A Localized Investigation of High Resolution Groundwater Flow Properties of the Saginaw Aquifer Mason, Michigan

Amanda Hayden

Follow this and additional works at: https://scholarworks.wmich.edu/masters_theses

Part of the Geology Commons, and the Hydrology Commons

Recommended Citation
https://scholarworks.wmich.edu/masters_theses/68

This Masters Thesis-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Master's Theses by an authorized administrator of ScholarWorks at WMU. For more information, please contact wmu-scholarworks@wmich.edu.
A LOCALIZED INVESTIGATION OF HIGH RESOLUTION GROUNDWATER FLOW PROPERTIES OF THE SAGINAW AQUIFER MASON, MICHIGAN

by

Amanda Hayden

A Thesis
Submitted to the Faculty of The Graduate College in partial fulfillment of the requirements for the Degree of Master of Science Department of Geosciences Advisor: David A. Barnes, Ph.D

Western Michigan University Kalamazoo, Michigan June 2012
THE GRADUATE COLLEGE
WESTERN MICHIGAN UNIVERSITY
KALAMAZOO, MICHIGAN

Date May 23rd, 2012

WE HEREBY APPROVE THE THESIS SUBMITTED BY

Amanda Hayden

ENTITLED A Localized Investigation of High Resolution Groundwater Flow Properties of the Saginaw Aquifer Mason, Michigan

AS PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science

Geosciences (Department)

Dr. David A. Barnes
Thesis Committee Chair

Geology (Program)

Dr. Duane R. Hampton
Thesis Committee Member

Dr. Alan E. Kehew
Thesis Committee Member

APPROVED

Dean of The Graduate College

Date June 2012
A LOCALIZED INVESTIGATION OF HIGH RESOLUTION GROUNDWATER FLOW PROPERTIES OF THE SAGINAW AQUIFER MASON, MICHIGAN

Amanda Hayden, M.S.
Western Michigan University, 2012

High resolution groundwater models can aid in better management of groundwater resources through more accurate characterization and quantification of aquifer systems. Detailed assessments of flow properties in the context of sedimentary facies can provide high quality data input for more accurate groundwater models.

The Pennsylvanian Grand River and Saginaw bedrock formations comprise the Saginaw Aquifer located in the Lansing, Michigan Tri-County region. The Saginaw Aquifer consists of a predominately shale and sandstone successions. These sandstone facies range up to 40 meters thick, and supply a significant amount water resources to the Lansing Tri-County area. Data used in this study was collected from conventional core inspection, porosity and permeability plug analysis, mini air permeameter measurements, and petrographic image analysis. These analysis were used to quantify a conservative set flow properties which correspond to existing sedimentary depositional facies descriptions.
ACKNOWLEDGMENTS

I would like to first thank and acknowledge my thesis advisor Dr. Dave Barnes for providing the inspiration for this research. I would also like to thank my thesis advising committee members: Dr. Alan Kehew and Dr. Duane Hampton for their constant support and encouragement.

A very special thanks to Niah Venable, a previous graduate student in the WMU Geosciences Department whose sedimentary analysis of this core suite laid the framework for my research.

I would like to express my gratitude to Cheryl Stanfield, from the MDEQ whose was responsible for the donation of the core suite used in this study as well as Carol Luukonen and Howard Reeves, Hydrologists at the Lansing USGS office and Weston Solutions Inc. who provided their time, insight and guidance.

I would like to also thank Western Michigan University, Graduate Student Advisory Council and the Lauren D. Hughes Environmental Scholarship for providing funding for my research and the Michigan Geological Repository for Research and Education (MGRRE) for the use of their facility and equipment.

Lastly, I would like to thank my family and friends and especially my husband Travis for giving me love, support and patience - even when it was difficult.

Amanda Hayden
# TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................. ii

LIST OF TABLES .......................................................................................... v

LIST OF FIGURES ....................................................................................... vii

CHAPTER

I. INTRODUCTION ..................................................................................... 1

II. BACKGROUND ....................................................................................... 4

  Michigan Geology ................................................................................. 4

  Geology of Saginaw Aquifer ............................................................... 5

  Saginaw Aquifer Groundwater Use and Characterization .......... 8

  Americhem Site ................................................................................... 12

III. MICROSCOPE ANALYSIS .................................................................. 16

  Objective ............................................................................................ 16

  Methods ............................................................................................. 16

  Results ................................................................................................. 21

IV. PERMEABILITY ANALYSIS ................................................................. 32

  Objective ............................................................................................ 32

  Methods ............................................................................................. 32

  Results ................................................................................................. 38

V. FLOW PROPERTY ANALYSIS ............................................................. 48

  Saginaw Aquifer Flow Properties .................................................... 48

  Gamma Ray Log Data ......................................................................... 53
Table of Contents—continued

CHAPTER

Origin of Saginaw Aquifer Flow Properties ................................................. 56
Correlation of Depositional Facies with Flow Property Data .................. 57

VI. GROUNDWATER MODEL ANALYSIS ...................................................... 58
  Saginaw Aquifer – Regional Assessment ............................................... 58
  Saginaw Aquifer Americhem Site ......................................................... 59
  Transmissivity Evaluation ........................................................................ 60
  Hydrogeological Flow Property Assessment ............................................. 63

VII. CONCLUSION ..................................................................................... 68

BIBLIOGRAPHY ....................................................................................... 70
LIST OF TABLES

2-1. Saginaw Aquifer depositional facies descriptions summarized from Venable (2006) .......................................................... 7


3-1. Point counting data, including Van Der Plas (1965) 2σ confidence interval correction range compared to visually estimated petrographic porosity values obtained using Pettijohn et al. (1987) as a guide ......................... 19

3-2. Porosity values obtained from conventional laboratory plug analysis, geometrically averaged PIA values for 10X and 25X magnifications and the visual estimation of porosity using a petrographic microscope. PIA porosity for MW-45-154' and BRSB-59/59A-183.5' was not able (NA) to be calculated due to a vast number of points during the 10X PIA analysis ......................................................................................... 21

3-3. Distribution of siderite concretions within the Americhem Saginaw thin section suite .............................................................................................................. 27

4-1. Statistical information pertaining to the high resolution permeability data set. The range of permeability values are based on 2 standard deviations from the mean value................................................................. 47

4-2. Statistical information pertaining to the variation in measurements collected for sample intervals within each facies ................................................................. 47

5-1. Averaged permeability values associated with Venable (2006) depositional facies compared to general permeability values for similar lithologies. Permeability values modified from Chilinger (1964), Freeze and Cherry (1979), and Spitz and Moreno (1996) ........................................ 49

5-2. Calculated hydraulic conductivity values from original permeability measurements using the conversion on the previous page. Hydraulic conductivity values for similar lithologies are calibrated from Freeze and Cherry (1979) and Spitz and Moreno (1996) ................................................................. 51

5-3. Statistical information pertaining to the gamma ray log and high resolution permeability data .......................................................................................... 55
List of Tables—continued

6-1a. Saginaw Aquifer flow property data collected from various hydrogeologic investigations .......................................................... 59

6-1b. Saginaw Aquifer flow property data collected from various hydrogeologic investigations .......................................................... 60

6-2. Transmissivity values for the Americhem core borings, horizontal properties and a modified single layer......................................................... 66
LIST OF FIGURES

2-1. A map of the bedrock formations found within Michigan's southern peninsula, modified from Dorr and Eschman (1970) .................................................. 4

2-2. Late Paleozoic to Cenozoic period aquifer systems and related stratigraphic formations, modified from Lukkonen and Simard (2004) ............... 5

2-3. Saginaw Aquifer thickness map modified from Westjohn and Weaver (1998) .................................................................................................................... 6

2-4. Location map and corresponding cross section illustrating the relationship between the Grand River member of the Saginaw Formation, modified from Venable et al. (2010) .................................................. 9

2-5. Vevay Township, Ingham County, Site location map. Modified from Luukkonen et al 2004 ............................................................................................................ 12


3-1. Distribution of sedimentary facies within the Americhem Saginaw Aquifer core thin section suite .......................................................................................... 16

3-2. Histograms presenting distribution of grain sorting (3-2a), roundness of grains (3-2b), and visually estimated porosity (3-2c) among the Americhem Saginaw Aquifer core thin section suite ......................................................... 17

3-3. Photomicrograph of a thin section from BRSB-60/60A-102' - facies 2a taken at 25X magnification presenting compaction features ............................................. 18

3-4(a-d). Photomicrographs taken from thin section MW-59 - 142' - facies 2b using a polarized microscope in PPL (3-4a and 3-4c) and Image Pro Plus version 5.1 image analysis software (3-4b and 3-4d). Photomicrographs 3-4a and 3-4b were taken at 10X magnification and photomicrographs 3-4c and 3-4d were taken at 25X magnification .................................................................................................................. 20

3-5(a-b). Photomicrograph of (a) MW-43-92' - facies 2a and (b) BRSB059/59A-142' - facies 2b highlighting the porosity of these facies and minimal compaction properties in these samples. Both photomicrographs were taken at 25X magnification .................................................. 23
List of Figures—continued

3-6(a-b). Photomicrographs taken at 25X magnification of (a) MW-45-145.5' - facies 2a and (b) BRB-59/59A-184' - facies 2b illustrating some of the clay and calcite cement features within these facies.  

3-7. Photomicrographs of (a) BRB-59/59A-228' - facies 1 and (b) MW-45-134' - facies 3 taken at 25X magnification depict the reduced porosity, decreased grain sizes and increased clay and cement in these facies.  

3-8. Photomicrograph of MW-44-146.5' - facies 2a highlighting siderite nodules commonly found in most of the existing thin sections.  

3-9(a-c). Correlation graphs reflecting how the PIA and visual estimated petrographic porosity data compares to conventional laboratory plug analysis.  

4-1. Photograph of the mini-air permeameter components utilized in this study. This unit was made by Temco, Inc - model MP-401.  

4-2. Modified Darcy equation used by Temco's SmartPerm™ software program to calculate permeability values. Equation modified from Temco (2006).  


4-4. Sample core image with measurement axes. Permeability measurements were collected on the x and z axes. Original image was modified from Venable (2006).  

4-5. Plot of laboratory air permeability (Lab k) versus air permeameter permeability (Air k).  

4-6a. Averaged permeability, sedimentary and gamma ray plots for MW-43 and MW-44. Modified from Venable (2006).  


4-6c. Averaged permeability, sedimentary and gamma ray plots for MW-47 and BRB-59/59A. Modified from Venable (2006).  

4-6d. Averaged permeability, sedimentary and gamma ray plots for BRB-60/60A and BRB-61/61A. Modified from Venable (2006).
List of Figures—continued

4-7a. Histogram presenting the distribution of permeability values from sedimentary facies 1, 4, and 5 ................................................................. 45

4-7b. Histogram presenting the distribution of permeability values from sedimentary facies 2a, 2b, and 3 ................................................................. 45

4-7c. Histogram presenting the distribution of permeability values from sedimentary facies 1, 2a, 2b, 3, 4 and 5 ................................................................. 46

5-1. Histogram of gamma ray values in counts per second for each depositional facies described in Venable (2006). Gamma ray values modified and calculated from the gamma rays logs and data used Venable (2006) ........................................................................................................ 54

6-1a. Map showing location of cross section in Figure 6-1b. Modified from Weston Solutions (2006) Report ................................................................. 61

6-1b. Cross section illustrating a two dimensional plot of gamma ray logs and permeability logs used to determine the major Saginaw Aquifer flow units. Modified from Venable (2006) ........................................................................................................ 62

6-2a. Location map of cores represented in Figure 6-2b and Figure 6-2c. Modified from Weston Solutions (2006) Report ................................................................. 63

6-2b. A modified three-dimensional depiction of the distribution of Americhem flow units within the subsurface. Figure created using MODFLOW software ................................................................. 64

6-2c. A modified three-dimensional depiction of the distribution of Americhem flow units within the subsurface. Figure created using MODFLOW software ................................................................. 65
CHAPTER I

INTRODUCTION

Pennsylvanian bedrock in central lower Michigan comprises an important groundwater producing aquifer. This shallow bedrock aquifer is composed of two main units: the Grand River and Saginaw Formations. The Saginaw Aquifer supplies water to a majority of areas located within the Lansing area Tri-Counties of Clinton, Eaton, and Ingham. In a 1992 study, approximately 90% of groundwater withdrawn from the Tri-Counties for municipal and private supply was produced from the Saginaw Aquifer (Luukkanen 1995). Because the Tri-County area significantly relies on the Saginaw Aquifer for water usage, better estimates and techniques are needed to quantify the amount of groundwater available for current and future use. Additional research on this Pennsylvanian aquifer unit is needed to better understand the flow properties which control water movement within the subsurface of this region. Further knowledge of flow properties can also provide insight into preferred flow paths within this aquifer. This becomes significant in circumstances involving current and/or potential contamination of this aquifer unit.

High resolution groundwater models are thought to aid in better management of groundwater resources through more accurate characterization and quantification of aquifer systems. Detailed assessments of flow properties in the context of sedimentary facies can provide high quality data for more accurate groundwater models. To test this hypothesis, a high resolution flow property investigation was completed for the Americhem site, located in the city of Mason, in Ingham County, Michigan. This site was chosen for investigation due to its current status and affiliation with the Michigan
Department of Environmental Quality (MDEQ). The Americhem site has a history of being a chemical holding and manufacturing plant which is in the process of creating and implementing a remediation plan due to prior contamination. As part of the site characterization by MDEQ and partnering environmental firm, Weston Solutions, eight bedrock wells were drilled. Core collected from these wells was used in this high resolution flow property investigation.

The goals of this small scale, high resolution investigation of the Americhem Site were to:

1. Develop a set of flow properties which correlate with the sedimentary facies established in Venable (2006).
2. Compare high resolution flow property data to existing lower resolution data for the Americhem Site and Saginaw Aquifer.
3. Test the utility of a high resolution permeability study conducted with a mini air permeameter
4. Determine whether this localized portion of the Saginaw Aquifer is controlled by matrix or secondary flow.
5. Explore why this aquifer able to produce high capacities of potable groundwater.

To complete these goals, a series of investigations was performed using the core collected from the eight bedrock wells. A petrophysical characterization was completed using thin sections from the Americhem core. This portion of the research was intended to petrographically classify and quantify aquifer porosity systems. This work also addresses the relative significance of fracture versus matrix control on Saginaw Aquifer flow properties. The methods and results of this study are found in chapter 3. The high
resolution permeability flow data was obtained using a mini air permeameter. The methods used to obtain this data and the results are outlined in chapter 4. Chapter 5 compares the permeability values to text references and discusses the relationship between the permeability data and existing geological data such as gamma ray logs. Chapter 6 compares the flow property data to existing values from Saginaw Aquifer specific groundwater models and site investigations, and displays the permeability data in a three dimensional perspective. Chapter 7 revisits the relationship between flow properties and sedimentary facies and their utility in creating more successful groundwater models.
CHAPTER II
BACKGROUND

Michigan Geology

The Michigan Basin is an intercratonic basin which generally consists of stacked bowl-shaped layers of mostly Paleozoic strata covered by 0 to 1200 feet of Pleistocene glacial deposits. It is suggested that Paleozoic subsidence and deposition coupled with later uplift helped to create the current shape of the Michigan Basin (Dorr and Eschman 1970). Figure 2-1 illustrates a representation of the Pleistocene subcrop and subsurface distribution of bedrock layers within the Michigan Basin.

Figure 2-1. A map of the bedrock formations found within Michigan's southern peninsula, modified from Dorr and Eschman (1970).
Michigan geology has been studied for a variety of reasons for almost 200 hundred years. Exploration for coal and oil resources has provided much of the data we have initially used for geological exploration and characterization. Water resource characterization has recently contributed significantly to the exploration of Michigan’s geology with the implementation of the Regional Aquifer-System Analysis (RASA) program's Michigan Basin research conducted during 1986-1994 (Westjohn and Weaver 1998). Figure 2-2 shows a nomenclature cross section of late Paleozoic to Cenozoic period aquifer systems and related stratigraphic formations within the Michigan Basin.

![Diagram of stratigraphic nomenclature and hydrogeologic units](Figure 2-2. Late Paleozoic to Cenozoic period aquifer systems and related stratigraphic formations, modified from Lukkonen and Simard (2004).)

**Geology of Saginaw Aquifer**

Historically, it has been thought that the Saginaw Aquifer comprises the Grand River and Saginaw Formations (Kelly 1936 and Velbel et al. 1994). The Saginaw Formation includes fine to medium grained sandstone, siltstone, shale, limestone and thin
seams of coal. In contrast, the Grand River Formation consists of medium to coarse-grained sandstone with siltstone and shale which appear to have been deposited by meandering channels (Venable et al. 2010). During the course of characterizing flow units within Michigan’s subsurface, the Saginaw and Grand River Formations have been identified as hydraulically connected and continuously grouped together even though, historically, they have been considered as two individual formations, with different

Figure 2-3. Saginaw Aquifer thickness map modified from Westjohn and Weaver (1998).
depositional and sedimentary facies (Dorr and Eschman 1970, Velbel et al. 1994, and Westjohn and Weaver 1996 and 1998). Figure 2-3 presents Saginaw Aquifer thickness throughout the Michigan Lower Peninsula.

Recent research conducted by Venable (2006), describes in detail the lithology and depositional environments of the Saginaw Aquifer. Her descriptions utilized the same core samples, thin sections and petrophysical logs used in this research investigation. Venable (2006) thoroughly studied the eight Americhem cores collected from the Saginaw Aquifer and classified intervals of each core into six different sedimentary

<table>
<thead>
<tr>
<th>FACIES</th>
<th>DEPOSITIONAL FACIES DESCRIPTION</th>
</tr>
</thead>
</table>
| 1      | Estuarine Sediments and Tidal Flats:  
Gray silty shale with fine to very fine light gray quartzose sandstone. Horizontal to rippled bedding planes. Rare to moderate bioturbation. Very fine plant remains at some bedding planes. |
| 2a     | Coarse/Medium-Grained Fluvial Channel Fills:  
Gray to tan and brown, fine to medium coarse grained quartzose sandstone. Iron staining often occurs within Facies 2a. Cross bedding is the dominant sedimentary structure with a coarsening upward sequence. Mud, coal, and plant remains typically occur in thin ribbons. Siderite nodules are common in shallow depths of core. |
| 2b     | Medium/Fine-Grained Fluvial Channel Fills:  
Gray fine to medium grained quartzose sandstone. Cross bedding and massive sedimentary structures occur in this facies although cross bedding is visually enhanced by mud and fine plant material outlining bedding planes. Few siderite nodules and coal clasts occur throughout this facies. |
| 3      | Interbedded Facies 1 and 2a/2b Flood Plain/Overbank Deposits:  
Interbedded gray silty shale and fine-grained quartzose sandstone (facies 1) and medium coarse grained quartzose sandstone layers which vary in thickness (facies 2a/2b). Facies 3 is defined as the interfingering of facies 1 & 2a/2b. |
| 4      | Paleosol, Coals and Shales:  
A range of gray to tan siltstone and fine quartzose sandstone with apparent mottling, mudstone with blocky to horizontal lamination, and gray silty shale with blocky black coal seams. Bioturbation and slickenside features can be seen as well as potential fracture traces. |
| 5      | Transgressive Marginal Marine Shales:  
Gray to black shale with horizontal lamination. Rich in silt and carbon rich particles. Fine plant remains are usually pyritized. Lingula sp fossils are rarely found. |

Table 2-1. Saginaw Aquifer depositional facies descriptions summarized from Venable (2006).
depositional facies. A summary of the Venable (2006) facies descriptions is listed in Table 2-1.

Results from the palynological analysis summarized in Venable (2006) suggest that a long hiatus or unconformity does not exist between the Grand River and Saginaw formations as previously thought by Velbel et al. (1994). This coupled with the interstratification of the six sedimentary depositional facies as illustrated in Figure 2-4 suggest that the Grand River Formation is not a separate formation but, instead a member (represented as facies 2a) of the fluvial-deltaic Saginaw Formation (Venable 2006 and Venable et al. 2010).

For purposes of this permeability study, it will be assumed that the Grand River is a member (facies 2a) within the Saginaw Formation, both are hydraulically connected and comprise the Saginaw Aquifer locally and regionally.

Saginaw Aquifer Groundwater Use and Characterization

In the greater Lansing area, the Saginaw Aquifer has been used as a private water supply as early as the late 1800's. Public/ municipal water supply use of this Pennsylvanian aquifer became common in the early 1900's and continues to increase with population and industry growth (Stuart 1945). The automobile industry along with other mass manufacturing industries increased groundwater demand in the 1920's and 1930's. Groundwater elevations decreased in pumping wells during World War II era. This coupled with the 1944 drought, was the first indication that groundwater resources were limited within the greater Lansing area (Stuart 1945).

Stuart (1945) discusses the Lansing area portion of the state-wide study of groundwater conditions conducted by the Geological Survey Division, Michigan
Figure 2-4. Location map and corresponding cross section illustrating the relationship between the Grand River member of the Saginaw Formation, modified from Venable et al. (2010).
Department of Conservation and the United States Geological Survey (USGS). This study outlined how the subsurface geology and associated physical properties essentially control the quality, quantity and transport of surface water and groundwater. Stuart (1945) also highlighted that more extensive research was needed, in order to fully understand the limitations of groundwater reservoirs and the affects population and industry have on groundwater resources.

A four year water supply development and management study for the Lansing Tri-County area was discussed in detail in Vanlier et al. (1973). This study identified four major uses of groundwater as manufacturing/cooling, urban, agricultural and recreation. In this study, the issues of regional and local recharge, storage capability, water quality and use were analyzed.

The Michigan Basin RASA study identified and described geologic and hydrogeologic unit extents, boundaries, thicknesses, hydraulic properties, hydraulic communication and groundwater quality of each water reservoir located within the study area (Westjohn and Weaver, 1996 and 1998, and Westjohn et al. 1990). A wealth of knowledge and data was obtained in this study and is the basis of several regional groundwater flow models (Hoaglund et al. 2002). Elements of regional groundwater models and data sets have been modified to assist with multi-county scale groundwater flow studies to assess water supply and distribution (Holtschlag et al. 1996).

A 2003 study conducted by the USGS and the Tri-County Regional Planning Commission was able to refine the multi-county scale groundwater flow model with a focus on the Vevey Township area within Ingham County (Figure 2-5). This study was able to assess and assist with public use planning, delineating Wellhead Protection Plan
(WHPP) zones as well as further understanding the effects the nearby quarry and current contamination may have on the public water supply (Luukkonen and Simard 2004).

**Figure 2-5.** Vevay Township, Ingham County, Site location map. Modified from Luukkonen et al 2004.

**Americhem Site**

The Americhem site is located in the city of Mason within Ingham County Michigan as shown in Figures 2-5 and 2-6. The site is surrounded by industrial, commercial and residential land use. The Leer Corporation (formally Wyeth) is to the west, a former pickle factory and Safety Kleen site is located to the northwest with residential and commercial properties to the south of the site. Sycamore Creek and related wetlands flank the site to the north and east. The Mason Esker extends in a northwest-southeast trend through the northern portion of the Americhem site as shown on Figure 2-6. Seven municipal wells surround the site. Research conducted by the
Figure 2-6. Americhem - Saginaw Aquifer core suite location map. Modified from Weston Solutions (2006) Report.
environmental firm Weston Solutions found that a portion of this site was first used as a gas station in the 1950s and 1960s. Since the 1970's, the Americhem Corporation has operated this property as a chemical storage and oil distribution facility (Weston Solutions (2006) Report).

Several site characterization studies have been completed by different environmental firms since 1991 to delineate potentially impacted areas within the subsurface. Currently the site remediation is handled by the MDEQ and Weston Solutions. The Weston Solutions (2006) Report illustrates their detailed study of the Americhem site's history, characterization and investigation to delineate chemical plumes within the subsurface. This report discusses the glacial drift aquifer as well as the Saginaw Bedrock Aquifer. Most of the existing contamination is located within the glacial drift aquifer, although laboratory analyses from water samples collected from the onsite bedrock wells detected several chemical constituents. Contaminants of concern for both aquifers include volatile organic compounds (VOCs) with an emphasis on chlorinated solvents and petroleum chemicals. Continued care is taken to monitor contaminant concentrations due to the proximity of the site to the Park Street municipal well and to Sycamore Creek.

During the site characterization process, Weston Solutions divided the Saginaw Aquifer into five units based on geophysical logs and core samples (Table 2-2). These five bedrock units are a general top to bottom description of site lithology and have similar components to the descriptions and classifications made by Venable (2006). The bedrock unit classifications defined by Weston Solutions did not incorporate or attempt to
define sedimentary or depositional facies. For this reason, this study will refer to Venable (2006) lithologic classifications and descriptions.

<table>
<thead>
<tr>
<th>BEDROCK UNIT</th>
<th>GEOLOGIC DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Varying thickness of interbedded shale layers and sandstone layers. Mudstone and limestone layers were also present. This unit appears to thin from the south to north creating a trough like feature. This may be a potential fracture or slump zone which may have created a pathway for glacial sediment deposition.</td>
</tr>
<tr>
<td>2</td>
<td>Generally very fine to medium sandstone. Minor coarse sand and fine gravel was also observed. Features include cross-bedding laminations; fractures were present.</td>
</tr>
<tr>
<td>3</td>
<td>Varying thickness of shale and sandstone layers. Siltstone and mudstone layers also observed.</td>
</tr>
<tr>
<td>4</td>
<td>Generally fine to medium sandstone.</td>
</tr>
<tr>
<td>5</td>
<td>Interbedded layers of shale and fine to medium sandstone. Conglomerate, coal and mudstone layers were also observed.</td>
</tr>
</tbody>
</table>

Table 2-2. Summary of Weston Solutions bedrock unit top to bottom descriptions from the Weston Solutions (2006) Report.
CHAPTER III
MICROSCOPE ANALYSIS

Objective

A series of qualitative and quantitative petrographic studies were completed for forty-nine thin sections from various depth intervals and sedimentary facies of the Americhem Saginaw Aquifer core described in Venable (2006). These microscopic analyses were performed with two main objectives. The first was to develop a better understanding of the mineralogical composition and main petrologic controls on porosity within the Saginaw Aquifer. The second objective was to develop quantitative data regarding porosity estimations using image analysis techniques which could be compared to conventional laboratory plug measured porosity. This was intended to establish a mechanism to estimate porosity for groundwater modeling from the Americhem Saginaw Aquifer core thin sections instead of relying on more costly and invasive laboratory porosity analysis.

Methods

Petrographic Descriptions

A distribution of thin sections to the depositional facies is presented in Figure 3-1. Note that no thin sections are available for facies 4.

![Figure 3-1. Distribution of sedimentary facies within the Americhem Saginaw Aquifer core thin section suite.](image-url)
The thin sections were studied using a petrographic microscope to determine mineralogy and textures and then characterized these properties using techniques found in Flugel (2004), Pettijohn et al. (1987), Scholle and Ulmer-Scholle (2003), Van Der Plas and Tobi (1965) and White (1967). Figure 3-2 presents histograms of grain sorting, grain roundness, and visually estimated porosity distribution. Compaction was evaluated by observing the distribution of point contacts, suturing and cementation. Examples of these are presenting in Figure 3-3.

Figure 3-2. Histograms presenting distribution of grain sorting (3-2a), roundness of grains (3-2b), and visually estimated porosity (3-2c) among the Americhem Saginaw Aquifer core thin section suite
Figure 3-3. Photomicrograph of a thin section from BRSB-60/60A-102’ - facies 2a taken at 25X magnification presenting compaction features.

**Point Counting**

Thin sections were analyzed by point counting representative thin sections for the five available sedimentary facies utilizing modified techniques found in White (1967). Areas of the thin sections were classified as cement, porosity or grains to calculate porosity percentages. Using the method in Van Der Plas and Tobi (1965), confidence limits were determined to represent the accuracy of the point count percentages. These porosity intervals were then compared to the visual porosity estimations of each thin section using Pettijohn et al. 1987 as a guide. Table 3-1 presents data obtained from this exercise.
Petrographic Image Analysis (PIA)

Porosity, determined from conventional laboratory core plug analysis was measured for twenty-six samples. Of these sampled locations, sixteen thin sections corresponded to the core plug sample intervals and were analyzed using the Petrographic Image Analysis (PIA) software, Image Pro Plus version 5.1 and modified methods described in Ehrlich et al. (1984), Ehrlich et al. (1991a), Ehrlich et al. (1991b), McCresh et al. (1991) and Ehrlich et al. (1997). The PIA was used to calculate the porosity of each thin section using digitized plane polarized light (PPL) photomicrographs of the thin sections. Each thin section was divided into two sections for photomicrographs to be collected at 10X magnification and divided into six sections for photomicrographs to be collected at 25X magnification. The porosity shown in Figures 3-4a and 3-4c is blue in color due to the blue epoxy used during thin section preparation. In each photomicrograph, grains, cement and porosity were isolated into separate categories using a digital filter to assign a different color to each pixel group based on their color intensity values in the enhanced PPL image (Ehrlich et al., 1984 and Ehrlich et al.,

Table 3-1. Point counting data, including Van Der Plas (1965) 2σ confidence interval correction range compared to visually estimated petrographic porosity values obtained using Pettijohn et al. (1987) as a guide.

<table>
<thead>
<tr>
<th>Thin Section</th>
<th>Sedimentary Facies</th>
<th>Point Count Porosity By Volume</th>
<th>Corresponding Van der Plas (1965) 2σ Confidence Interval</th>
<th>Point Count Porosity Range of Sample</th>
<th>Visual Petrographic Porosity Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-47-56'</td>
<td>1</td>
<td>3.6%</td>
<td>1%</td>
<td>2.6 - 4.6%</td>
<td>10%</td>
</tr>
<tr>
<td>MW-60-102'</td>
<td>2a</td>
<td>20.3%</td>
<td>4.5%</td>
<td>15.8 - 24.8%</td>
<td>30%</td>
</tr>
<tr>
<td>MW-43-175'a</td>
<td>2b</td>
<td>28%</td>
<td>4.5%</td>
<td>23.5 - 32.5%</td>
<td>40%</td>
</tr>
<tr>
<td>MW-45-134'</td>
<td>3</td>
<td>22%</td>
<td>4%</td>
<td>18 - 26%</td>
<td>20%</td>
</tr>
<tr>
<td>MW-44-201.5'</td>
<td>5</td>
<td>0.2%</td>
<td>1%</td>
<td>0 - 1.2%</td>
<td>&lt;5%</td>
</tr>
</tbody>
</table>
1991a). By assigning different colors to the grains, cement and porosity in the photomicrograph, as shown in Figure 3-4b and 3-4d, the image analysis software used color thresholding to calculate porosity (Ehrlich et al., 1991a).

![Photomicrographs](image)

Figure 3-4 (a-d). Photomicrographs taken from thin section MW-59 - 142’ - facies 2b using a polarized microscope in PPL (3-4a and 3-4c) and Image Pro Plus version 5.1 image analysis software (3-4b and 3-4d). Photomicrographs 3-4a and 3-4b were taken at 10X magnification and photomicrographs 3-4c and 3-4d were taken at 25X magnification.

The porosity percentage was obtained by comparing the number of porosity assigned pixels to the sum of cement and grain assigned pixels. Each of the photomicrographs taken at different magnifications were geometrically averaged to get an average porosity percentage for each thin section. Table 3-2 presents a comparison of the conventional plug porosity to the averaged 10X and 25X magnifications of the PIA generated porosity and the visually estimated petrographic porosities for these sixteen samples.
Table 3-2. Porosity values obtained from conventional laboratory plug analysis, geometrically averaged PIA values for 10X and 25X magnifications and the visual estimation of porosity using a petrographic microscope. PIA porosity for MW-45-154' and BRSB-59/59A-183.5' was not able (NA) to be calculated due to vast number of points during the 10X PIA analysis.

Results

Qualitative Petrographic Description

As indicated in Figure 3-1, the majority of the available thin sections were collected from the sedimentary facies 2a and 2b. These facies are the key aquifer flow units within the Saginaw Aquifer. The mineral composition of matrix grains in facies 2a and 2b is primarily quartz with less than 5% plagioclase grains. Utilizing description techniques found in Appendix A of Pettijohn et al. (1987), the roundness of the grains range from subangular to rounded, however, a majority of the grains are described as subangular to subrounded (Figure 3-2b). This indicates textural immaturity most likely
due to minimal transport and reworking. The grain sortings range from poor to well sorted (Figure 3-1a). This is most likely due to different sedimentary deposition environments. Depositional environments with well sorted samples suggest higher energy, channel environments. Facies 2a and 2b thin sections appear to have minimal preferred alignment of grains.

Thin sections from facies 2a and 2b have minimal grain contacts in some areas. Other portions exhibit inhomogeneous packing and texture with grain suturing and elongated grain contacts (Figure 3-5b). Most thin sections however do not exhibit signs of significant compaction which indicates that porosity was somehow preserved during the rock forming compaction process.

Evidence of clay and calcite cement is observed between the matrix grains for the facies 2a and 2b thin sections. Clay cements were present but did not dominate the intergranular pore space in most of the thin sections as presented in Figure 3-6. The more dominating calcite cement exhibits tiny holes within what should be a massive texture, which indicates dissolution. Calcite dissolution can be caused by an aggressively low pH fluid which can dissolve calcite and feldspar (Kehew, 2000).

Cement dissolution between grains was apparent in thin sections (Figures 3-5a and b). Evidence of remnant cement and plagioclase grains suggest that the original grain matrix was preserved with cement during compaction. After the diagenesis of the Saginaw Formation, it is thought that the dissolution of more soluble calcite cement and plagioclase grains occurred. For these reasons, both minor compactional textures and cement dissolution associated with the current open framework textures suggest that porosity was preserved during the compaction process.
Figures 3-5 (a-b). Photomicrograph of (a) MW-43-92' - facies 2a and (b) BRSB-59/59A-142' - facies 2b highlighting the porosity of these facies and minimal compaction properties in these samples. Both photomicrographs were taken at 25X magnification.
Figure 3-6 (a-b). Photomicrographs taken at 25X magnification of (a) MW-45-145.5'-facies 2a and (b) BRSB-59/59A-184' - facies 2b illustrating some of the clay and calcite cement features within these facies.
Facies 1 and 3 thin sections also have similar quartzose and plagioclase grain composition but with more evidence of compaction and decreased porosity percentages compared to facies 2a and 2b. Figure 3-7 shows evidence of moderate grain alignment with decreased size in matrix grains and porosity. There is also evidence of calcite cement dissolution. Point contacts, elongated grain contacts and suturing are more dominant in these facies indicating a greater loss of porosity due to compaction.

There is no evidence of grain fracturing in the existing suite of thin sections. The lack of fracturing and well preserved porosity indicates that the Saginaw Aquifer (at least in the Americhem site area) is matrix dominated. This is not to say that fractures do not exist within the Americhem site subsurface but it is likely that if present, they are not the major contributing component to the flow.

A majority of the thin sections from available facies contain iron carbonate concretions which appear to be siderite nodules as shown in Figure 3-8. Table 3-3 presents the distribution of siderite nodules within the thin section suite. This correlates with the siderite nodules observed in the Venable (2006) analysis of the Americhem Saginaw Aquifer core.

Siderite precipitation can help to preserve porosity during early diagenesis or compaction (Mozley, 1989). Or, it can decrease porosity during deep burial process when multiple generations of siderite nodules precipitate due to the dissolution of feldspar matrix grains (Kierkegaard, 1998). In either environment the presence of these iron carbonate concretions can affect porosity.
Figure 3-7 (a-b). Photomicrographs of (a) BRSB-59/59A-228' - facies 1 and (b) MW-45-134' - facies 3 taken at 25X magnification depict the reduced porosity, decreased grain sizes and increased clay and cement in these facies.
Figure 3-8. Photomicrograph of MW-44-146.5’- facies 2a highlighting siderite nodules commonly found in most of the existing thin sections.

<table>
<thead>
<tr>
<th>FACIES</th>
<th>Total Number of Thin Sections</th>
<th>Number of Thin Sections With Siderite Nodules</th>
<th>Percentage of Thin Sections With Siderite Nodules</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACIES 1</td>
<td>6</td>
<td>6</td>
<td>100%</td>
</tr>
<tr>
<td>FACIES 2a</td>
<td>16</td>
<td>15</td>
<td>94%</td>
</tr>
<tr>
<td>FACIES 2b</td>
<td>18</td>
<td>17</td>
<td>94%</td>
</tr>
<tr>
<td>FACIES 3</td>
<td>8</td>
<td>7</td>
<td>88%</td>
</tr>
<tr>
<td>FACIES 5</td>
<td>1</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 3-3. Distribution siderite concretions within the Americhem Saginaw Aquifer thin section suite.

The repeated occurrence of siderite nodules observed within these samples could potentially be another reason why the large amounts of matrix controlled porosity was preserved during compaction. It is difficult to determine using a petrographic microscope whether the siderite has been subjected to dissolution or that the euhedral crystal facies
result from mineral precipitation. Figure 3-8 may indicate potential overgrowth features on some of the matrix grains, and suggests siderite precipitation. Further investigation using a scanning electron microscope (SEM) is suggested to determine the dissolution or precipitation of these features. It is also recommended the chemical characterization of siderite be conducted. Studies in Mozley (1989) show that chemical composition of siderite can determine whether pore water is from a marine or fresh water depositional environment. This further research could help to provide more data to further prove the previously described depositional facies of the formations comprising this aquifer as mentioned in Venable (2006).

*Quantitative Analysis*

The conventional laboratory plug porosity analysis data was compared to PIA generated porosity data and the visually estimated porosity values in Figures 3-9a-c. Unfortunately the data correlation did not produce predicted results. The 10X and 25X magnification correlation coefficients ($R^2$ values) are not as high as would have been expected for linear trend lines (0.2159 and 0.44735 respectively).

The 25X magnification shows the best data correlation using a linear trend line as comparison. The 10X magnification data indicate a very poor correlation. This is most likely explained by only using two photomicrographs used during the 10X magnification image analysis process, and that the image analysis software is constrained by the number of units it can count. By increasing the magnification of each photomicrograph, the image analysis software is able to better quantify the porosity of the image as in the 25X magnification case, which produced greater correlation coefficients value. The
a. Petrographic Image Analysis (PIA) Porosity
10X Magnification

- Facies 2a
- Facies 2b
- Facies 3
- Best Fit Trendline

Trendline Equation:
\[ y = 0.387x + 14.27 \]
\[ R^2 = 0.2159 \]

b. Petrographic Image Analysis Porosity
25X Magnification

- Facies 2a
- Facies 2b
- Facies 3
- Best Fit Trendline

Trendline Equation:
\[ y = 0.5874x + 11.524 \]
\[ R^2 = 0.44735 \]
**Figure 3-9 (a-c).** Correlation graphs reflecting how the PIA and visually estimated petrographic porosity data compares to the conventional laboratory plug porosity analysis.

conventional laboratory plug porosities were also compared to the visually estimated porosities shown on Figure 3-9c. Once again, less than desired correlation coefficients were obtained with this data set.

Location of where the samples were collected can be an explanation for the less than desired correlation discrepancy of porosity values. The thin sections were cut from or near the same interval as the plugs but not from the plug itself. This could cause small scale heterogeneities which could have skewed these results. Should similar studies be completed, it is suggested that PIA be completed on thin sections created from the plugs used for comparison as described in Younger (1992).
The major reason for this discrepancy is most likely due to microporosity. The traditional laboratory plug analysis is able to account more accurately for microporosity within the sample. In contrast the image analysis porosity values are limited by what the petrographic microscope can see. The photomicrograph is also limited during the pixel assignment portion of the filtering process.

Although the quantitative comparison of this exercise was disappointing this petrographic study did provide evidence of cement dissolution and lack of fracturing at the microscopic level. This indicates that the flow properties within the Saginaw Aquifer are most likely matrix dominated at the Americhem site scale. This study also provided insight for future projects utilizing PIA data.
CHAPTER IV
PERMEABILITY ANALYSIS

Objective

A high resolution quantitative air permeameter study was performed on the Ameritech Saginaw Aquifer core suite to collect localized permeability measurements. Permeability values were measured and evaluated in order to establish permeability ranges for each sedimentary facies described in Venable (2006). These permeability ranges can then be utilized during future groundwater modeling analyses instead of solely relying on standard permeability values obtained from aquifer matrix composition and/or costly field and laboratory tests.

Methods

Equipment

A mini air permeameter, made by Temco, Inc (model MP-401) was utilized in this study as shown in Figure 4-1. This unit consists of a nitrogen tank, gas regulator, an absolute transducer to monitor the injection pressure and flow pressure, electronic mass flow meters to monitor the gas flow rate, and a measuring probe. The measuring probe is mounted on a stand controlled by an air cylinder so consistent pressure is applied to each core sample. (Temco, 2006).

The mini air permeameter unit is connected to a computer which runs the Temco’s SmartPerm™ software program. This software collects the measured data and calculates permeability values in millidarcies (mD) based on the modified Darcy equation shown in Figure 4-2 (Temco, 2006).
As the probe is lowered onto the sample, the o-ring at the tip of the probe creates a seal to ensure the nitrogen gas is not prematurely leaked into the atmosphere. This mini air permeameter unit has a variety of tips with different diameters which can be selected for core samples with various lengths and diameters. Tip #3, with an outer diameter (OD) of 3/8 inch and an inner diameter (ID) of 1/8 inch (Temco, 2006) was used to collect the core sample permeability measurements in this study based on the diameter and length of the Americhem Saginaw Aquifer core suite samples.

As the probe is lowered onto the sample, the flow valve is opened which allows the nitrogen to pass through the flow rate and pressure monitoring units, the measuring probe and finally through the sample as shown in Figure 4-3. As the nitrogen moves...
\[ K_a = \frac{2 \mu Q_b P_b T_{act}}{a G_0 (P_1^2 - P_2^2) T_{ref}} \times 1000 \]

\( K_a \) = air or gas Permeability in md (millidarcys)
\( \mu \) = viscosity, centipoise(cp) of gas, at its average flowing temperature and pressure in core
\( Q_b \) = volumetric flow rate, standard cubic centimeters per second (scc/sec), referenced to \( P_b \)
\( P_b \) = standard Reference Pressure for mass flow meters, atmospheres absolute (default value = 1.000)
\( P_1 \) = upstream pressure (pressure at tip), atmospheres absolute
\( P_2 \) = downstream pressure (pressure at tip), atmospheres absolute
\( a \) = internal radius of probe tip seal
\( G_0 \) = geometrical shape factor function, dimensionless
\( T_{ref} \) = reference temperature of mass flow meters, K, default value = 294 K (=21°C), or 530 R (=70 °C)
\( T_{act} \) = actual flowing temperature of gas, K or R

**Figure 4-2.** Modified Darcy equation used by Temco’s SmartPerm™ software program to calculate permeability values. Equation modified from Temco (2006).

through the sample, instantaneous flow rates, flow pressures and permeability values are measured, calculated and displayed using the SmartPerm™ software interface screen.

The computer program measures these instantaneous values and notifies the user once stabilized criteria are met. The default stabilization criteria were utilized in this study.

For more specific information pertaining to the stabilization criteria, please see the Temco, Inc. Instruction Manual for Mini-Permeameter (2006). Care was taken to use a consistent flow pressure range of 20 to 25 pound per square inch absolute (psia) for each core sample.
Air Permeameter Unit Calibration

Before each sampling event the air permeameter unit was calibrated with the current atmospheric temperature and pressure in the laboratory. This atmospheric pressure measured in psia is then used in the computation of each permeability measurement. By setting the unit to atmospheric pressure each time, it corrects for any changes in the atmosphere between different data collection events.

Data Collection

Permeability measurements were collected at approximately one foot intervals and/or intervals in which a change in a sedimentary sedimentary facies occurred. Approximately 1085 sample intervals were evaluated throughout the core suite and utilized for this study. Permeability measurements were collected at each interval three to six times depending upon the material of each sample. Multiple measurements were taken at various locations within the interval to ensure the results represented the sample
location as accurately as possible. At each sample interval, permeability was measured on the x and z axes as shown in Figure 4.4. During the field collection of the core suite, the lateral orientation (x and z axes) of each core was not noted, therefore horizontal homogeneity is assumed during this analysis. Permeability values at each sampling interval were geometrically averaged for one permeability measurement per sampling interval.

Shale-dominated samples associated with facies 1, 3, 4 and 5 commonly required a longer-than-average stabilization period (if stabilization was even achieved). This is due to lack of open pores for the nitrogen to flow through and increased flow pressures within the equipment. These samples were typically measured 3 times. Samples that were sandstone dominated (facies 2a, 2b and 3) were measured on average four to six times due to their variability in pore connectivity and cementation and also to verify whether or not the probe was placed on a grain, which would produce a false low permeability value for that measurement.

It should be noted that flow pressures did vary depending upon the sample grain size (and therefore sedimentary facies). Shale and siltstone dominated samples, even with a low flow rate (10 cc/min) still had flow pressures higher than 25 psia and at times did not stabilize within the default flow pressure threshold of 50 psia. These samples were allowed to stabilize with the lowest flow rate pressure possible and/or after approximately 5 minutes, readings were collected with or without achieving stabilization.
Figure 4-4. Sample core image with measurement axes. Permeability measurements were collected on the x and z axes. Original image was modified from Venable (2006).

Samples consisting of poorly-cemented sandstone units occasionally did not have enough resistance to create a flow pressure value of 20 psia, even with a flow rate of 2000 cc/min which is the maximum flow rate value for this equipment. Care was taken to discriminate and not include measurements collected with poor core/probe seals and uneven surfaces. Most locations with permeability values greater than 2000 mD had flow pressures ranging from 16.5-25 psia. Care was also taken to include samples whose flow pressure was at least 2 psia units above the calibrated atmospheric pressure.
Data Calibration

Twenty-six plug samples were collected from various intervals within sedimentary facies 2a, 2b and 3. These samples were sent to Omni Laboratories Inc., located in Houston, Texas for permeability plug analysis. Omni Laboratories used a suite of routine core analyses which included: permeability to air, porosity, sample drying, grain density and a sample description for each plug. The plugs were then analyzed using the mini air permeameter. Care was taken to use the smallest probe tip (tip #1) since the plug diameters were cut smaller than the original core samples.

Results

Equipment Calibration

The Omni Laboratory permeability values were plotted against the mini air permeameter permeability values as presented in Figure 4.5. A linear correlation can be made between the two data sets with a good correlation coefficient. It appears that the laboratory permeability values are greater than mini air permeameter permeability values, especially as permeability increases. Decreased permeability measurements collected from the mini air permeameter may be due to the plug cutting process. While making a plug, the outer edges may have been filled in by small particles or grains. Also, the markings on the samples made by the laboratory, may have plugged or clogged potentially permeable areas when putting the tip on the samples. It should be noted that five data points were not included in this analysis due to the inability to achieve a proper seal between the measuring probe and plug (MW-45-134', MW-154', MW-47-125', BRSB-59/59A-80 and BRSB-60/60A). Taking these factors into account, the mini air permeameter does produce accurate yet conservative permeability measurements. It is
recommended that in future studies, permeameter measurements be collected on core samples before obtaining plugs from each interval and/or before plugs are sent to the laboratory for analysis.

**Figure 4-5.** Plot of laboratory air permeability (Lab k) versus air permeameter permeability (Air k).

**Permeability Values**

The results of the high resolution, localized permeability data collected for each boring location is shown in Figures 4.6 a-d. Using boring logs modified from Venable (2006), each boring location figure consists of a gamma ray log plot, interpreted sedimentary facies and a plot of the geometrically averaged permeability values. This information enables groundwater modelers to subdivide the aquifer and assign more realistic permeability to specific depths instead of using one value for an entire formation or sedimentary facies within the groundwater model. Chapter 5 will further discuss the relationships between the permeability data and gamma ray logs shown in Figure 4-6a-d.
Histograms illustrating how frequently certain permeability values occur within each facies are presented in Figure 4.7. These also illustrate the permeability range for each sedimentary facies. Using statistical analysis, permeability ranges for each facies can be obtained. Table 4-1 presents a mean, median, mode and standard deviation for each sedimentary facies. From these calculations, permeability ranges were created for each sedimentary facies. It is the goal that these localized ranges can be used in future groundwater models of any scale. Chapters 5 and 6 will discuss the utility of these ranges and compare them with other data sets and types.

**Air Permeameter Measurement Variation**

As previously mentioned, each sample interval location was measured three to seven times, depending on the sample composition. Variability occurred within each set of measurements. Table 4-2 presents the calculated mean standard deviation and standard deviation range for each sedimentary facies. Facies 1, 4 and 5 have smaller averaged standard deviations between measurements. This means that the measurements collected for each sample interval for these facies were relatively close in range when compared to sedimentary facies 2a, 2b and 3. Facies 2a, 2b and 3 have a wider range of averaged permeability values listed on Table 4-1 due to variations in grain size, and the amount of cementation. This wide range of values and larger standard deviations between each measurement of a sample interval, indicates a wide variation in measurements for these facies.

The air permeameter was able to capture the small scale variability in each sample. By capturing this variability the averaged permeability value was able to better account for small scale heterogeneities of the core and thus provide a more accurate
Figure 4-6a. Averaged permeability, sedimentary and gamma ray plots for MW-43 and MW-44. Modified from Venable (2006).
Figure 4-6b. Averaged permeability, sedimentary and gamma ray plots for MW-45 and MW-46. Modified from Venable (2006).
Figure 4-6c. Averaged permeability, sedimentary and gamma ray plots for MW-47 and BRSB-59/59A. Modified from Venable (2006).
Figure 4-6d. Averaged permeability, sedimentary and gamma ray plots for BRSB-60/60A and BRSB-61/61A. Modified from Venable (2006).
Figure 4-7a. Histogram presenting the distribution of permeability values from sedimentary facies 1, 4 and 5.

Figure 4-7b. Histogram presenting the distribution of permeability values from sedimentary facies 2a, 2b and 3.
Figure 4-7c. Histogram presenting the distribution of permeability values from sedimentary facies 1, 2a, 2b, 3, 4 and 5.
Table 4-1. Statistical information pertaining to the high resolution permeability data set. The range of permeability values are based on 2 standard deviations from the mean value.

<table>
<thead>
<tr>
<th>Depositional Facies</th>
<th>Mean Permeability Value (mD)</th>
<th>Median Permeability Value (mD)</th>
<th>Mode Permeability Value (mD)</th>
<th>Standard Deviation ( \sigma ) (mD)</th>
<th>Range of Measured Permeability Values (mD)</th>
<th>Range of Statistical Permeability Values 2( \sigma ) (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32</td>
<td>13</td>
<td>9</td>
<td>73</td>
<td>3.66 - 582</td>
<td>0 - 178</td>
</tr>
<tr>
<td>2a</td>
<td>1125</td>
<td>860</td>
<td>176</td>
<td>940</td>
<td>4.46 - 4554</td>
<td>0 - 3005</td>
</tr>
<tr>
<td>2b</td>
<td>921</td>
<td>779</td>
<td>374</td>
<td>653</td>
<td>4.86 - 3799</td>
<td>0 - 2227</td>
</tr>
<tr>
<td>3</td>
<td>577</td>
<td>113</td>
<td>7</td>
<td>888</td>
<td>3.32 - 3836</td>
<td>0 - 2353</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>9</td>
<td>5</td>
<td>9</td>
<td>2.29 - 54.5</td>
<td>0 - 30</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>14</td>
<td>11</td>
<td>7</td>
<td>4.73 - 35.4</td>
<td>1 - 29</td>
</tr>
</tbody>
</table>

Table 4-2. Statistical information pertaining to the variation of measurements collected for sample intervals within each facies.

value. In order to decrease the amount of variation between measurements at one sample, it is suggested that future studies collect a greater number of measurements and/or conduct an initial standard deviation test before collecting mass amounts of sample measurements.
CHAPTER V
FLOW PROPERTY ANALYSIS

Saginaw Aquifer Flow Properties

Flow properties including hydraulic conductivity and permeability are used to quantify and characterize aquifers. These types of data can be costly to gather and are usually intermittent. This often leads to assumptions during the aquifer characterization process. The eight core locations collected for the Americhem site (approximately 60 acres) is an impressive data set to distinguish aquifer, site and high resolution scale flow properties.

Permeability (k) and hydraulic conductivity (K) are both used to measure and quantify how easily water or other fluids can move through subsurface materials, though they each have different units. It is common in literature, conversation and site characterization to interchange these terms but unfortunately this can cause confusion. This is because while, they are related concepts, they are not the same.

Permeability

Fetter (2001) describes permeability as a way to quantify how easily a liquid can flow through a porous medium, independent of the liquid properties and hydraulic gradient. Using the Darcy equation as reference, permeability can be described as:

\[ k = Cd^2 \]

Where \( k \) = permeability, \( C \) = shape factor, and \( d \) is the diameter of individual grains. Permeability is typically measured in the units of a darcy (D), millidarcy (mD), centimeter\(^2\) or feet\(^2\). The high resolution permeability measurements from this study can be compared to existing permeability values found in literature and textbooks. Table 5-1
<table>
<thead>
<tr>
<th>Depositional Facies</th>
<th>Mean Permeability Value (mD)</th>
<th>Range of Measured Permeability Values (mD)</th>
<th>Range of Statistical Permeability Values (mD) 2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 silty shale and very fine/fine sandstone</td>
<td>32</td>
<td>3.66 582</td>
<td>0 178</td>
</tr>
<tr>
<td>2a medium/coarse sandstone</td>
<td>1125</td>
<td>4.46 4554</td>
<td>0 3005</td>
</tr>
<tr>
<td>2b fine/medium sandstone</td>
<td>921</td>
<td>4.86 3799</td>
<td>0 2227</td>
</tr>
<tr>
<td>3 interbedded layers of silty shale and fine/medium/coarse sandstone</td>
<td>577</td>
<td>3.32 3836</td>
<td>0 2353</td>
</tr>
<tr>
<td>4 siltstone, fine sandstone and mudstone</td>
<td>12</td>
<td>2.29 54.5</td>
<td>0 30</td>
</tr>
<tr>
<td>5 shale with coal and plant fragments</td>
<td>15</td>
<td>4.73 35.4</td>
<td>1 29</td>
</tr>
</tbody>
</table>

**Table 5-1.** Averaged permeability values associated with Venable (2006) depositional facies compared to general permeability values for similar lithologies. Permeability values modified from Chilinger (1964), Freeze and Cherry (1979), and Spitz and Moreno (1996)
presents the mean and range of permeability measurements obtained from the Americhem core and a synthesis of permeability values for similar aquifer material available in literature.

**Hydraulic Conductivity**

Hydraulic conductivity measures the rate at which a fluid moves through a porous medium. This proportionality coefficient takes into consideration the specific fluid properties during computation (Fetter 2001 and Freeze and Cherry 1979).

\[
K = \frac{k \rho g}{\mu}
\]

Where \( K \) = hydraulic conductivity, \( k \) = permeability, \( \rho \) = fluid density, \( g \) = acceleration due to gravity and \( \mu \) = dynamic fluid viscosity. Hydraulic conductivity is measured in a wide variety of units. More common units include: meters per second or day, feet per second or day and gallons per day per feet\(^2\).

The measurements obtained from the mini air permeameter were collected in permeability units (millidarcies). Hydraulic conductivity values are common in literature and field tests. Therefore the conversion below was used to convert the mini air permeameter and laboratory values for comparison.

\[
\begin{align*}
1 \text{ darcy} &= 9.87 \times 10^{-9} \text{ cm}^2 \quad \text{or} \quad 1 \text{ mD} = 9.87 \times 10^{-6} \text{ cm}^2 \\
1 \text{ darcy} &= 9.87 \times 10^{-13} \text{ m}^2 \quad \text{or} \quad 1 \text{ mD} = 9.87 \times 10^{-9} \text{ m}^2 \\
K &= k_i \times \frac{\rho \times g}{\mu}
\end{align*}
\]

\( K \) = Hydraulic Conductivity in \( \frac{\text{m}}{\text{s}} \)

\( k_i \) = Permeability (intrinsic) in \( \text{m}^2 \)

\( \rho \) = Water Density = 1000 \( \text{Kg/m}^3 \) (at 20 \( \text{C} \))

\( g \) = Gravitation Acceleration Constant = 9.8 \( \frac{\text{m}}{\text{s}^2} \)

\( \mu \) = dynamic viscosity of water = 0.001 \( \text{Pa} \cdot \text{s} \) (at 20 \( \text{C} \))

Substituting and solving for \( K \) results in

\[
K = k_i \times 9.8 \times 10^6 \frac{1}{\text{m} \cdot \text{s}}
\]
<table>
<thead>
<tr>
<th>Depositional Facies</th>
<th>Mean Calculated Hydraulic K Value (m/s)</th>
<th>Range of Calculated Hydraulic K Values (m/s)</th>
<th>Range of Calculated Statistical Hydraulic K Values (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2σ</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>silty shale and</td>
<td>3.10 x 10^-7</td>
<td>3.54 x 10^-8</td>
<td>5.63 x 10^-6</td>
</tr>
<tr>
<td>very fine/fine</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>sandstone</td>
<td></td>
<td></td>
<td>1.72 x 10^-6</td>
</tr>
<tr>
<td>2a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>medium/coarse</td>
<td>1.09 x 10^-5</td>
<td>4.31 x 10^-8</td>
<td>4.40 x 10^-5</td>
</tr>
<tr>
<td>sandstone</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fine/medium</td>
<td>8.91 x 10^-4</td>
<td>4.70 x 10^-8</td>
<td>3.67 x 10^-5</td>
</tr>
<tr>
<td>sandstone</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>interbedded layers</td>
<td>5.58 x 10^-4</td>
<td>3.21 x 10^-8</td>
<td>3.71 x 10^-5</td>
</tr>
<tr>
<td>of silty shale and</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>fine/medium</td>
<td></td>
<td></td>
<td>2.27 x 10^-5</td>
</tr>
<tr>
<td>coarse sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>siltstone, fine</td>
<td>1.16 x 10^-7</td>
<td>2.22 x 10^-8</td>
<td>5.27 x 10^-7</td>
</tr>
<tr>
<td>sandstone and mudstone</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>2.90 x 10^-7</td>
</tr>
<tr>
<td>shale with coal and</td>
<td>1.45 x 10^-7</td>
<td>4.58 x 10^-8</td>
<td>3.42 x 10^-7</td>
</tr>
<tr>
<td>plant fragments</td>
<td></td>
<td></td>
<td>9.67 x 10^-9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.81 x 10^-7</td>
</tr>
</tbody>
</table>

Table 5-2. Calculated hydraulic conductivity values from original permeability measurements using the conversion on the previous page. Hydraulic conductivity values for similar lithologies are calibrated from Freeze and Cherry (1979), and Spitz and Moreno (1996).

Freeze and Cherry 1979
Table 2.2 (m/s)

<table>
<thead>
<tr>
<th></th>
<th>Low Values</th>
<th>High Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>10^-10</td>
<td>10^-4</td>
</tr>
<tr>
<td>Shale</td>
<td>10^-11</td>
<td>10^-6</td>
</tr>
</tbody>
</table>

Spitz & Moreno 1996
Figure 2.5 (m/s)

<table>
<thead>
<tr>
<th></th>
<th>Low Values</th>
<th>High Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Sandstone</td>
<td>10^-7</td>
<td>10^-3</td>
</tr>
<tr>
<td>Karstic Sandstone</td>
<td>10^-7</td>
<td>10^-5</td>
</tr>
<tr>
<td>Dense Shale</td>
<td>10^-11</td>
<td>10^-8</td>
</tr>
<tr>
<td>Fractured Shale</td>
<td>10^-9</td>
<td>10^-5</td>
</tr>
</tbody>
</table>

Horizontal Hydraulic K Values
Spitz & Moreno 1996
Appendix B Table B.3 (m/s)

<table>
<thead>
<tr>
<th></th>
<th>Low Values</th>
<th>High Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone 29% Porosity</td>
<td>2.32 x 10^-5</td>
<td>5.4 x 10^-3</td>
</tr>
<tr>
<td>Sandstone</td>
<td>3.3 x 10^-9</td>
<td>5.4 x 10^-3</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1.42 x 10^-9</td>
<td>1.42 x 10^-3</td>
</tr>
<tr>
<td>Sandstone</td>
<td>4.75 x 10^-8</td>
<td>4.75 x 10^-8</td>
</tr>
<tr>
<td>Sandstone</td>
<td>3.4 x 10^-7</td>
<td>3.4 x 10^-7</td>
</tr>
<tr>
<td>Sandstone, fine-grained</td>
<td>2.31 x 10^-9</td>
<td>2.31 x 10^-9</td>
</tr>
<tr>
<td>Sandstone, fine</td>
<td>5 x 10^-9</td>
<td>2.27 x 10^-9</td>
</tr>
<tr>
<td>Sandstone, medium-grained</td>
<td>3.59 x 10^-9</td>
<td>3.59 x 10^-9</td>
</tr>
<tr>
<td>Sandstone, silty</td>
<td>2.52 x 10^-8</td>
<td>2.52 x 10^-8</td>
</tr>
<tr>
<td>Sandstone, coarse</td>
<td>1.07 x 10^-5</td>
<td>1.07 x 10^-5</td>
</tr>
<tr>
<td>Sandstone arkosic, siltone, and shale</td>
<td>4.74 x 10^-10</td>
<td>7.1 x 10^-10</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.4 x 10^-6</td>
<td>1.4 x 10^-6</td>
</tr>
<tr>
<td>Shale</td>
<td>2.4 x 10^-6</td>
<td>2.6 x 10^-6</td>
</tr>
<tr>
<td>Shale</td>
<td>1.16 x 10^-13</td>
<td>4.75 x 10^-13</td>
</tr>
<tr>
<td>Shale</td>
<td>2 x 10^-6</td>
<td>2 x 10^-6</td>
</tr>
<tr>
<td>Siltstone</td>
<td>0.1 x 10^-10</td>
<td>1.42 x 10^-10</td>
</tr>
<tr>
<td>Siltstone-shale</td>
<td>2 x 10^-6</td>
<td>2 x 10^-6</td>
</tr>
<tr>
<td>Siltstone-shale</td>
<td>2.8 x 10^-7</td>
<td>2.8 x 10^-7</td>
</tr>
</tbody>
</table>
Table 5-2 presents the calculated hydraulic conductivity values corresponding to the Venable (2006) sedimentary facies as well as hydraulic conductivity measurements found in literature for similar subsurface materials.

**Evaluation**

The permeability values for facies 1 exceeded the shale ranges of Freeze and Cherry and (1979) and Spitz and Moreno (1996) and the hydraulic conductivity values coincided well with the Spitz and Moreno (1996) Appendix B Sandstone, arkosic, siltstone, and shale range.

The mean permeability values and ranges of facies 2a exceeded the Freeze and Cherry (1979) and Spitz and Moreno (1996) ranges for sandstone and karstic sandstone and was within the Chilinger 1964 sandstone range. The mean hydraulic conductivity mean values and ranges for facies 2a are greater than the Freeze and Cherry (1979) and Spitz and Moreno (1996) ranges for sandstone. This facies is comparable to the coarse and medium sandstone ranges provided in Spitz and Moreno (1996) Appendix B.

The mean permeability values of facies 2b and 3 exceeded the sandstone Freeze and Cherry (1979) range and were within the Spitz and Moreno (1996) karstic sandstone range. When comparing facies 2b to the fine grained range of Chilinger (1964), the higher range of 2b values approached Chilinger's (1964) range limit of 4,000 mD. The hydraulic conductivity mean values for facies 2b were closer to the Freeze and Cherry (1979) and Spitz and Moreno (1996) sandstone ranges and closely matched the Spitz and Moreno (1996) Appendix B fine grained sandstone value and ranges.

Facies 3 is considered a combination of sandstone and shale, although the hydraulic conductivity ranges for this facies more closely resembled the sandstone and
dense sandstone ranges from Freeze and Cherry (1979) and Spitz and Moreno (1996). This wide range coincided with many of the ranges found in Spitz and Moreno (1996) Appendix B.

Permeability values for facies 4 and 5 exceeded the shale ranges of Freeze and Cherry (1979) and Spitz and Moreno (1996). The hydraulic conductivity means and range of facies 4 best fit within the Spitz and Moreno (1996) Appendix B Siltstone-Shale ranges and they hydraulic conductivity values from facies 5 approach the shale ranges in all three references.

Facies 2a, 2b and 3 produced higher than average permeability values. These values highlight the importance of the Saginaw Aquifer and its matrix grain properties. As referenced in chapter 4 the air permeameter measurement were typically less than the laboratory results. Taking this into account, actual permeability (and hydraulic conductivity) measurements may be greater than the mean and ranges listed in Tables 5-1 and 5-2.

**Gamma Ray Log Data**

Down-hole wire-line logging is a common technique used to evaluate flow properties. It is a relatively inexpensive and quick tool that does not require vast amounts of time and training to analyze. One form of down-hole wire-line logging is a gamma ray log. The data for these logs is collected by measuring the amount of radioactivity in the subsurface materials in counts per second. Shale dominated layers typically contain more radioactive elements, as such clay/shale layers will produce relatively high values of counts per second. Conversely, sandstone dominated layer have few radioactive...
elements and will produce fewer counts per second on a gamma log (Ellis and Singer 2007 and Conger and Low 2006).

Gamma ray logs were collected from each of the eight monitoring well/bore hole locations. Based on their associated depths, the collected gamma ray values were categorized into the different depositional facies determined in Venable 2006. Figure 5-1 presents a histogram showing the distribution of gamma ray values among the different sedimentary facies. Statistical analysis was completed on the gamma ray data and the results are summarized in Table 5-3.

**Figure 5-1.** Histogram of gamma ray values in counts per second for each depositional facies described in Venable (2006). Gamma ray values modified and calculated from the gamma ray logs and data used in Venable (2006).
<table>
<thead>
<tr>
<th>Depositional Facies</th>
<th>Mean Gamma Ray Log Value (counts/sec)</th>
<th>Mean Permeability Value (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>109</td>
<td>32</td>
</tr>
<tr>
<td>2a</td>
<td>21</td>
<td>1125</td>
</tr>
<tr>
<td>2b</td>
<td>39</td>
<td>921</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>577</td>
</tr>
<tr>
<td>4</td>
<td>126</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>162</td>
<td>15</td>
</tr>
</tbody>
</table>

**Table 5-3.** Statistical information pertaining to the gamma ray log data and high resolution permeability data.

It is obvious in Figure 5-3 that a majority values for facies 2a and 2b are within the 25 to 50 counts per second range, and facies 4 and 5 tend to dominate intervals greater than the 100 counts per second. Facies 1 and 3 are not dominated by sandstone or shale but instead a mixture of both materials. This explains the distribution of these gamma ray data sets among various gamma intervals. Based on discussions in Ellis and Singer (2007), these values are comparable to typical gamma ray values.

It is fairly easy to determine sandstone or shale rich components there may be utility in developing a mean value for each facies, just as in Chapter 4 for permeability mean values. Even though the ranges may be broad, it does shed light onto new data collected and may speed up or help to better categorize the Saginaw Aquifer, at a minimum on the local scale of the Americhem site.

Table 5-3 also compares the statistical permeability mean values with the gamma ray log data set. It is a goal that these gamma ray data intervals can be used to distinguish other gamma ray log plot data sets completed within the Saginaw Aquifer but outside of the Americhem site location. By indentifying common gamma ray data at depth, it may be possible to more effectively map the Venable (2006) sedimentary facies and their associated flow properties throughout the Saginaw Aquifer.
Origin of Saginaw Aquifer Flow Properties

Microscope and Visual Analysis

As mentioned in Chapter 3, correlation between PIA porosity results and conventional laboratory porosity were fair at best. Recommendations were made to promote better correlations in future studies. The microscope analysis portion of this study did shed light into the how much microporosity may play in the Saginaw Aquifer's flow properties.

It was originally thought that the higher than expected values of permeability/hydraulic conductivity of the Saginaw Aquifer were due in most part due to secondary features (Vanlier et al., 1973 and Weston Solutions 2006 Report), similar to the fracture controlled Marshall Sandstone Aquifer (Westjohn and Weaver 1998). During the microscopic portion of this study, evidence of fracturing was not encountered at the microporosity scale. There was a lack of cement over growths on grains which would have indicated fracturing. Also, at the macroscale, visual inspection of the core did not identify any significant amount of fracturing. It is possible that the eight locations within this study did not penetrate the portions of the local scale of the aquifer which are fracture dominated. However, the permeability obtained from the laboratory and air permeameter analyses yielded such high values, that it is likely that matrix permeability alone is enough to generate the high permeability of the Saginaw Aquifer. It should be pointed out that the matrix within the samples collected from this local site do appear to be intact and produce higher than average permeability values.
Correlation of Depositional Facies with Flow Property Data

Venable (2006) identified six depositional facies to geologically explain the Saginaw Formation. In determining these facies, Venable (2006) was able to utilize existing gamma ray logs and localized core from the Americhem site to provide a more detailed description of the Saginaw Formation material and the processes which deposited them. These facies can be considered "geologic facies". Utilizing the above research, flow properties have been determined for each facies. By linking flow data to the Venable (2006) facies, these facies can more easily be transcribed and used in hydrogeologic investigation of the Saginaw Aquifer. By being able to adapt the correlating geological facies to a "flow facies" or "flow unit" the Saginaw Aquifer data set can potentially be expanded utilizing existing and future geologic data in hydrogeologic investigations.
CHAPTER VI

GROUNDWATER MODEL ANALYSIS

Saginaw Aquifer - Regional Assessment

Groundwater models are a tool to manage and better understand water resources. Data obtained from the Michigan Basin portion of the RASA study has been used in several groundwater models of the Saginaw Aquifer at different scales. Current groundwater models at various scales depict the Saginaw Aquifer as a single unit with one set of flow property values (Holtschlag et al. 1996, Hoaglund et al. 2002, and Luukkonen and Simard, 2004). Tables 6-1a and b present available flow property values used in various hydrogeologic investigations of the Saginaw Aquifer. It should be noted that most of the values used in this table were collected from the sandstone portion of the Saginaw Aquifer which is considered to be homogenous for ease of incorporating into groundwater modeling software.

The horizontal hydraulic conductivity values from Table 6-1a are within the literature ranges presented in Table 5-2. In fact, some of the values from Table 6-1a were referenced from the texts used in Table 5-2. The mean hydraulic conductivity values from Table 5-2 for facies 2a, 2b and 3 tend to be at least one magnitude greater than corresponding values used in Table 6-1a. This difference may be due to the varying amounts of cement and cement dissolution on the local and regional scale. Another explanation for this difference may be the laterally intermittent fine grained lenses within the single Saginaw Aquifer unit. Lastly, the values measured in this study could be considered more valid given the high resolution nature and its statistically significant results of this study.
<table>
<thead>
<tr>
<th>Location</th>
<th>Value/Range</th>
<th>Conversion</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional - Michigan Basin</td>
<td>4% - 34%</td>
<td>--</td>
<td>Westjohn et., al 1990</td>
</tr>
<tr>
<td>Ingham Co. (very well cemented)</td>
<td>3.20%</td>
<td>--</td>
<td>Westjohn et., al 1990</td>
</tr>
<tr>
<td>Ingham Co. (moderate to well cemented sandstone)</td>
<td>18% - 20%</td>
<td></td>
<td>Westjohn et., al 1990</td>
</tr>
</tbody>
</table>

**Horizontal Hydraulic Conductivity**

<table>
<thead>
<tr>
<th>Location</th>
<th>Value/Range</th>
<th>Conversion</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional - Saginaw Aquifer</td>
<td>1.9 x 10⁻² - 2.7 x 10⁻⁹ cm/s</td>
<td>1.9 x 10⁻⁷ - 2.7 x 10⁻¹² m/s</td>
<td>Westjohn et., al 1990</td>
</tr>
<tr>
<td>Regional - Saginaw Aquifer</td>
<td>2.83</td>
<td>1 x 10⁻⁴ m/s</td>
<td>Hoaglund et. al, 2002</td>
</tr>
<tr>
<td>Regional - Saginaw Aquifer</td>
<td>2.83 x 10⁴</td>
<td>1 x 10⁻⁷ m/s</td>
<td>Hoaglund et. al, 2002</td>
</tr>
<tr>
<td>Lansing Tri-County Area</td>
<td>7.5 ft/d</td>
<td>2.65 x 10⁻⁴ m/s</td>
<td>Holtschlag et al, 1996</td>
</tr>
<tr>
<td>Ingham Co. (very well cemented)</td>
<td>2.7 x 10⁻⁸ - 4.2 x 10⁻⁸ cm/s</td>
<td>2.7 x 10⁻¹⁰ - 4.2 x 10⁻¹⁰ m/s</td>
<td>Westjohn et., al 1990</td>
</tr>
<tr>
<td>Ingham Co. (moderate to well cemented sandstone)</td>
<td>2.7 x 10⁻⁸ - 3.3 x 10⁻⁸ cm/s</td>
<td>2.7 x 10⁻¹⁰ - 3.3 x 10⁻¹⁰ m/s</td>
<td>Westjohn et., al 1990</td>
</tr>
<tr>
<td>Bay City, Mi.</td>
<td>1.15 m/d</td>
<td>1.33 x 10⁻⁵ m/s</td>
<td>Stark and McDonald, 1980</td>
</tr>
</tbody>
</table>

**Vertical Hydraulic Conductivity**

<table>
<thead>
<tr>
<th>Location</th>
<th>Value/Range</th>
<th>Conversion</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional - Saginaw Aquifer</td>
<td>2.83 ft/day</td>
<td>1 x 10⁻⁴ m/s</td>
<td>Hoaglund et. al, 2002</td>
</tr>
<tr>
<td>Regional - Saginaw Aquifer</td>
<td>2.83 x 10⁴ ft/day</td>
<td>1 x 10⁻⁷ m/s</td>
<td>Hoaglund et. al, 2002</td>
</tr>
<tr>
<td>Regional-Saginaw Aquifer</td>
<td>0.001 to 55 ft/day</td>
<td></td>
<td>Westjohn and Weaver 1996</td>
</tr>
</tbody>
</table>

**Table 6-1a.** Saginaw Aquifer flow property data collected from various hydrogeologic investigations.

**Saginaw Aquifer Americhem Site Scale**

Flow unit properties corresponding the Venable (2006) geological facies have been plotted in a two-dimensional cross section presenting in Figures 6-1 a-b. This cross section was created using Petra Software® and the interpolated permeability values from this study. The gamma ray and interpolated permeability data logs are also included the cross section for reference. This figure illustrates that the Saginaw Aquifer portion of the Americhem Site is not a continuous layer, but instead it is comprised of interbedded flow units. Figure 6-1b also demonstrates the flow unit extents at depth and highlight the heterogeneities within the Saginaw Aquifer at the local scale.
Table 6-1b. Saginaw Aquifer flow property data collected from various hydrogeologic investigations.

Three-dimensional interpretations of the flow unit facies within the Americhem core is presented in Figures 6-2b and 6-2c. These figures were created using Groundwater Modeling System (GMS®) and MODFLOW software. It is apparent that there are four layers with significant flow properties within the extent that is typically considered to be the one-unit Saginaw Aquifer. These figures also highlight the location of the small scale, and intermittent lenses with low flow properties within the Saginaw Aquifer that may decrease productivity over their intervals.

Transmissivity Evaluation

To better estimate groundwater flow patterns, a known hydraulic conductivity for a unit can be multiplied by the saturated thickness of the aquifer, resulting in what is known as the transmissivity (T) (Fetter 2001) where:
\[ T = bK \]

\( T \) = transmissivity in length units\(^2\)/time, \( b \) = saturated thickness of the aquifer (length) and \( K \) = hydraulic conductivity (length/time). Common transmissivity measurements include ft\(^2\)/d or m\(^2\)/s. Figures 6-1b, 6-2b and 6-2c were used to assist in the development of transmissivity values or "usable" depths for each bore hole location, horizontal flow property units and a modified single layer transmissivity value as indicated on Table 6-2. These transmissivity values for the single layer aquifer approach in Table 6-2 are within the ranges specified in Table 6-1b. Unfortunately, field transmissivity data for the Americhem site was not available for comparison.

**Figure 6-1a.** Map showing location of cross section in Figure 6-1b. Modified from Weston Solutions (2006) Report.
Figure 6-1b. Cross section illustrating a two dimensional plot of gamma ray logs and permeability logs used to determine the major Saginaw Aquifer flow units. Modified from Venable (2006).
**Hydrogeological Flow Property Assessment**

By incorporating geological data usually reserved for sedimentary models, groundwater models can become a more accurate and robust tool. This study, along with others in Anderson (1989) and Flach et. al (1998), discuss and prove the benefits of utilizing qualitative data and bridging the gap between traditional sedimentary model data and hydrological model data sets.

High resolution permeability data obtained from this study has been used to create a qualitative assessment of flow properties for sedimentary facies developed in Venable (2006). The utility of the high resolution data set can assist in better determining the amount of "useable" aquifer by being able to better qualify and quantify the

**Figure 6-2a.** Location map of core represented in Figure 6-2b and Figure 6-2c. Modified from Weston Solution (2006) Report.
Figure 6-2b. A modified three-dimensional depiction of the distribution of Americhem flow units within the subsurface. Figure created using MODFLOW software.
Figure 6-2c. A modified three-dimensional depiction of the distribution of Americhem flow units within the subsurface. Figure created using MODFLOW software.
<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Depositional Facies</th>
<th>Depth Interval (ft bgs)</th>
<th>Thickness of Layer (ft)</th>
<th>Mean Hydraulic Conductivity Values</th>
<th>Transmissivity Values</th>
<th>Weighted Transmissivity Value For Single Aquifer Flow Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-43 2a</td>
<td>814 - 790</td>
<td>24</td>
<td>1.09 x 10^{-5}</td>
<td>2.62E-04</td>
<td>9.60 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>MW-43 2a</td>
<td>774 - 759</td>
<td>15</td>
<td>1.09 x 10^{-5}</td>
<td>1.64E-04</td>
<td>9.33 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>MW-43 2b</td>
<td>759 - 709</td>
<td>50</td>
<td>8.91 x 10^{-6}</td>
<td>4.46E-04</td>
<td>1.01 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-44 2a</td>
<td>797 - 776</td>
<td>21</td>
<td>1.09 x 10^{-5}</td>
<td>2.29E-04</td>
<td>1.33 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-44 3</td>
<td>776 - 746</td>
<td>30</td>
<td>5.58 x 10^{-6}</td>
<td>1.67E-04</td>
<td>8.06 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>MW-44 2a</td>
<td>746 - 736</td>
<td>10</td>
<td>1.09 x 10^{-5}</td>
<td>1.09E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-45 2a</td>
<td>801 - 789</td>
<td>12</td>
<td>1.09 x 10^{-5}</td>
<td>1.31E-04</td>
<td>9.09 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>MW-45 3</td>
<td>789 - 756</td>
<td>33</td>
<td>5.58 x 10^{-6}</td>
<td>1.84E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-45 2a</td>
<td>756 - 745</td>
<td>11</td>
<td>1.09 x 10^{-5}</td>
<td>1.20E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-45 2b</td>
<td>745 - 707</td>
<td>38</td>
<td>8.91 x 10^{-6}</td>
<td>3.39E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-45 5</td>
<td>707 - 703</td>
<td>4</td>
<td>1.16 x 10^{-7}</td>
<td>4.64E-07</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-45 2b</td>
<td>703 - 677</td>
<td>26</td>
<td>8.91 x 10^{-8}</td>
<td>2.32E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-46 2a</td>
<td>801 - 765</td>
<td>36</td>
<td>1.09 x 10^{-5}</td>
<td>3.92E-04</td>
<td>1.33 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-46 3</td>
<td>765 - 756</td>
<td>9</td>
<td>5.58 x 10^{-6}</td>
<td>5.02E-05</td>
<td>8.06 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>MW-46 2a</td>
<td>756 - 734</td>
<td>22</td>
<td>1.09 x 10^{-5}</td>
<td>2.40E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-46 2b</td>
<td>734 - 699</td>
<td>35</td>
<td>8.91 x 10^{-6}</td>
<td>3.12E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-46 2a</td>
<td>699 - 689</td>
<td>10</td>
<td>1.09 x 10^{-5}</td>
<td>1.09E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-46 2b</td>
<td>689 - 664</td>
<td>25</td>
<td>8.91 x 10^{-8}</td>
<td>2.23E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-47 2a</td>
<td>824 - 818</td>
<td>6</td>
<td>1.09 x 10^{-5}</td>
<td>6.54E-05</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-47 3</td>
<td>818 - 773</td>
<td>45</td>
<td>5.58 x 10^{-6}</td>
<td>2.51E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-47 2a</td>
<td>773 - 757</td>
<td>16</td>
<td>1.09 x 10^{-5}</td>
<td>1.74E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-47 2b</td>
<td>757 - 729</td>
<td>28</td>
<td>8.91 x 10^{-6}</td>
<td>2.49E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-47 1</td>
<td>729 - 719</td>
<td>10</td>
<td>3.10 x 10^{-7}</td>
<td>3.10E-06</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>MW-47 2b</td>
<td>719 - 712</td>
<td>7</td>
<td>8.91 x 10^{-8}</td>
<td>6.24E-05</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-59 2a</td>
<td>813 - 788</td>
<td>25</td>
<td>1.09 x 10^{-5}</td>
<td>2.73E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-59 2b</td>
<td>788 - 782</td>
<td>6</td>
<td>8.91 x 10^{-6}</td>
<td>5.35E-05</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-59 3</td>
<td>782 - 761</td>
<td>21</td>
<td>5.58 x 10^{-6}</td>
<td>1.17E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-59 2a</td>
<td>761 - 755</td>
<td>6</td>
<td>1.09 x 10^{-5}</td>
<td>6.54E-05</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-59 2b</td>
<td>755 - 715</td>
<td>40</td>
<td>8.91 x 10^{-6}</td>
<td>3.56E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-59 2a</td>
<td>715 - 714</td>
<td>1</td>
<td>1.09 x 10^{-5}</td>
<td>1.09E-05</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-59 1</td>
<td>714 - 700</td>
<td>14</td>
<td>3.10 x 10^{-7}</td>
<td>4.34E-06</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-59 2b</td>
<td>700 - 680</td>
<td>20</td>
<td>8.91 x 10^{-8}</td>
<td>1.78E-04</td>
<td>1.06 x 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>BRSB-60 2a</td>
<td>797 - 780</td>
<td>17</td>
<td>1.09 x 10^{-5}</td>
<td>1.85E-04</td>
<td>9.09 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-60 3</td>
<td>780 - 753</td>
<td>27</td>
<td>5.58 x 10^{-4}</td>
<td>1.51E-04</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-60 2a</td>
<td>753 - 735</td>
<td>18</td>
<td>1.09 x 10^{-5}</td>
<td>1.96E-04</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-60 2b</td>
<td>735 - 700</td>
<td>35</td>
<td>8.91 x 10^{-4}</td>
<td>3.12E-04</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-60 2a</td>
<td>700 - 694</td>
<td>6</td>
<td>1.09 x 10^{-7}</td>
<td>6.54E-05</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-61 2a</td>
<td>825 - 810</td>
<td>15</td>
<td>1.09 x 10^{-5}</td>
<td>1.64E-04</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-61 3</td>
<td>810 - 785</td>
<td>25</td>
<td>5.58 x 10^{-4}</td>
<td>1.40E-04</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-61 2b</td>
<td>785 - 763</td>
<td>22</td>
<td>1.09 x 10^{-5}</td>
<td>2.40E-04</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-61 2b</td>
<td>763 - 732</td>
<td>31</td>
<td>8.91 x 10^{-4}</td>
<td>2.76E-04</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>BRSB-61 2a</td>
<td>732 - 720</td>
<td>12</td>
<td>1.09 x 10^{-5}</td>
<td>1.31E-04</td>
<td>9.50 x 10^{-4}</td>
<td></td>
</tr>
</tbody>
</table>

Table 6-2. Transmissivity values for the Americhem core borings, horizontal flow properties and a modified single layer.
Venable (2006) sedimentary facies and using the depth and flow property ranges provided earlier in this study. It is the goal of this research that this data will assist future groundwater models of the Saginaw Aquifer on multiple scales.
CHAPTER VII
CONCLUSION

During the course of this study a set of high resolution flow properties have been developed to correspond and relate to Saginaw Formation sedimentary facies established in Venable (2006). These flow properties were compared with existing data obtained from previous hydrogeologic investigations, groundwater models and literature values. The high resolution flow property data set was within or exceeded local and regional scale ranges. This lends credibility to the procedures in this study and reaffirms the robustness of this aquifer.

Previous research indicated that the reason for the impressive flow capacity of this aquifer is due to fractures within the bedrock. Microscopic and visual inspection of the core did not find evidence of fractures. Instead, the microscopic inspection highlighted the dissolution of cement within the sandstone portions of the bedrock, with minor evidence of compaction. The relatively high permeability flow rates in the sandstone samples further the support the suggestion that the permeability of the Saginaw Aquifer is matrix controlled. Presence of heavily cemented pore networks within the sandstone facies during compaction worked to preserve porosity and pore throats. The later partial dissolution of cements allows the Saginaw Aquifer to produce vast quantities of water for municipal and industrial use without any additional fracturing.

During this study two main methods were used to collect the data. The microscopic PIA analysis did not prove to be as helpful as initially thought though, it is strongly suggested that these resources be reviewed to determine more effective
quantitative results. The qualitative portion of this method proved to be of value in order to better evaluate and understand the framework grains and pore relationships within the Saginaw Aquifer unit.

The mini air permeameter was able to collect rapid, and consistent data measurements for over 1,500 feet of core from the eight boring locations. Multiple readings were collected in order to report an averaged value for each core interval. A series of statistical analyses was conducted on the permeability data set to determine accuracy. The variation within the data set corresponding to each sedimentary facies was anticipated due to the heterogeneity of cementation and lithology at this scale.

The majority of the collected air permeameter measurements were less than the corresponding laboratory plug data intervals that were used for calibration of the air permeameter results. Likely causes for this differences was discussed in chapter 4. It is for this reason that the mini air permeameter values are considered to be a more conservative estimate for the Saginaw Aquifer flow properties.

The ability to utilize sedimentary or geological data within a groundwater model can be an effective way increase the accuracy of the model. By incorporating existing geological information into a groundwater model, it may be possible to provide a more complete data set to be used to generate a more realistic model. The Saginaw Aquifer provides water for a large population and industry. It is for this reason the Saginaw Aquifer needs to be better understood in order to adequately protect and utilize this valuable resource. It is the goal of this research that the flow property values obtained from this study will be able to better assist future groundwater models of the Saginaw Aquifer for regional, local and site scales.
BIBLIOGRAPHY


Chilingar, G.V., 1964, Relationship, Between Porosity, Permeability, and Grain-Size Distribution of Sands and Sandstones, *Developments in Sedimentology*, vol. 1, pgs 71-75.


