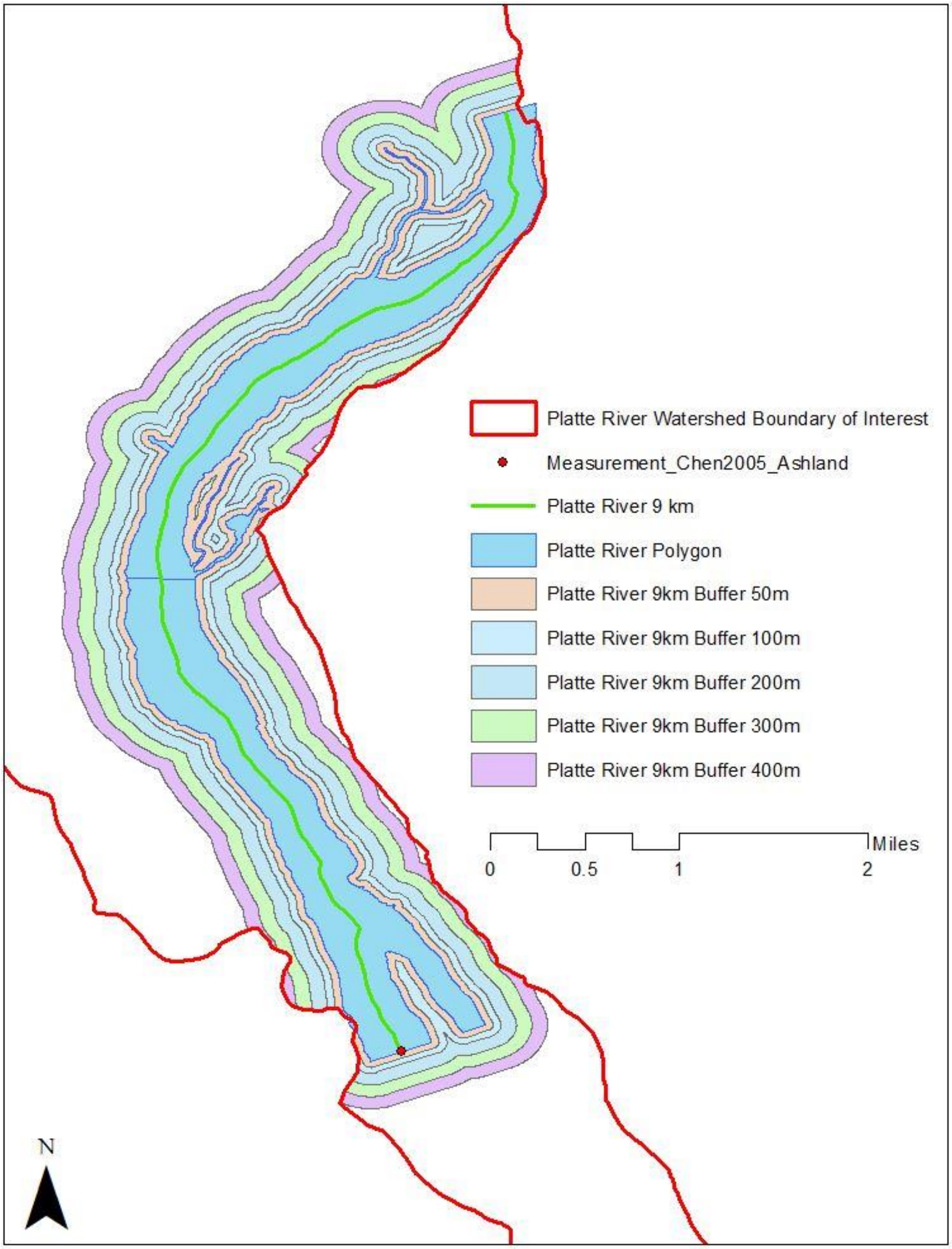
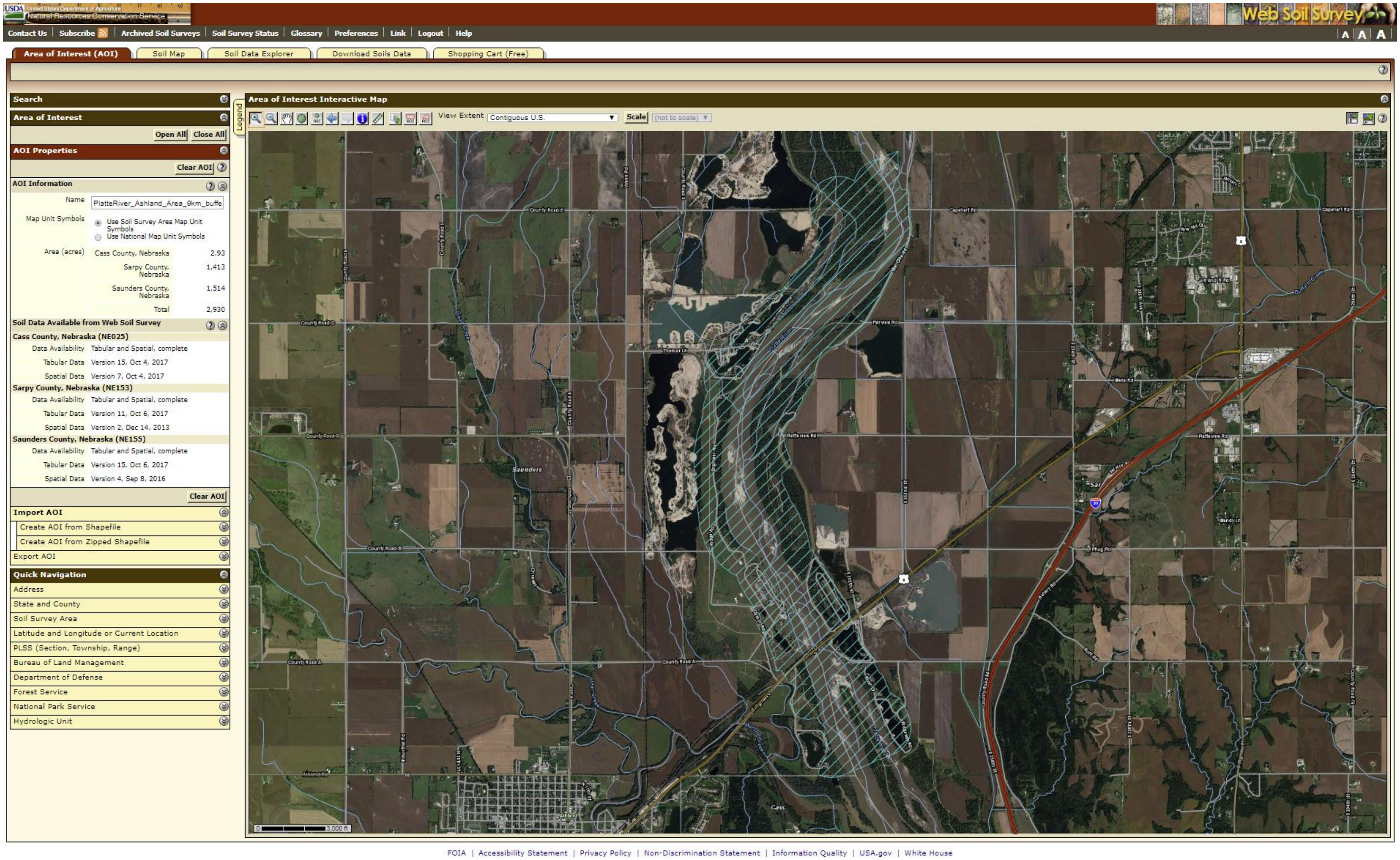


Figure A.4. Platte River 9 km upstream distance with the polygon shapefile and 5 buffer zones of different distances from the stream border.



AOI Information

Name: PlatteRiver_Ashland_Area_9km_buffe

Map Unit Symbols: ● Use Soil Survey Area Map Unit Symbols ○ Use National Map Unit Symbols

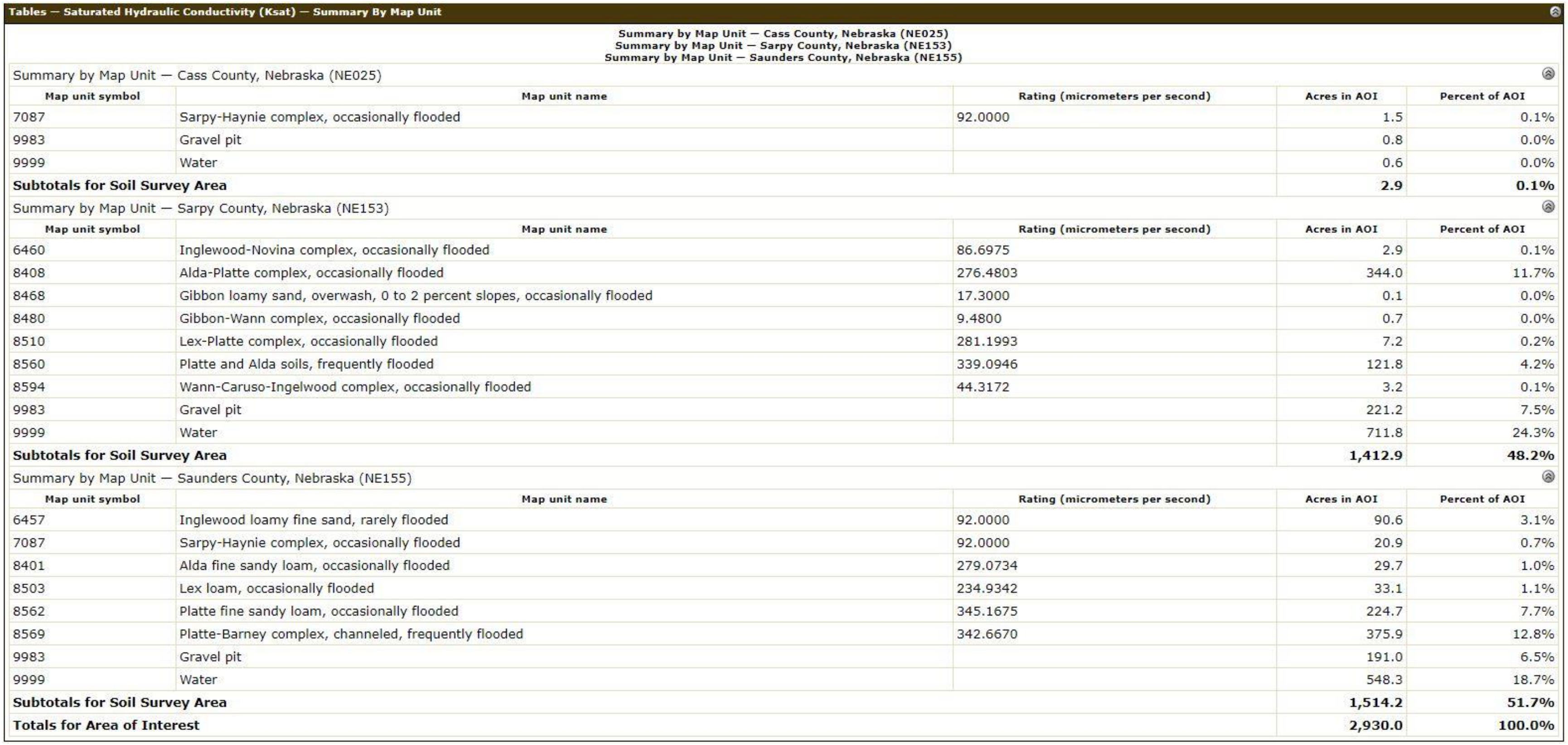
Area (acres)		
	Cass County, Nebraska	2.93
	Sarpy County, Nebraska	1,413
	Saunders County, Nebraska	1,514
	Total	2,930

Soil Data Available from Web Soil Survey

Cass County, Nebraska (NE025)	
Data Availability	Tabular and Spatial, complete
Tabular Data	Version 15, Oct 4, 2017
Spatial Data	Version 7, Oct 4, 2017
Sarpy County, Nebraska (NE153)	
Data Availability	Tabular and Spatial, complete
Tabular Data	Version 11, Oct 6, 2017
Spatial Data	Version 2, Dec 14, 2013
Saunders County, Nebraska (NE155)	
Data Availability	Tabular and Spatial, complete
Tabular Data	Version 15, Oct 6, 2017
Spatial Data	Version 4, Sep 8, 2016

View Extent: Contiguous U.S.

Figure A.5. Platte River 9 km upstream distance with the polygon shapefile and 5 buffer zones of different distances from the stream border in the WSS.



Tables — Saturated Hydraulic Conductivity (Ksat) — Summary By Map Unit

Summary by Map Unit — Cass County, Nebraska (NE025)
Summary by Map Unit — Sarpy County, Nebraska (NE153)
Summary by Map Unit — Saunders County, Nebraska (NE155)

Summary by Map Unit — Cass County, Nebraska (NE025)

Map unit symbol	Map unit name	Rating (micrometers per second)	Acres in AOI	Percent of AOI
7087	Sarpy-Haynie complex, occasionally flooded	92.0000	1.5	0.1%
9983	Gravel pit		0.8	0.0%
9999	Water		0.6	0.0%
Subtotals for Soil Survey Area			**2.9**	**0.1%**

Summary by Map Unit — Sarpy County, Nebraska (NE153)

Map unit symbol	Map unit name	Rating (micrometers per second)	Acres in AOI	Percent of AOI
6460	Inglewood-Novina complex, occasionally flooded	86.6975	2.9	0.1%
8408	Alda-Platte complex, occasionally flooded	276.4803	344.0	11.7%
8468	Gibbon loamy sand, overwash, 0 to 2 percent slopes, occasionally flooded	17.3000	0.1	0.0%
8480	Gibbon-Wann complex, occasionally flooded	9.4800	0.7	0.0%
8510	Lex-Platte complex, occasionally flooded	281.1993	7.2	0.2%
8560	Platte and Alda soils, frequently flooded	339.0946	121.8	4.2%
8594	Wann-Caruso-Ingelwood complex, occasionally flooded	44.3172	3.2	0.1%
9983	Gravel pit		221.2	7.5%
9999	Water		711.8	24.3%
Subtotals for Soil Survey Area			**1,412.9**	**48.2%**

Summary by Map Unit — Saunders County, Nebraska (NE155)

Map unit symbol	Map unit name	Rating (micrometers per second)	Acres in AOI	Percent of AOI
6457	Inglewood loamy fine sand, rarely flooded	92.0000	90.6	3.1%
7087	Sarpy-Haynie complex, occasionally flooded	92.0000	20.9	0.7%
8401	Alda fine sandy loam, occasionally flooded	279.0734	29.7	1.0%
8503	Lex loam, occasionally flooded	234.9342	33.1	1.1%
8562	Platte fine sandy loam, occasionally flooded	345.1675	224.7	7.7%
8569	Platte-Barney complex, channeled, frequently flooded	342.6670	375.9	12.8%
9983	Gravel pit		191.0	6.5%
9999	Water		548.3	18.7%
Subtotals for Soil Survey Area			**1,514.2**	**51.7%**
Totals for Area of Interest			**2,930.0**	**100.0%**

Figure A.6. The resulting Soil's Saturated Hydraulic Conductivity (K_{soil}) Summary Table as shown by the Web Soil Survey for Platte River 9 km upstream distance from the measurement location used by Chen (2005). K_S values are given in the column labelled as Rating.

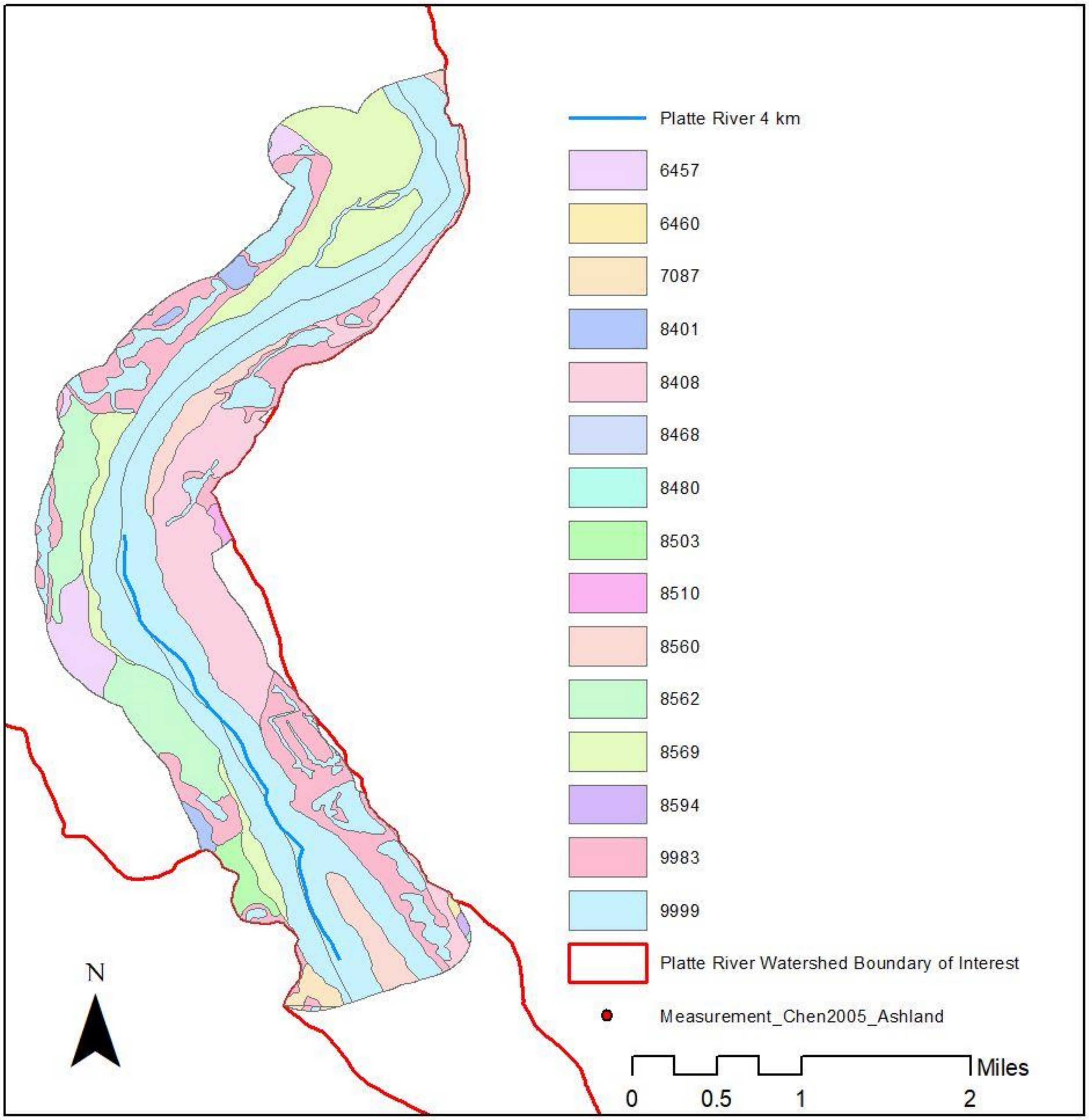


Figure A.7. The resulting intersects between the soil map unit and the 400 m buffer zones from 9 km upstream distance at Platte River, NE. The area each soil map unit represent were used to calculate the average K_S for this particular point.

Procedure for K_S estimation from soil map unit's K_{soil} and land cover data at Platte River, NE.

The Platte River in Nebraska was used in this example. The site was previously used by Chen (2005) to measure K_S using permeameter. The protocol is as follow:

1. Follow step 1 to 5 from the "Procedure for K_S estimation from catchment soil at Platte River, NE" above.
2. Create a 25 m diameter from the stream polygon border and assume this as the stream bank area.
3. Download the National Land Cover Database (NLCD) for this particular location. (see Figure A.7)
4. Convert the NLCD from raster to shapefile and clip the NLCD shapefiles with the buffer zones.
5. Identify the area that do not contribute to soil erosion to stream (e.g., open water, developed lands, wetlands, etc.) and ignore these in the land use calculation.
6. Perform an area weighted average with both the land use area code that contribute to the streambed sediment and the soil type from the WSS data.
7. Streambank area soil erosion was assumed to have a flat contribution of 10% to the area weighted average. Forestland was assumed to have less contribution to the streambed sediment deposit (i.e., 0.1 – 0.9×), whereas cropland and pasture land were assumed to have more contribution (i.e., 1.3 – 4.5× and 1.9 – 3.7×, respectively).
8. Repeat the same procedure for the 4 km upstream distance stream and for all respective buffer zones.
9. Calculate the average, maximum, minimum, and the standard deviation for statistical analysis purposes.
10. Repeat the same approach for all other locations and perform the RMSE and linear distance to find the error between this method and the field measurement values. This analysis was only performed at 18 of the 23 locations.

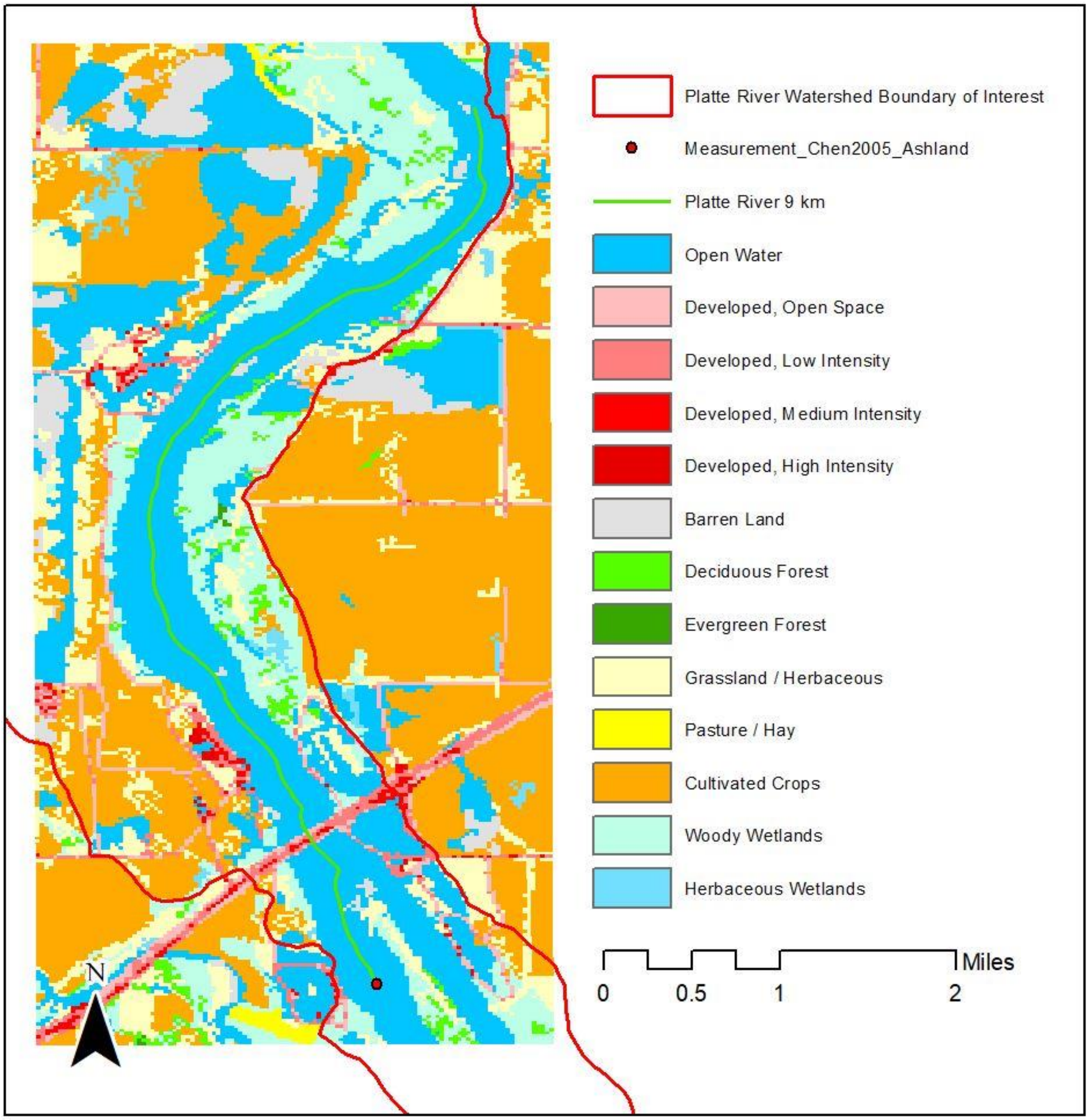


Figure A.8. The National Land Cover Database (NLCD) raster file overlayed on the 9 km upstream distance from the measurement location used by Chen, 2005 in Platte River, NE.

Procedure for K_S estimation from soil map unit's K_{soil} and stream distance contribution at Platte River, NE.

The Platte River in Nebraska was used in this example. The site was previously used by Chen (2005) to measure K_S using permeameter. In this example, the upstream distance of 4 km was used. The protocol is as follow:

1. Follow step 1 to 4 from the "Procedure for K_S estimation from catchment soil at Platte River, NE" above.
2. Divide the upstream distance stream into 10 equal parts. Figure A.8 shows the Platte River with 4 km upstream distance divided into 10 equal parts with 400 m buffer zones.
3. Create buffer zones for each stream polygon distance part and use each of the buffer zone to calculate the area weighted average K_S.
4. Assign the weight of each part as shown in the distribution at Allt Dubhaig shown in Figure 3.5 and Table 3.3.
5. Repeat the same procedure for the 4 km upstream distance stream and for all respective buffer zones.
6. Calculate the average, maximum, minimum, and the standard deviation for statistical analysis purposes.
7. Repeat the same approach for all other locations and perform the RMSE and linear distance to find the error between this method and the field measurement values. This analysis was only performed at 8 of the 23 locations.

Table A.1. Calculation of aquifer-derived K for four streams used in this study (i.e., South Platte River, Connetquot Brook, Gulf Brook, and Morse Brook) where the aquifer K is not readily available.

Location	Known parameters from the literature	Aquifer Hydraulic Conductivity, K [m/d]
South Platte River near Crook, CO	T = 20,000 – 50,000 ft^2/day (1858 – 4645 m^2/day); B = 33 – 164 ft (10 – 50 m)	37.2 – 464.5 [a]
Connetquot Brook near Islandia, NY	T = 10,000 – 12,000 ft^2/day (929 – 1115m^2/day); B = 40 – 230 ft (12 – 70 m)	13 – 91 [a]
Gulf Brook near Pepperrell, MA	Q_W = 10.8 Mgal/day (4.08×10^4 m^3/day); Δs = 10.67 m; Δt = 1 hour Calculated T = 1247 m^2/day B = 50 ft (~15 m)	82 [b]
Morse Brook near Devens, MA	Q_W = 10.3 Mgal/day (3.89×10^4 m^3/day); Δs = 6.1 m; Δt = 1 hour Calculated T = 2081 m^2/day B = 40 ft (~12 m)	152.4 [b]

[a] When aquifer K was unknown, but T and B were known, $K = T/B$ was used to calculate the aquifer K

[b] When neither of the aquifer K nor the aquifer T were known, $T = \frac{2.303 Q_w \log(t_2 - t_1)}{4\pi(s_2 - s_1)}$ was first used to estimate T, and then $K = T/B$ was used to estimate the aquifer K

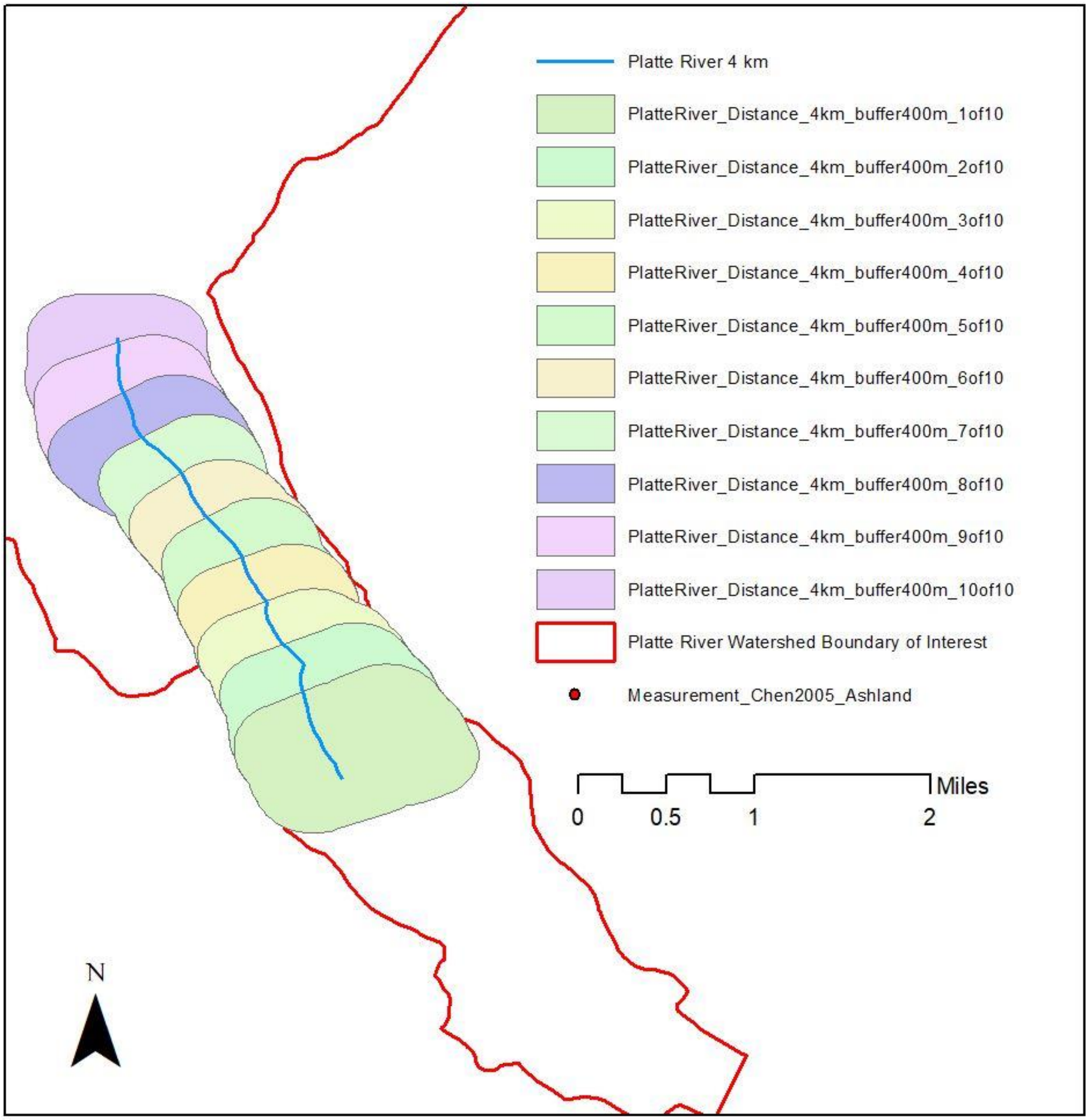


Figure A.9. Platte River with 10 equal distance part and 400 m buffer zones from the measurement location used by Chen, 2005.

APPENDIX B

Supplemental Information for

Chapter 5

Evaluation of Knowledge-based Water Management Perspectives in Michigan using a Co-orientation Approach

Co-orientation Survey Form for Expert Participants.

Thank you for participating in this study. The purpose of this survey is to explore how government agencies, researchers, and community leaders view sustainable water resource management issue, specifically high capacity water withdrawal in the State of Michigan. The survey asks you to share your views and to make some predictions about how the public and local community views this issue. Please answer these questions as completely and honestly as possible. We want to assure you that the answers you provide will not be used in any that violates your privacy and everything will be kept anonymous.

1. In what capacity have you been involved in the sustainable water resources study issue (check all that apply)?
   ☐ Michigan DEQ ☐ Local government official
   ☐ Academic Researcher ☐ Local watershed or environmental organization
   ☐ Other (please specify): ___________________________________

2. How much do you know about high volume / high capacity water withdrawal in the State of Michigan?
   ☐ Nothing ☐ A little ☐ Some ☐ A good deal ☐ A lot

3. How much do you know about high volume hydraulic fracturing activities in the State of Michigan?
   ☐ Nothing ☐ A little ☐ Some ☐ A good deal ☐ A lot

4. How much do you think the average Michigan citizen knows about high volume / high capacity water withdrawal in the State of Michigan?
   ☐ Nothing ☐ A little ☐ Some ☐ A good deal ☐ A lot

5. How much do you think the average Michigan citizen knows about sustainable water resource management and practices?
   ☐ Nothing ☐ A little ☐ Some ☐ A good deal ☐ A lot

6. Please rate the following issues in terms of:

A. How important each issue is to the <u>local community</u>; AND

B. How important each issue is to <u>agencies</u>, such as the DEQ?

1 = not at all	2 = slightly	3 = somewhat	4 = very	5 = extremely

A. How important to the community?		B. How important to agencies?
1 2 3 4 5	Sustainable water resource management and practices	1 2 3 4 5
1 2 3 4 5	Preserving river / stream ecology and the environment (e.g.: fish population, riparian vegetation, etc.)	1 2 3 4 5
1 2 3 4 5	Preserving and/or improving <u>groundwater</u> resources in Michigan	1 2 3 4 5
1 2 3 4 5	Preserving and/or improving <u>surface water</u> resources in Michigan	1 2 3 4 5
1 2 3 4 5	Right to access clean freshwater resources	1 2 3 4 5
1 2 3 4 5	Users that consume large amount of water (e.g.: agricultural, industrial, fracking, etc.)	1 2 3 4 5
1 2 3 4 5	Water related outdoor and recreational activities (e.g.: kayaking, etc.)	1 2 3 4 5
1 2 3 4 5	High capacity <u>surface water</u> withdrawal in Michigan	1 2 3 4 5
1 2 3 4 5	High capacity <u>groundwater</u> withdrawal in Michigan	1 2 3 4 5
1 2 3 4 5	Water resources diversion from the Great Lakes Basin	1 2 3 4 5
1 2 3 4 5	The impact of high volume hydraulic fracturing (“fracking”) activities towards water resources in the State of Michigan	1 2 3 4 5

7. How often do you think the local community gets information about sustainable water management from the following sources?

1 = never	2 = rarely	3 = sometimes	4 = often	5 = very often

1	2	3	4	5	National media
1	2	3	4	5	Local media
1	2	3	4	5	Local community members
1	2	3	4	5	DEQ websites
1	2	3	4	5	Commercial well drillers / contractors
1	2	3	4	5	Public meetings
1	2	3	4	5	Environmental and/or watershed conservation groups or NGOs
1	2	3	4	5	Business groups (e.g., Chamber of Commerce, Tourism Board, Industries' website, etc.)
1	2	3	4	5	Social Media (e.g., Facebook, Twitter, etc.)

Briefly describe any other sources you think the public relies on to find out about sustainable water management?

8. Please indicate how much do <u>you</u> agree with the following statements.

1 = strongly disagree	2 = disagree	3 = not sure	4 = agree	5 = strongly agree

1	2	3	4	5	The local community care about water resources for current & future generation.
1	2	3	4	5	High volume groundwater withdrawal is a serious issue in Michigan.
1	2	3	4	5	Water resource diversion from the Great Lakes Basin is a serious issue.
1	2	3	4	5	Water resources related problems have increased in the last 10-15 years.
1	2	3	4	5	Agricultural activities (e.g.: irrigation, etc.) consume the most amount of water and/or groundwater.
1	2	3	4	5	Agricultural related water consumptions are NOT sustainable in the long run.
1	2	3	4	5	Industrial activities consume the most amounts of water and/or groundwater.
1	2	3	4	5	Industrial related water consumptions are NOT sustainable in the long run.
1	2	3	4	5	Hydraulic fracturing activities consume the most amounts of water and/or groundwater.
1	2	3	4	5	Hydraulic fracturing related water consumptions are NOT sustainable in the long run.

1	2	3	4	5	Combined, residential home owners water wells consume the most amount of groundwater.
1	2	3	4	5	Residential home owners water wells consumptions are NOT sustainable in the long run.
1	2	3	4	5	Sustainable water resource management will maintain and/or improve water quality and stream ecology.
1	2	3	4	5	The community has the right to participate in sustainably managing water resources in their area.
1	2	3	4	5	Regulation ensuring sustainable water management can possibly restrict economic growth.
1	2	3	4	5	More research needs to be done on sustainable water resource management program.
1	2	3	4	5	High volume hydraulic fracturing activities will adversely impact the environment, specifically water quantity.
1	2	3	4	5	High volume hydraulic fracturing activities will adversely impact the environment, specifically water quality.
1	2	3	4	5	Sustainable water resource management regulation shall not limit access to freshwater resources.

9. Please rate each of the following for:

A. How much do <u>local community members</u> think each causes unsustainable water resources management; AND

B. How much do <u>agencies</u>, such as the DEQ, think each causes unsustainable water resources management?

1 = <u>not</u> at all	2 = slightly	3 = somewhat	4 = a lot	5 = extremely	X = don't know

A. What does the <u>community</u> think causes unsustainable water management?							B. What do <u>agencies</u> think causes unsustainable water management?					
1	2	3	4	5	X	Agricultural related water withdrawals	1	2	3	4	5	X
1	2	3	4	5	X	Industrial related water withdrawals	1	2	3	4	5	X
1	2	3	4	5	X	Hydraulic fracturing related water withdrawals	1	2	3	4	5	X
1	2	3	4	5	X	Combined residential wells water withdrawals	1	2	3	4	5	X

1	2	3	4	5	X	Water resource diversion from the Great Lakes Basin	1	2	3	4	5	X
1	2	3	4	5	X	Lack of regulations	1	2	3	4	5	X
1	2	3	4	5	X	Lack of enforcement of existing regulations	1	2	3	4	5	X
1	2	3	4	5	X	Extreme weather event	1	2	3	4	5	X
1	2	3	4	5	X	Climate change	1	2	3	4	5	X

Briefly describe any other factors that cause unsustainable water management?

10. Below is a list of outcomes that may be associated with unsustainable water withdrawal. Please rate each in terms of:

A. How much it concerns the <u>local community</u>; AND
B. How much it concerns <u>agencies</u>, such as the DEQ?

1 = <u>not</u> at all	2 = slightly	3 = somewhat	4 = a lot	5 = extremely	X = don't know

A. How concerned is the community?							B. How concerned are agencies?					
1	2	3	4	5	X	Drop in aquifer water table and/or well going dry	1	2	3	4	5	X
1	2	3	4	5	X	Deterioration in water quality	1	2	3	4	5	X
1	2	3	4	5	X	Restriction of water dependent economic activity	1	2	3	4	5	X
1	2	3	4	5	X	Drop in surface water level and/or surface water going dry (surface water = stream or lake)	1	2	3	4	5	X
1	2	3	4	5	X	Negative impact on stream ecology (e.g.: fish and riparian vegetation, etc.)	1	2	3	4	5	X
1	2	3	4	5	X	Competition for water resources	1	2	3	4	5	X
1	2	3	4	5	X	Health risks	1	2	3	4	5	X

Briefly describe any other outcomes that might result from unsustainable water withdrawal?

11. Please indicate how much you agree with the following statements about <u>how the public feels about</u> the efforts of natural resource management agencies, such as the Michigan DEQ and DNR.

1 = strongly disagree	2 = disagree	3 = not sure	4 = agree	5 = strongly agree

The local community believes that agencies…

1	2	3	4	5	… know what are causing potential unsustainable water resource management.
1	2	3	4	5	… want to preserve water resources in Michigan.
1	2	3	4	5	are trying to provide the public with useful information about sustainable water resource management and practices.
1	2	3	4	5	… are making a reasonable effort to ensure sustainable use of water resources.
1	2	3	4	5	… have the right people working on sustainable water resources issue.
1	2	3	4	5	… have tried to enforce sustainable water resource regulation.
1	2	3	4	5	… want to minimize problems on economic development due to regulations.
1	2	3	4	5	… understand concerns of the local community.
1	2	3	4	5	try to actively engage the community about sustainable use of water resources.
1	2	3	4	5	… communicate effectively with the public.
1	2	3	4	5	… treat community members fairly.
1	2	3	4	5	know what to do to improve sustainable water resource management and practices.
1	2	3	4	5	… don’t care about the feelings of the community.
1	2	3	4	5	… want to improve the local economy.
1	2	3	4	5	… are not interested in ensuring sustainable water resources management.

12. Please rate the following water management strategies in terms of the following:

A. How <u>effective</u> you think each would be at ensuring sustainable water management; AND

B. How <u>practical</u> you think each would be to implement?

1 = <u>not</u> at all	2 = slightly	3 = somewhat	4 = a lot	5 = extremely	X = don’t know

A. How effective?		B. How practical?
1 2 3 4 5 X	More rigorous water regulation for agricultural activities	1 2 3 4 5 X

1	2	3	4	5	X	More rigorous water regulation for industrial activities	1	2	3	4	5	X
1	2	3	4	5	X	More rigorous water regulation for fracking and energy industry	1	2	3	4	5	X
1	2	3	4	5	X	More rigorous water regulation for residential water withdrawal	1	2	3	4	5	X
1	2	3	4	5	X	Strict review for all individual high volume / high capacity water withdrawal proposal	1	2	3	4	5	X
1	2	3	4	5	X	More outreach and education about sustainable water management practices for public, especially for stakeholders	1	2	3	4	5	X
1	2	3	4	5	X	Strictly prohibit water diversion from the Great Lakes Basin (e.g., Great Lakes Compact)	1	2	3	4	5	X
1	2	3	4	5	X	Strict prohibition of any water withdrawal at locations with sensitive stream ecology	1	2	3	4	5	X
1	2	3	4	5	X	Water use audit	1	2	3	4	5	X

Co-orientation Survey Form for Non-expert Participants.

Thank you for participating in this study. This survey gives you an opportunity to share your views about sustainable water resources management, specifically high capacity water withdrawal in the State of Michigan and about how agencies, such as the Michigan Department of Environmental Quality (MDEQ), are addressing this issue. Please answer these questions as completely and honestly as possible. We want to assure you that the answers you provide will not be used in any that violates your privacy and everything will be kept anonymous.

1. Are you born or grew-up in the Great Lakes States (i.e.: MI, OH, IN, IL, WI, MN, NY, PA)?
   ☐ No ☐ Yes
2. Are you involved in any local organizations that deal with sustainable water management and practices?
   ☐ No ☐ Yes → If yes, please list: ____
3. Do you own or work at a property or properties with active groundwater pumping well(s) and/or surface water pumping?
   ☐ No → If no, please skip to Question #5
   ☐ Yes → If yes, is the well(s) / water source registered as high volume water withdrawal (i.e., pumping rate is > 70 gallons per minute) ☐ No ☐ Yes
4. What is the groundwater pumping well(s) used for?
   ☐ Residential ☐ Industrial
   ☐ Agricultural ☐ Others, please specify: __________________________
5. How much do you think you know about sustainable water resources management and practices?
   ☐ Nothing ☐ A little ☐ Some ☐ A good deal ☐ A lot
6. How much do you think you know about high volume / high capacity water withdrawals and their respective impacts?
   ☐ Nothing ☐ A little ☐ Some ☐ A good deal ☐ A lot
7. How much do you think you know about high volume hydraulic fracturing ("fracking") activities and their respective impacts?
   ☐ Nothing ☐ A little ☐ Some ☐ A good deal ☐ A lot
8. Please rate the following issues in terms of:
   A. How important each issue is to you; AND
   B. How important each issue is to agencies, such as the DEQ?

1 = not at all	2 = slightly	3 = somewhat	4 = very	5 = extremely

A. How important is this to you?	B. How important is this to agencies?
____________________	________________________

1	2	3	4	5	Sustainable water resource management and practices	1	2	3	4	5
1	2	3	4	5	Preserving river / stream ecology and the environment (e.g.: fish population, riparian vegetation, etc.)	1	2	3	4	5
1	2	3	4	5	Preserving and/or improving <u>groundwater</u> resources in Michigan	1	2	3	4	5
1	2	3	4	5	Preserving and/or improving <u>surface water</u> resources in Michigan	1	2	3	4	5
1	2	3	4	5	Right to access clean freshwater resources	1	2	3	4	5
1	2	3	4	5	User that consume large amount of water (e.g.: agricultural, industrial, fracking, etc.)	1	2	3	4	5
1	2	3	4	5	Water related outdoor and recreational activities (e.g.: kayaking, etc.)	1	2	3	4	5
1	2	3	4	5	High capacity <u>surface water</u> withdrawal in Michigan	1	2	3	4	5
1	2	3	4	5	High capacity <u>groundwater</u> withdrawal in Michigan	1	2	3	4	5
1	2	3	4	5	Water resources diversion from the Great Lakes Basin	1	2	3	4	5
1	2	3	4	5	The impact of high volume hydraulic fracturing (“fracking”) activities towards water resources in the State of Michigan	1	2	3	4	5

9. How often do you get information about sustainable water resources management from the following sources?

1 = never	2 = rarely	3 = sometimes	4 = often	5 = very often

1	2	3	4	5	National media
1	2	3	4	5	Local media
1	2	3	4	5	Local community members
1	2	3	4	5	DEQ websites
1	2	3	4	5	Commercial well drillers / contractors
1	2	3	4	5	Public meetings
1	2	3	4	5	Environmental and/or watershed conservation groups or NGOs
1	2	3	4	5	Business groups (e.g., Chamber of Commerce, Tourism Board, Industries' website, etc.)
1	2	3	4	5	Social Media (e.g., Facebook, Twitter, etc.)

Briefly describe any other sources you rely on to find out about sustainable water resources management?

10. Please indicate how much <u>you</u> agree with the following statements.

1 = strongly disagree	2 = disagree	3 = not sure	4 = agree	5 = strongly agree

1	2	3	4	5	I care about sustainable water resources management for current and future generation.
1	2	3	4	5	High volume groundwater withdrawal is a serious issue in Michigan.
1	2	3	4	5	Water resource diversion from the Great Lakes Basin is a serious issue.
1	2	3	4	5	Water resources related problems have increased in the last 10-15 years.
1	2	3	4	5	Agricultural activities (e.g.: irrigation, etc.) consume the most amount of water and/or groundwater.
1	2	3	4	5	Agricultural related water consumptions are NOT sustainable in the long run.
1	2	3	4	5	Industrial activities consume the most amounts of water and/or groundwater.
1	2	3	4	5	Industrial related water consumptions are NOT sustainable in the long run.

1 2 3 4 5	Hydraulic fracturing activities consume the most amounts of water and/or groundwater.
1 2 3 4 5	Hydraulic fracturing related water consumptions are NOT sustainable in the long run.
1 2 3 4 5	Combined, residential home owners water wells consume the most amount of groundwater.
1 2 3 4 5	Residential home owners water wells consumptions are NOT sustainable in the long run.
1 2 3 4 5	Sustainable water resource management will maintain and/or improve water quality and stream ecology.
1 2 3 4 5	I have the right to participate in sustainably managing water resources in my area.
1 2 3 4 5	Regulation ensuring sustainable water management can possibly restrict economic growth.
1 2 3 4 5	More research needs to be done on sustainable water resource management program.
1 2 3 4 5	High volume hydraulic fracturing activities will adversely impact the environment, specifically water quantity.
1 2 3 4 5	High volume hydraulic fracturing activities will adversely impact the environment, specifically water quality.
1 2 3 4 5	Sustainable water resource management regulation shall not limit access to freshwater resources.

11. Please rate each of the following for:
    C. How much you think each causes unsustainable water resource management; AND
    D. How much agencies, such as the DNR and DEQ, think each causes unsustainable water resource management?

1 = not at all	2 = slightly	3 = somewhat	4 = a lot	5 = extremely	X = don't know

A. How much do you think this cause unsustainable water resource management?		B. How much do agencies think this causes unsustainable water resource management?
1 2 3 4 5 X	Agricultural related water withdrawals	1 2 3 4 5 X

1	2	3	4	5	X	Industrial related water withdrawals	1	2	3	4	5	X
1	2	3	4	5	X	Hydraulic fracturing related water withdrawals	1	2	3	4	5	X
1	2	3	4	5	X	Combined residential wells water withdrawals	1	2	3	4	5	X
1	2	3	4	5	X	Water resource diversion from the Great Lakes Basin	1	2	3	4	5	X
1	2	3	4	5	X	Lack of regulations	1	2	3	4	5	X
1	2	3	4	5	X	Lack of enforcement of existing regulations	1	2	3	4	5	X
1	2	3	4	5	X	Extreme weather event	1	2	3	4	5	X
1	2	3	4	5	X	Climate change	1	2	3	4	5	X

Briefly describe any other factors that you think may cause unsustainable water resource management?

12. Below is a list of outcomes that may be associated with unsustainable water management. Please rate each in terms of:
    C. How much it concerns <u>you</u>; AND
    D. How much it concerns <u>agencies</u>, such as the DEQ?

1 = <u>not</u> at all	2 = slightly	3 = somewhat	4 = a lot	5 = extremely	X =don't know

A. How concerned are you?							B. How concerned are agencies?					
1	2	3	4	5	X	Drop in aquifer water table and/or well going dry	1	2	3	4	5	X
1	2	3	4	5	X	Deterioration in water quality	1	2	3	4	5	X
1	2	3	4	5	X	Restriction of water dependent economic activity	1	2	3	4	5	X
1	2	3	4	5	X	Drop in surface water level and/or surface water going dry (surface water = stream or lake)	1	2	3	4	5	X
1	2	3	4	5	X	Negative impact on stream ecology (e.g.: fish and riparian vegetation, etc.)	1	2	3	4	5	X
1	2	3	4	5	X	Competition for water resources	1	2	3	4	5	X
1	2	3	4	5	X	Health risks	1	2	3	4	5	X

Briefly describe any other outcomes that you think might result from high volume groundwater withdrawal?

13. Please indicate how much you agree with the following statements about the efforts of management agencies, such as the Michigan DEQ.

1 = strongly disagree	2 = disagree	3 = not sure	4 = agree	5 = strongly agree

The agencies…

1	2	3	4	5	… know what is causing potential unsustainable water resource management.
1	2	3	4	5	… want to preserve water resources in Michigan.
1	2	3	4	5	… are trying to provide the public with useful information about sustainable water resource management and practices.
1	2	3	4	5	… are making a reasonable effort to ensure sustainable use of water resources.
1	2	3	4	5	… have the right people working on sustainable water resources issue.
1	2	3	4	5	… have tried to enforce sustainable water resource regulation.
1	2	3	4	5	… want to minimize problems on economic development due to regulations.
1	2	3	4	5	… understand concerns of the local community.
1	2	3	4	5	… try to actively engage the community about sustainable use of water resources.
1	2	3	4	5	… communicate effectively with the public.
1	2	3	4	5	… treat community members fairly.
1	2	3	4	5	… know what to do to improve sustainable water resource management and practices.
1	2	3	4	5	… don’t care about the feelings of the community.
1	2	3	4	5	… want to improve the local economy.
1	2	3	4	5	… are not interested in ensuring sustainable water resources management.

Do you have any additional comments on how the agencies have handled this problem?

14. Please rate the following sustainable water management strategies in terms of the following:
    C. How effective do you think each would be at improving and ensuring sustainable water resource management; AND
    D. Given limited agency resources, how practical do you think each would be to implement?

1 = not at all	2 = slightly	3 = somewhat	4 = a lot	5 = extremely	X = don’t know

A. How effective?	B. How practical?
____________________	____________________

1 2 3 4 5 X	More rigorous water regulation for agricultural activities	1 2 3 4 5 X
1 2 3 4 5 X	More rigorous water regulation for industrial activities	1 2 3 4 5 X
1 2 3 4 5 X	More rigorous water regulation for fracking and energy industry	1 2 3 4 5 X
1 2 3 4 5 X	More rigorous water regulation for residential water withdrawal	1 2 3 4 5 X
1 2 3 4 5 X	Strict review for all individual high volume / high capacity water withdrawal proposal	1 2 3 4 5 X
1 2 3 4 5 X	More outreach and education about sustainable water management practices for public, especially for stakeholders	1 2 3 4 5 X
1 2 3 4 5 X	Strictly prohibit water diversion from the Great Lakes Basin (e.g., Great Lakes Compact)	1 2 3 4 5 X
1 2 3 4 5 X	Strict prohibition of any water withdrawal at locations with sensitive stream ecology	1 2 3 4 5 X
1 2 3 4 5 X	Water use audit	1 2 3 4 5 X

Briefly describe any other water management strategies you would like agencies to implement.

15. Gender: ☐ Male ☐ Female

16. Age: ☐ Under 18 ☐ 18-29 ☐ 30-39 ☐ 40-49
☐ 50-59 ☐ 60-69 ☐ 70-79 ☐ 80 or older

17. Where do you live in Michigan (city and/or county)? ____

18. Are you currently employed?
☐ No → If no, what is your status (retired, unemployed, full-time parent, etc.): ___________________

☐ Yes → If yes, briefly describe your line of work:____

19. Do you have any additional comments?

THANK YOU FOR YOUR TIME!