Hydrogeological Characterization of Contaminated Glacial Sediments in South Central Wisconsin

By

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HYDROGEOLOGICAL CHARACTERIZATION OF CONTAMINATED GLACIAL SEDIMENTS IN SOUTH CENTRAL WISCONSIN

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Unconsolidated sediments often overlie significant bedrock aquifers within North America and are important to characterize for groundwater and contaminant studies. However, the dynamic nature of ice margins results in heterogeneous sediments that are difficult to characterize geologically and hydraulically. In this study, a detailed investigation of the unconsolidated sediment was completed to determine how best to characterize the hydrogeology by integrating multiple independent and high-resolution data sets including: stratigraphic logs, grain size analysis, surface geophysics, hydraulic head profiles, and volatile organic compound concentrations. The unconsolidated sediments were found to be highly heterogeneous geologically but with low vertical hydraulic contrasts. Where found, vertical hydraulic contrasts were typically a result of four geologic features: top of rock, sand-diamict contact, interbedded diamict, and mud beds. High contaminant concentrations are consistent with hydraulic contrasts indicated by the geology and hydraulic testing. Detailed contaminant profiles also help identify subtle geologic heterogeneities important for contaminant migration.
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DECLARATION OF WORK PERFORMED

I declare that with the exception of the items listed below, all work presented in this thesis was performed by me.

Colby Steelman, G360 Centre for Applied Groundwater Research, University of Guelph, performed all surface electrical resistivity surveys on site and data analysis (signal inversion) of on site data.

Volatile organic compound analysis using shake flask and purge and trap methods were performed by Rashmi Jadeja and Maria Gorecka, G360 Centre for Applied Groundwater Research, University of Guelph.

Existing Quaternary cores from 2004 and 2005 were logged by Ben Swanson and reinterpreted by myself (Tara Harvey), G360 Centre for Applied Groundwater Research, University of Guelph.

Hydraulic head profiles were measured quarterly by myself and a variety of staff from the G360 Centre for Applied Groundwater Research, University of Guelph.
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<th>Description</th>
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<tbody>
<tr>
<td>DI</td>
<td>Deionized water</td>
</tr>
<tr>
<td>DNAPL</td>
<td>Dense non-aqueous phase liquids</td>
</tr>
<tr>
<td>ERT</td>
<td>Electrical resistivity tomography</td>
</tr>
<tr>
<td>Fm.</td>
<td>Formation</td>
</tr>
<tr>
<td>Grp.</td>
<td>Group</td>
</tr>
<tr>
<td>HGU</td>
<td>Hydrogeologic unit</td>
</tr>
<tr>
<td>HSU</td>
<td>Hydrostratigraphic Unit</td>
</tr>
<tr>
<td>K</td>
<td>Hydraulic conductivity</td>
</tr>
<tr>
<td>Kv</td>
<td>Vertical hydraulic conductivity</td>
</tr>
<tr>
<td>mbgs</td>
<td>Meters below ground surface</td>
</tr>
<tr>
<td>masl</td>
<td>Meters above sea level</td>
</tr>
<tr>
<td>Mbr.</td>
<td>Member</td>
</tr>
<tr>
<td>MLS</td>
<td>Multilevel system</td>
</tr>
<tr>
<td>MP-##</td>
<td>2004 core hole name</td>
</tr>
<tr>
<td>MP-##U</td>
<td>2015 core hole name</td>
</tr>
<tr>
<td>PID</td>
<td>Photoionization detector</td>
</tr>
<tr>
<td>QA/QC</td>
<td>Quality assurance and quality control</td>
</tr>
<tr>
<td>SU</td>
<td>Stratigraphic unit</td>
</tr>
<tr>
<td>TOR</td>
<td>Top of rock</td>
</tr>
<tr>
<td>VOA</td>
<td>Volatile organic analysis</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compounds</td>
</tr>
</tbody>
</table>
1.0 Introduction

Unconsolidated glacial sediments deposited at or near an ice margin are extensive across the southern part of Canada and the northern part of the United States. These sediments often overlie significant bedrock aquifer systems (Stephenson et al. 1988), which are important drinking water sources to many cities (Kidd 2002; de Loë et al. 2005). The overlying unconsolidated sediments are important as they influence the rate and distribution of recharge to the shallow groundwater flow system and contaminant migration over time. In addition, due to the nature and hydraulic properties of unconsolidated sediments, they may also be important aquifers themselves (Anderson 1989; Slomka and Eyles 2013), or act as low hydraulic conductivity barrier, protecting underlying aquifers from contamination. As a result, understanding the spatial distribution and hydraulic role of unconsolidated sediments is important in groundwater studies. This study aims to better understand the relationship between the geology and hydrogeology of the unconsolidated sediments of an ice marginal environment in Wisconsin.

Unconsolidated sediments near an ice margin are particularly difficult to characterize, both geologically and hydraulically. This is due to the dynamic nature of ice marginal environments that results in heterogeneous sediment deposition and spatially variable erosion within different depositional settings (glaciofluvial, glaciolacustrine, and ice proximal) occurring laterally along the margin. In addition, the repeated advance and retreat of the glacier produces variable depositional environments over time and consequently vertical heterogeneity within the unconsolidated sediments. Not only is there large scale spatial sediment heterogeneity between different depositional settings, but ice marginal deposits are also internally heterogeneous with the sedimentation style and the magnitude and type of heterogeneity dependent on the depositional environment as well as the available parent material (Thomas et al. 1985; Stephenson et al. 1988; Maizels 1993; Evans et al. 2006; Ó Cofaigh et al. 2008; Clayton et al. 2008).

Given the highly complex nature of the ice margin, how do we characterize the geology and hydrogeology of these systems? Typically, characterization of these sediments uses only a few lower quality geologic core logs to inform both the geologic framework and hydraulic properties of a site. This method uses lithologic units alone as a proxy for hydrogeologic units, with the assumption that the hydraulic properties within a lithologic unit are homogeneous (Stephenson...
et al. 1988; Anderson 1989). This method is inadequate for several reasons; first, these geologic logs are typically lower resolution and thus do not capture relevant details important for reconstructing the three dimensional aspect of these deposits that is critical for understanding groundwater flow systems; second, using lithologic units as a proxy for hydrogeologic units may not be adequate as geologic information alone cannot identify hydraulic properties and contrasts within the flow system (Parker et al. 2006; Meyer et al. 2014); thirdly, most empirically derived estimates of hydraulic conductivities based on lithology cover a range of values over several orders of magnitude, resulting in significant uncertainty.

A more robust method to characterize these heterogeneous systems is to integrate complementary geologic, hydraulic, geophysical, and geochemical high-resolution one-dimensional and/or two-dimensional data sets to inform a three-dimensional conceptualization of a site. In this approach a detailed (centimeter scale resolution) geologic core log is collected for facies analysis to provide a more informed understanding of the possible three-dimensional distribution of the sediments. The centimeter scale resolution is important for characterizing subtle geologic heterogeneities that are important for contaminant transport; although they may not be as important for groundwater flow (Blasting and Hinchey 1993; Guilbeault et al. 2005; Phillips et al. 2007). Surface geophysical investigations are integrated to constrain the lateral distribution of the unconsolidated sediment away from boreholes. Together these two data sets can provide a robust geologic framework. To understand the groundwater flow system, the geologic data set is then hydraulically calibrated with in situ hydraulic measurements. With direct evidence of the hydraulic behaviour of the geologic system, hydrogeologic units (HGUs) can be more accurately delineated. These three primary data sets can further be complimented with laboratory measurements (e.g. grain size analysis, permeameter, moisture content, and volatile organic carbon concentrations) to provide a more complete and confident interpretation of the spatial distribution and hydraulic properties of the unconsolidated glacial sediments.

The use of facies analysis is particularly important in the integrated approach since it provides information that helps to translate one or two-dimensional data sets into a three dimensional geologic framework. Facies analysis is a geologic method that uses detailed sedimentological description and a process-based understanding of depositional environments to group sediments into facies associations. Facies associations are thought to record genetically-related processes in specific depositional environments. These facies associations are then analysed in the context of the regional stratigraphic framework to identify stratigraphic units on site that can
help with the development of a three-dimensional site conceptual model. An improved understanding of the depositional environments of the unconsolidated sediments and how they have changed through time will provide unique insights into their heterogeneity, lateral continuity, and geometry and will make it easier to predict the subsurface geology in locations without adequate geologic data. A facies analysis approach will not only be useful for understanding the geologic heterogeneity but will also provide important insight into the hydrogeologic heterogeneity and hydrogeologic units once calibrated with *in situ* hydraulic data.

It is important to calibrate geologic data with *in situ* hydraulic data since a detailed understanding of the geologic heterogeneity may not necessarily provide an understanding of hydrogeologic heterogeneity (Parker et al. 2006; Meyer et al. 2014). The integration of detailed *in situ* hydraulic data and geologic data will help to understand what geologic features are hydraulically significant. Once the hydraulically significant features are identified, it is hypothesized that the geologic framework for the site can be used to infer the hydraulics of the system where high resolution data are limited.

Multilevel systems (MLSs) are most effective at obtaining high-resolution *in situ* hydraulic data as they provide depth discrete *in situ* hydraulic information that when combined with high-resolution geologic logs can provide important information on the hydraulic behaviour of the subsurface (Cherry et al. 2006; Parker et al. 2006; Meyer et al. 2008; Meyer et al. 2014; Best et al. 2015). Meyer et al. 2008 and Meyer et al. 2016 suggests that the integration of *in situ* high-resolution hydraulic head profiles and geologic logs is important for defining HGUs, specifically with helping to delineate the boundaries of these units. Although Meyer et al. 2016’s hydraulic head profile method was successful in delineating HGUs, their study was carried out in fractured sedimentary bedrock, which in comparison to ice marginal sediments, are relatively homogeneous and simple in their stratigraphic architecture. This method has been used in unconsolidated materials in glaciofluvial or glaciolacustrine settings (Guilbeault et al. 2005; Parker et al. 2006; Best et al. 2015) but has yet to be tested in ice marginal environments where glaciofluvial, glaciolacustrine, and ice proximal conditions all co-exist. Here we test whether integration of the Meyer et al. 2016 hydraulic head profiles and facies analysis methods provides an improved understanding of the groundwater flow system in this complex depositional setting.
In this context, this research aims to better understand the relationship between the geology and hydrogeology of the unconsolidated sediments in an ice marginal environment and how a detailed geologic investigation, on a centimeter scale, integrated with other high-resolution data sets might be used to inform the hydrogeology of a site at the plume scale. This research is achieved by collecting and integrating multiple independent and high-resolution data sets including; sedimentological core logs for facies analysis, grain size analysis, surface geophysical surveys, in situ hydraulic head profiles, and sediment volatile organic compound (VOC) concentrations, in order to provide a comprehensive understanding of the spatial distribution and hydraulic properties of the unconsolidated sediments at a contaminated site in Cottage Grove, Wisconsin.

The research site in Cottage Grove, Dane County, Wisconsin is an example of an ice marginal environment, where multiple advances and retreats of glaciers created sedimentary deposits that change rapidly in their sedimentological characteristics and geometry both laterally and vertically in the subsurface. As is common in other ice marginal environments, the existing geological framework for this site does not contain enough detail of the unconsolidated sediment to provide a comprehensive understanding of their heterogeneity, spatial distribution, and hydraulic properties. Although there is a wealth of knowledge at the site, previous investigations have not used facies analysis to better understand the depositional settings on site, stratigraphic sequence, and 3-dimensional geometry of glacial deposits. The study will provide important site-specific information required to improve the site conceptual model, better represent recharge in the numeric model, and understand plume behaviour in the unconsolidated sediments and shallow bedrock. Although the heterogeneity will be site specific, this site mirrors the heterogeneity seen in other ice marginal sites. Therefore, investigations at this site provide an example of how to conduct detailed and integrated investigations of ice marginal environments that will help inform flow and transport models at a scale that is important for spatially and temporally variable recharge and for understanding contaminant distribution, transport, and migration pathways.
2.0 Background

2.1 Site History

The research site is located at an industrial facility in Cottage Grove, Dane County, Wisconsin, just east of Madison (Figure 2.1). This site was contaminated sometime prior to 1970 by dense non-aqueous phase liquids (DNAPL) when a chemical recycling and distribution facility was operational (HSI GeoTrans 1998). During that time, waste storage of chemical solvents leaked into the subsurface and migrated through the unconsolidated sediments and preferentially accumulated between 43 and 54 metres below ground surface (mbgs) within the Lone Rock Formation of the Tunnel City Group (Figure 2.2; HSI GeoTrans 1998; Swanson et al. 2005; Casado 2012; Lima et al. 2012). A smaller secondary plume still exists within the unconsolidated sediments (HSI GeoTrans 1998; Miao 2008; Casado 2012). The DNAPL is primarily a combination of chlorinated aliphatics, aromatic hydrocarbons, and ketones (HSI GeoTrans 1998; Parker et al. 2006).

Contamination at the site was discovered by new facility owners in 1982 and since then several remediation efforts have been implemented; including a pump and treat hydraulic barrier system, air sparging, and soil vapour extraction (HSI GeoTrans 1999). The total area of the dissolved phase plume within the Lone Rock Formation is approximately 4.24 km² and extends approximately 2.8 km to the east of the facility (HSI GeoTrans 1998; Lima et al. 2012). The plume extent within the Lone Rock Formation and unconsolidated sediment have been delineated as part of these remediation efforts. The current study will provide an enhanced understanding of the contaminant distribution within the unconsolidated sediment.
Figure 2.1: Study site map showing the location of the 5 new unconsolidated sediment cored holes and 6 existing 2004 holes within the three physiographic elements (modified from Clayton and Attig 1997a) and in relation to the existing surface geophysical lines. The three physiographic elements include: drumlinized till plain dominated by diamicth and originally called uniform subglacial till by Clayton and Attig (1997a); glaciofluvial dominated by sand and gravel and originally called collapsed meltwater stream sediment by Clayton and Attig (1997a); and glaciolacustrine dominated by mud and peat and originally called offshore lake sediment overlain by peat by Clayton and Attig (1997a). MLS-Multilevel monitoring system.
2.2 Previous Research

Research by the G360 Centre for Applied Groundwater Research was initiated in 2003. Initial investigations focused on the bedrock units and examined (i) the hydrogeological controls on contaminant distribution in order to determine why the main contaminant plume did not penetrate further than the Lone Rock Formation in the source zone (Austin 2005) and (ii) the lateral migration of the contaminant plume to determine to what extent the plume was retarded relative to average linear groundwater velocity (Meyer 2005). Other bedrock-focused theses studied the long term contaminant distribution and degradation and quantified the degree of biodegradation (Miao 2008) and defined hydrogeologic units (HGUs) based on hydraulic head profiles and integration of geologic data (Meyer 2013).

Investigations of the unconsolidated sediment overlying bedrock units were completed in 2004 and 2010 (Swanson et al. 2005; Parker et al. 2006; Casado 2012). Using a transect approach, these investigations focused on understanding contaminant migration within the unconsolidated
sediments and top of rock (shallow) plume, which was discharging into a nearby man made pond (Swanson et al. 2005; Casado 2012). The current thesis aims to expand upon the previous unconsolidated sediment investigations by using a facies analysis approach for geologic interpretation to focus on characterizing the spatial distribution and heterogeneity of the unconsolidated sediments and their hydraulic properties. As a result, holes in this study were not located to produce a transect, but instead to provide insight into the three different physiographic elements at the site; drumlinized till plain, glaciofluvial, and glaciolacustrine (Figure 2.1).

2.3 Ice Marginal Deposits

Ice marginal deposits can be composed of till plain sediments, glaciofluvial sediments, and glaciolacustrine sediments as well as positive relief landforms such as drumlins, eskers, and moraines. In general, many of these deposits are considered relatively homogeneous, and thus have been represented as one or two units within models (Winiarski et al. 2013). However, the glacial history, specific glacial processes, available parent material, presence and quantity of meltwater, and position relative to the ice sheet will not only result in internal heterogeneity within a deposit but will also affect the type of unconsolidated sediment deposited, its grain size distribution, and the stratigraphy, resulting in site-specific and scale-specific heterogeneity (Quigley et al. 1985; Thomas et al. 1985; Stephenson et al. 1988; Maizels 1993; Evans et al. 2006; Ó Cofaigh et al. 2008; Clayton et al. 2008; Salamon 2009). Changes within these factors, both temporally and spatially, can produce very geologically and hydraulically complex successions of sediments.

For example, till plain sediments are deposited by advancing or retreating glacial ice. As such, till can form via several processes including subglacial deposition or deformation and deposition of englacial, subglacial, or supraglacial sediments during ice advances, retreat, stagnation and melting (Benn and Evans 1996; Evans et al. 2006; Kessler et al. 2012). Tills are classified based on the process of deposition, including subglacial traction till, meltout till, flow till, and lodgement till (Hambrey and Glasser 2003). And although all of these sediments are categorized as “till”, each class has different sedimentary characteristics, structures, and degree of consolidation (Benn and Evans 1996; Evans et al. 2006; Kessler et al. 2012). Till deposits are typically associated with deposition by ice. However, lithologically similar deposits can form as a result of other processes such as debris flows. Therefore, diamict is used to describe poorly
sorted sediment with a mix of particles from clay to boulders without genetic interpretation, whereas till is a diamicl known to have been deposited directly by glacial ice.

In general, tills are laterally extensive and commonly considered relatively homogeneous aquitards capable of protecting underlying aquifers (Sharpe et al. 2002). However, these sediments can be heterogeneous with finer or coarser grained layers (Eyles et al. 1983; Meriano and Eyles 2009; Boyce and Eyles 2000) and can have changes to the dominant grain size based on depositional processes and sediment sources (Narloch et al. 2015). To complicate things, internal heterogeneities such as sand lenses and fractures also exist within till sediments (Williams and Farvolden 1967; Grisak and Cherry 1975; Jakobsen and Klint 1999; Boyce and Eyles 2000; Kessler et al. 2012) and can act as preferential flow paths to groundwater and contaminants (Fortin et al. 1991; Damgaard et al. 2013) as well as increasing the bulk hydraulic conductivity of the sediments (Stephenson et al. 1988; Damgaard et al. 2013).

Glaciolacustrine sediments are deposited where glacial meltwater has ponded and are dominated by silt and clay facies, but can also contain sand and gravel facies from prograding deltas, sediment gravity flows, or subglacial fans (Bennett et al. 2000; Person et al. 2012). These sediments are commonly thought of as relatively homogeneous aquitards (Desloges and Gilbert 1994) but can contain heterogeneities (Eyles and Clague 1991; Desloges and Gilbert 1994). Similar to till, preferential pathways from fractures or other interpreted stratigraphic windows can increase the bulk hydraulic conductivity of glaciolacustrine sediments, diminishing their aquitard properties (Nelson et al. 1991; McKay and Fredericia 1995; Parker et al. 2004; Person et al. 2012; Evans et al. 2013).

Glaciofluvial sediments are deposited by glacial meltwater and form sand and gravel deposits that can extend for 100s of kilometers or infill isolated channel forms (Pisarska-Jamrozy 2006). Glaciofluvial sediment is typically dominated by sand and gravel facies but can also contain mud facies (Clague 1976; Anderson 1989). These sediments show some variability in both the lateral and vertical directions with fining away from the glacial margin and both coarsening and fining upwards successions depending on diurnal or seasonal discharge variations and if the glacier is advancing or retreating (Anderson 1989; Pisarska-Jamroży and Zielinski 2014). Glaciofluvial sediments in general are considered aquifer units; however heterogeneities within these sediments result in variable and anisotropic hydraulic conductivities and the presence of internal
heterogeneities such as mud drapes can impede groundwater flow (Anderson 1989; Goutaland et al. 2013). Other internal heterogeneities such as coarser sand or gravel lenses within sand can result in preferential pathways for groundwater and contaminants (Winiarski et al. 2013; Goutaland et al. 2013).

Drumlins are also found within the study site and are streamlined hills oriented parallel to the flow of ice and formed subglacially by depositional and erosional processes (Menzies 1979; Stokes et al. 2011). Drumlins are commonly found in till plains and have variable internal compositions since they can be composed of existing sediment eroded into streamlined shapes (Johnson et al. 2010; Stokes et al. 2011; Eyles et al. 2016). Consequently, drumlin internal composition has been simplified into five classes: i) mainly bedrock, ii) part bedrock/part till, iii) mainly till, iv) part till/part sorted sediments, and v) mainly sorted sediments (Stokes et al. 2011). The combination of bedrock, till, and sand results in heterogeneous drumlin sediments that may also contain the internal heterogeneities common to each of these sediment types (Menzies 1979; Stokes et al. 2011; Jónsson et al. 2014). As a result, determining drumlin geologic composition and hydraulic properties, similar to other glacial sediments, proves difficult without drilling and recovering core.

In summary, internal deposit heterogeneities within till plain, drumlin, glaciofluvial, and glaciolacustrine sediment can consist of mud, sand, or gravel lenses, interbeds, changes in clast or matrix characteristics and changes in abundance or types of fractures (Benn and Evans 1996; Evans et al. 2006; Kessler et al. 2012) introducing further hydraulic complexity into the sediment, which can be very hard to predict. In addition, these deposits can form complex successions as a result of complex sequence of advances and retreats and be intermixed due to glacial deformation, making it even more difficult to predict their geologic and hydraulic properties. The complexity of glacial deposits emphasizes the need for site specific investigations and the need to model these sediments as a more complete system within geologic and groundwater flow models.

2.4 Site Geology

Unconsolidated sediments across Cottage Grove and Dane County were deposited at the edge of the Laurentide ice sheet (Green Bay Lobe) during the late Wisconsinan glaciation approximately 20,000 years ago (Mickelson 1983). Although Dane County was likely glaciated
before the Wisconsinan Glaciation, little to no evidence of these glaciations remain (Mickelson 1983; Clayton and Attig 1997b; Syverson and Colgan 2004). The unconsolidated sediments range from 1 m thick in the southwest to 10s of meters in much of the county, or even more than 100 m in deep valleys (Clayton and Attig 1997b), and overlie Ordovician dolomite and Cambrian sandstone (Colgan and Mickelson 1997). The shallow bedrock sediments on site include the St. Peter Formation sandstone that unconformably overlies older stratigraphic units including the Prairie du Chien Group and St. Lawrence Formation Dolostone or the Tunnel City Group sandstone (Figure 2.2).

The Green Bay Lobe, of the Wisconsinan glaciation, covered much of Dane County with the exception of the Driftless area (Figure 2.3). The maximum extent of the Green Bay Lobe was during the Johnstown Phase, approximately 18,000 years before present (Clayton and Attig 1997b). During this Phase, the Green Bay Lobe likely experienced several minor retreats and advances (Mickelson 1983; Clayton and Attig 1997b). The succeeding Milton Phase (approximated 16,000 or 14,000 years before present; Colgan and Mickelson 1997; Clayton and Attig 1997b) is marked mostly by glacial retreat, with a minor pause to create the Milton Moraine (Mickelson 1983). The final glacial advance to reach Dane County was the Lake Mills Phase but ice during this phase likely did not cover the site (Figure 2.3).

Glacial deposits within Dane County are predominantly diamict interpreted as till, which cover approximately two thirds of the County, including sediments within Cottage Grove (Figure 2.3). Till units in Cottage Grove and most of Dane County are considered part of the Horicon Member of the Holy Hill Formation (Rayne et al. 1996; Clayton and Attig 1997b; Bradbury et al. 1999). Till deposited by different glacial advances are only identifiable by stratigraphic position and not lithology (Whittecar and Mickelson 1977; Clayton and Attig 1997b). Therefore, field identification of different till units is typically achieved with structural relations such as cross-cutting (Whittecar and Mickelson 1977); however, till from two glacial advances may show evidence of glaciofluvial deposits at the contact (Whittecar and Mickelson 1977). It is important to note that not all diamict units encountered are likely to be till and the use of facies analysis can aid in the distinction between glacial and non-glacial diamict.

The Horicon Member is characterized by brown gravelly, clayey, silty sand (Colgan and Mickelson 1997; Clayton and Attig 1997b). Specifically, in Dane County this diamict is typically reddish brown, brown, light reddish brown, or light brown and is considered to be fairly
homogeneous with a matrix composition of 55-85% sand (average 61%), 5-30% silt (average 29%), and 5-20% clay (average 10%) with several percentages of gravel, which can contain boulders greater than 2 m in diameter (Mickelson 1983; Attig et al. 1988; Colgan and Mickelson 1997; Clayton and Attig 1997b). Interbeds of sand and gravel are common and may be fairly laterally continuous or discontinuous (Colgan and Mickelson 1997). The gravel is composed of local bedrock material as well as materials from several hundred kilometers to the north-northeast in northeast Wisconsin and Canada (Mickelson 1983; Clayton and Attig 1997b). Gravel particles within the diamict are most commonly carbonate (60-90%), but can also consist of chert (15-40%), and other mafic rocks (0-6%); (Clayton and Attig 1997b). Diamict within Dane County is fairly continuous and only interrupted by glaciofluvial sediments and some organic materials (Mickelson 1983).

Figure 2.3: Generalized Dane County surficial glacial geology showing the drumlinized till plain, hummocky zone, driftless zone, and major moraines in the county. Modified from Mickelson and McCartney 1979 and Clayton and Attig 1997a. Red box indicates extent of Figure 2.4.
Most drumlins within Dane County were likely created during the Johnstown Phase, as they are parallel to Johnstown flow lines (Colgan and Mickelson 1997; Clayton and Attig 1997b). Studies of drumlins deposited by the Green Bay Lobe in Dane County have found that drumlins can be composed of sand and gravel, few have bedrock cores, but most are thought to be entirely composed of till, at least at surface (Mickelson 1983; Colgan and Mickelson 1997); however, the composition of most drumlins within Dane County is unknown (Mickelson 1983). A surficial carapace of till is expected to cap all drumlins in Dane County but is lithologically indistinguishable from till within the drumlin (Whittecar and Mickelson 1977). It is believed that these internally variable drumlins were formed by erosion of existing sediments and thus little stratigraphic evidence is recorded during their formation (Eyles et al. 2016).

There are many moraines within Dane County of different sizes (Figure 2.3; Clayton and Attig 1997b), though no moraines are located on site (Figure 2.4). The large Johnstown moraine lies to the west of the site, whereas several smaller moraines lie to the north of the site (Figure 2.3).

Glaciofluvial sediments within the county tend to be well sorted sand and gravel with fine materials having been naturally washed away. These deposits are relatively uniform and are typically distributed in northeast-southwest trending deposits at surface across the county and near the site (Figure 2.4) (Mickelson and McCartney 1979). Glaciolacustrine silt and clay are typically horizontally bedded and glaciolacustrine sands are horizontally cross-bedded (Figure 2.4; Clayton and Attig 1997b).
Figure 2.4: Surface geology map with approximate locations of drumlins surrounding Cottage Grove, Dane County, Wisconsin (modified from Clayton and Attig 1997a). Location of this map within Dane County is shown in Figure 2.3.

2.5 Surface Electrical Resistivity Surveys

Understanding the heterogeneity of unconsolidated sediments and the depositional environment at a site can be accomplished through detailed geologic logs obtained from continuously cored holes. Fairly accurate interpretations can be drawn from multiple detailed geologic logs with the incorporation of site specific geologic history (Desrocher et al. 2011). A limitation is that core logs only provide isolated vertical data, but when combined with surface geophysics, informed interpretations between corehole locations can be made from these planar geophysical transects that provide information on specific subsurface properties. For example, electrical resistivity provides information about the electrical properties of the subsurface, which largely depends on porosity, saturation, and clay content (Cant 1992; Loke et al. 2013). Resistivity will also be affected by the grain size, pore connectivity, and fluid conductance (Van Dam 2012).
Resistivity data sets are typically inverted to obtain a representative model of the subsurface; these models are non-unique and thus tend to be smoothed representations of the actual material parameter distribution (Van Dam 2012; Loke et al. 2013). However, when combined with detailed geologic logs, this indirect method provides useful insight into the three-dimensional nature of the deposits and proves to be a complementary data set for the interpretation of unconsolidated sediment (Loke et al. 2013).

### 2.6 Hydraulic Conductivity

Hydraulic conductivity (K) is a fundamental hydraulic property. The range of K in unconsolidated sediments depends on factors such as grain size, sorting, and packing and can be between $10^{-11}$ m/s to $10^{-4}$ m/s for till plain sediments (Howard et al. 1995; Jakobsen and Klint 1999; Meriano and Eyles 2003), $10^{-7}$ m/s to $10^{-3}$ m/s for glaciofluvial sediments (Anderson 1989; Goutaland et al. 2013), and $10^{-10}$ m/s to $10^{-6}$ m/s for glaciolacustrine sediments (Nelson et al. 1991). These large ranges in K suggest that knowing the type of unconsolidated deposit may not provide much insight into determining the specific K of that sediment.

To get a better understanding of K, grain size distribution analysis is often used to make K estimates based on empirical equations. It is the relationship between grain size and K that permits this correlation; however, this method is limited. For example, samples with similar grain size distributions may actually have different K (up to 2 orders of magnitude different) due to aspects such as consolidation (Stephenson et al. 1988). In addition, grain size distribution analysis is destructive and can lead to the breakdown of particles into smaller sizes or the inadequate separation of cemented or calcified grains.

Grain size distribution may provide approximate values of K; however, this method uses a small subsample of core to calculate a variable that is known to be scale dependent. Larger scale tests are considered more accurate since they can incorporate internal heterogeneities of the system that grain size distribution analysis cannot, such as natural packing, grain orientation, fractures, and sand lenses. These heterogeneities can act as preferential flow paths to groundwater (Winiarski et al. 2013; Goutaland et al. 2013) and have been shown to increase bulk K by several orders of magnitude (Stephenson et al. 1988; Nelson et al. 1991; Parker et al. 2004; Person et al. 2012; Kessler et al. 2012).
2.7 Hydraulic Investigations of Unconsolidated Sediment

The standard method of determining hydraulic properties of the subsurface is to use lithologic units as a proxy for hydrogeologic units (HGUs), with the assumption that all hydraulic properties within a lithologic unit are homogeneous (Stephenson et al. 1988; Anderson 1989). However, Parker et al. (2006) demonstrated the inadequacies of the method since high-resolution vertical hydraulic head profiles installed in unconsolidated Quaternary sediments identified changes in vertical hydraulic conductivity that were not predicted by the core. Similarly, Best et al. 2015 found that hydraulic head profiles identified only two groundwater flow units within the complex Paris Moraine despite a much more variable lithological profile. In both these studies, and others (Guilbeault et al. 2005; Meyer et al. 2008; Meyer et al. 2014; Meyer et al. 2016) high-resolution vertical hydraulic head profiles combined with high-resolution geological information were shown to be a more useful tools for delineating HGUs than lithologic units (Figure 2.5) because they can isolate specific geologic features responsible for inflections in the hydraulic head profile.

Recommendations for groundwater studies typically suggest the use of nested piezometers for gathering hydraulic data, including hydraulic head, and groundwater samples (Aller et al. 1991; Desrocher et al. 2011). These nested piezometers are an improvement to the conventional method of installing a long screened well in a single hole, but do not provide the vertical spatial resolution of a multilevel monitoring system (MLS) required to identify the location of changes in vertical hydraulic conductivity as presented in Cherry et al. (2006; Figure 2.6). The lower resolution of nested piezometers makes it difficult to accurately define vertical hydraulic gradients, both the location and magnitude, due to blending of head values over large intervals (Meyer et al. 2014). In contrast, the use of MLSs allow depth-discrete high-resolution head measurements to be taken within a single borehole. Heterogeneities in subsurface hydraulic conductivity (K) cause inflections in flow lines and equipotential lines between units with distinct hydrologic properties (Freeze and Witherspoon 1967). Therefore, MLSs can be used to identify locations of contrasting vertical hydraulic conductivity (Kv). Detailed MLS head profiles have been found to readily identify key components of a groundwater flow system (Guilbeault et al. 2005; Parker et al. 2006; Meyer et al. 2014; Best et al. 2015; Meyer et al. 2016) and the integration with a detailed geologic understanding of the core can adequately pinpoint specific lithologic boundaries or features causing hydraulic contrasts. Identifying hydraulically significant
geologic features will improve site conceptual models and aid in the prediction of hydraulic properties where only geologic data is available.

Figure 2.5: Comparison of hydrogeologic unit delineation based on lithologic (standard method) units versus hydraulic head profiles and lithologic units (integrated method). Notice that hydrogeologic units determined by the integrated methods may not correspond to lithologic unit boundaries but may ignore them or divide supposedly homogeneous lithologic units into multiple hydrogeologic units. Modified from Meyer et al. 2014.
Figure 2.6: Comparison of hydraulic head profiles and vertical hydraulic gradient profiles from a nested piezometer and multilevel system. The higher-resolution MLS system pinpoints specific geologic features causing vertical hydraulic gradients. Higher gradients correspond to a larger contrast in K, whereas lower or unresolvable gradients correspond to lower contrast in K (Meyer et al. 2014). Modified from Meyer et al. 2014.
3.0 Methods

3.1 Research Approach

Several high-resolution data sets were collected to characterize the spatial distribution, and hydraulic properties of the unconsolidated sediment on site. Geologic data sets collected included detailed sedimentological logs from 5 newly cored holes, geologic logs from 6 previously drilled holes, quantitative grain size analysis of lithology and specific facies, and borehole natural gamma logs. These newly obtained data sets were combined with existing surface electrical resistivity geophysical surveys to obtain a better understanding of the distribution of sediments. Multilevel systems (MLSs) were installed to investigate hydraulic properties from hydraulic head profiles. Estimates of hydraulic conductivity were made using sediment samples from the core and grain size distribution and falling head permeameter measurements conducted in the laboratory. Volatile organic compound (VOC) samples were also collected from 4 of the 5 coreholes and analyzed for 35 contaminants of concern at the site to investigate the contaminant distribution within the unconsolidated sediments. This section outlines the methodology used in the field and laboratory to collect each data set.

3.2 Field Methods

3.2.1 Coring

Five holes (MP-19U, MP-23U, MP-25U, MP-27U, and MP-28U) were drilled between July 27th and August 18th, 2015 by Cascade Drilling L.P. using a rotosonic drill rig (model BL RS 300). Holes were located along or near existing surface geophysics lines and within three different surficial physiographic elements: till plain/drumlin, glaciofluvial, and glaciolacustrine (Figure 2.1). Each hole was continuously cored through the unconsolidated sediments and approximately 3 m into bedrock. Coring advanced in 1.5 m (5 ft) runs, to decrease VOC losses, except in MP-28U where coring advanced in 3 m (10 ft) runs since no VOCs were being sampled. After the core barrel (15.2 cm inner diameter) had advanced 3 m (2 runs extracted), an outer casing (19.9 cm outer diameter) was advanced to stabilize the hole. No drilling fluids were utilized during coring, while tap water was occasionally used to advance the outer casing.
During extraction, the core was placed into thick plastic sleeves and supported underneath by metal trays (Figure 3.1) to reduce sediment deformation and compression. Coring of the next 1.5 m run only commenced after logging and sampling of the previous run was almost complete to ensure VOC losses were minimized.

![Core extraction from core barrel into the thick plastic sleeves. Supportive metal tray used to decrease sediment deformation.](image)

Once geological logging was complete and all sediment samples had been collected, the recovered sediment was temporarily repackaged into the plastic sleeves, arranged by depth, and stored under tarps at each hole location until screened by TetraTech for proper disposal. All sediments above the water table were spread at the surface of each location. All sediments below the water table were screened with a photoionization detector (PID). Sediments reading less than 10 ppm after 15 seconds, were spread on a waste sediment pile on Hydrite property and any sediment with readings above 10 ppm after 15 seconds were drummed for proper disposal.
Six existing holes (MP-9, MP-10, MP-11, MP-12, MP-13R, and MP-14) were drilled through the unconsolidated sediment and into bedrock in 2004 using similar rotosonic drilling methods (Swanson et al. 2005). These holes were located to create a north-south transect along the west side of the pond orthogonal to groundwater flow (Figure 2.1; MP-11, MP-12, MP-13R, and MP-14) for focused investigations of contaminant concentrations across the mixed VOC plume within the unconsolidated sediments and shallow bedrock near the pond. Additional holes were located on the drumlin (MP-9) and the east side of the pond (MP-10) to measure up gradient and down-gradient concentrations within the shallow groundwater plume. The pond holes are very close to the contact between two of the three surface physiographic elements (Figure 2.1). MP-11 is considered within the glaciofluvial element whereas MP-12, MP-13R, and MP-14 are considered within the till plain element. MP-9 is completely within the till plain element and MP-10 is completely within the glaciofluvial element.

### 3.2.2 Core Expansion

Occasionally the retrieved core, from the 2015 field season, was significantly longer than the distance drilled. The reason for this expansion is unknown but could be due to slumped sediments or the release of overlying pressure or vibrational disturbance of drilling, creating a fluidized condition expanding sediments and enhancing mobilization into the core barrel. Cores longer than 1.5 m after the removal of suspected slumped sediment were logged as two separate runs to preserve field lengths. After logging and sampling each hole, all expanded runs, and associated sample depths, were linearly compressed using a unique compression factor calculated for each run (Eq. 3.1):

$$\text{compression factor} = \frac{\text{length of recovered core (m)}}{\text{distance drilled (1.5 m)}} \quad \text{(Eq. 3.1)}$$

All depths were adjusted by dividing field depths by the core-run-derived unique compression factors. The final compressed data was confined to known top and bottom depth of each run. Therefore, depth uncertainties are constrained to less than 1.5 m.

### 3.2.3 Core Logging

For the 2015 field season, following core extraction and prior to core logging and sampling, outer disturbed sediments affected by drag along the core barrel were scraped off to reveal less
disturbed inner core sediment (Figure 3.2) and the core was photographed with a set of three overlapping high-resolution photos, both before and after sampling.

Detailed high resolution (cm scale) logging of all 2015 cores (MP-19U, MP-23U, MP-25U, MP-27U, and MP-28U) were completed at the centimeter scale to capture changes in grain size, visual gravel percent, sorting, Munsell Soil colour, contact characteristics, sedimentary structures, plasticity, wetness, and clast characteristics (i.e. clast size, roundness, lithology; Figure 3.3). Texture was captured based on the Hambrey and Glasser’s (2003) classification scheme (Figure 3.4) and a hierarchal system (primary, secondary, tertiary) based on their dominance. Only one primary grain size was logged but several secondary and tertiary grain sizes were captured based on visual percentage; secondary was logged as between 10-50% visually, whereas tertiary was logged as between 0-20% visually. In addition to individual grain sizes, the overall visual percentage of gravel was estimated for grains greater than 2 mm in diameter (granules and above). Colour was identified for each unit using the Munsell Soil colour chart. Contacts between beds were captured based on changes in one or several of the properties (i.e., colour, grain size, moisture, and visual percent gravel). Contacts were identified even when these changes were very slight. Each contact was defined as gradational, sharp planar, sharp irregular, or erosional. When present, sedimentary structures such as horizontal laminations, interbedded sediments, grading, and deformation were captured during logging. Plasticity was also determined by quantifying a diameter obtained from rolling the sediment. Sediment plasticity, a measure of clay content, was described as non-plastic (>6 mm diameter can be rolled), low (6-3 mm), medium (3-1 mm), or high (<1 mm). Clast lithology was logged in a hierarchy system (primary, secondary and tertiary) depending on abundance and classified as carbonate, sandstone, metamorphic, igneous, or other (typically chert).
Geologic logging of the 2004 rotosonic cores used a different logging technique focused on visual inspection to provide textural descriptions (Swanson et al. 2005), instead of gathering a more comprehensive suite of sedimentary characteristics needed for facies analysis. Of note, this logging technique did not use the term “diamict” to describe poorly sorted sediments and likely underestimated silt content and overestimated sand content, as evaluated by re-examination of core logs in comparison to the 2015 cores. Therefore, while these core logs have reasonable detail to be complementary to the 2015 core logs, they are considered to be lower quality due to less detailed inspection and documentation. Each core log from the 2004 study was revisited for the purpose of the present study; lithologic unit textures were modified based on field notes to conform with the style of sediment descriptions from the 2015 cores. Specifically, units that were described as containing sand, gravel, and mud are now classified as diamict, whereas units that were described as sand and mud or sand and gravel are now classified as muddy sand or gravelly sand, respectively. The 2004 logs were incorporated into this study by careful comparison to the 2015 core logs.
All sediment characteristics collected through geologic and geophysical logging were considered in order to group various sediment types into facies associations that are thought to record genetically-related processes in a specific depositional environment. These facies associations were then compared to the regional stratigraphic framework to finalize the interpretation of each borehole log. Cores were correlated using the facies associations and surface geophysics in order to create a geologic framework and depositional model for the site. Specifically, geophysics informed the lateral continuity of facies along north-south and east-west transects providing x-y dimension data to complement the detailed vertical delineation of facies variability. Other geologic logs exist on site but none are appropriately detailed to give sedimentary descriptions and contact information beyond the approximate location of top of rock.
Figure 3.3: Example G360 Group logging sheet suited for consistent, high-resolution logging of lithologic and sedimentary characteristics of the core.
Figure 3.4: Textural classifications based on Hambrey and Glasser 2003.

3.2.4 Sampling

3.2.4.1 Volatile Organic Compounds and Moisture Content

VOC and moisture content samples were collected in tandem within the 2015 cores approximately every foot from 4 of the 5 holes; only moisture content samples (no VOC samples) were collected in MP-28U (see Appendix A.1 for sample numbers and sampling frequency). All details for collected samples (i.e., sample number, station number, run number, start and end distance, time, etc.) were recorded on an iPad using a unique field app designed by the G360 Centre for Applied Groundwater Research.

Sample locations within each core were chosen to capture potential changes in contaminant concentrations and moisture content between sediment types or as a result of heterogeneities within sediment types. Each VOC and moisture content sample was collected using a disposable 10 ml syringe with an open-ended barrel (the needle end cut off). Disposable syringes were used to reduce possible cross-contamination between samples and reduce the need for decontamination of equipment. The syringe barrel was pushed into the exposed clean sediment to collect approximately 20 g of sediment. Each VOC sample was pushed using the syringe plunger into a 40 ml volatile organic analysis (VOA) bottle containing 15 ml of methanol, capped, and stored on ice in the field (Figure 3.5). Moisture content samples were placed into 40 ml or 20 ml VOA bottles, capped, and placed in a cooler without ice until the end of the day.
Duplicate VOC and moisture content samples were collected approximately every 20 samples. Each VOC and moisture content vial was pre-weighed, to an accuracy of 0.001 g, and labeled with a unique barcode and ID number.

Figure 3.5: VOC and moisture content sampling method developed by G360 Group scientists using disposable syringes. A) syringe barrel inserted into undisturbed sediment, B) ~ 20 g of sediment collected, C) samples transferred to VOA bottles with unique barcodes, D) moisture content samples with unique barcodes.

At the end of each day, VOC samples and moisture content samples were weighed. VOC samples were immediately packaged for shipping by Teflon taping the bottle neck and cap, bubble wrapping the VOA vial, and sealing each sample in an individual ziploc bag. These precautions reduced the chances of samples breaking and reduce the possibility of volatile losses and cross contamination. Samples were then packaged into coolers with ice and three trip blanks, containing only methanol, then priority shipped overnight to a lab at the University of Guelph where they were kept in a fridge until processed. Moisture content samples were kept at room temperature until the end of the field efforts then bubble wrapped, packed into coolers.
without ice, and priority shipped back to the University of Guelph. Methanol blanks from the top and bottom of each methanol bottle were packaged the same as VOC samples but shipped back in a separate cooler to ensure no cross contamination.

### 3.2.4.2 Grain Size Distribution and Falling Head Permeameter

Sediment samples were collected (Figure 3.6) from the 2015 cores to investigate the lithologic characteristics and hydraulic properties within and between holes using grain size and falling head permeameter analyses. A minimum of 300 g of sediment was collected for grain size samples and a minimum of 100 g for falling head permeameter samples then placed into pre-labelled Ziploc bags. In both cases, duplicate samples for each were collected approximately every tenth sample. Each sample was collected from a section of core between 5 cm and 10 cm long. The metal spatula, used for sample collection, was wiped clean with a paper towel between samples in the same run and decontaminated using deionized (DI) water between runs.

Figure 3.6: Grain size and falling head permeameter sampling. A) Removal of 5-10 cm of sediment per sample for 100-300 g. Sample locations marked by red golf t’s (white golf t’s indicate VOC sample locations), B) Grain size sample in labelled bag with unique barcode.

Samples were stored on ice until the end of the day when they were re-packaged with fresh ice. Grain size and permeameter samples were priority shipped approximately once a week in iced coolers to the University of Guelph where they were dried in a fume hood for several months at room temperature to allow volatilization of VOCs.
3.2.5 Downhole Geophysics-Natural Gamma

Prior to the installation of Westbay® multilevel systems within the 2015 holes, each hole was logged for down hole natural gamma using a 2PGA-1000 Natural Gamma probe (Figure 3.7). Natural gamma was the only downhole geophysics tool used due to the instability of the hole and the ability of the gamma tool to read through steel casing. The 2PGA-1000 probe detects natural gamma radiation emitted from sediments enriched in potassium-feldspar and is therefore a good indicator of clay content or feldspathic sand. Logging with the natural gamma probe occurred during both descending and ascending; however, due to tension on the cable, ascending logs are considered more accurate and therefore presented here. While ascending, the logging speed was 0.8 m/min and measurements were taken every 0.01 m.

Figure 3.7: Natural gamma logging at MP-19U. A) tripod set up over hole; B) winch set up and data collection.

3.2.6 Multilevel Systems

Westbay® multilevel systems (MLS) were installed in each of the 2015 boreholes within 10 days of drilling. High-resolution MLSs were designed using detailed geologic logs and natural gamma logs collected during drilling and with knowledge of the water table depth. These MLS designs
included monitoring zones with either a measurement port or a measurement and pumping port. Pumping ports were included in zones with different sediment types that were thick enough to isolate for monitoring. Measurement ports allow for head profiling and groundwater sampling, whereas pumping ports allow for in situ hydraulic testing, such as slug tests.

Location of seals and monitoring zones in each system were carefully selected to minimize blending between units likely to have different hydraulic properties and to maximize the total number of monitoring zones in order to obtain high-resolution head and groundwater chemistry profiles. The possible locations of boundaries between hydraulically distinct units were estimated using stratigraphic logs. Within each hypothesized unit several monitoring zones were placed to investigate the hydraulic homogeneity of that unit. Seals were placed at the boundaries of identified hydraulically distinct units to ensure minimal blending of hydraulic properties (see Figures A.4 and A.9 in Appendix A.2 for full zone location rationale and Meyer et al. 2014 for detailed methods).

Prior to installation, each piece within the Westbay® system was carefully laid out in the correct order and numbered to ensure proper assemblage. During installation, each Westbay® system component was checked and double checked to ensure the system was assembled according to the design. In addition, during installation each coupling within the Westbay® system casing was pressure tested using mini packers and a joint testing tool to ensure no leakage. Once installed, MLSs were backfilled using Red Flint # 40 filter pack sand and ⅜" mined bentonite chips (Hole Plug), which was passed through a ¼" sieve to remove dust or fines and improve settling rates while filling the annular space. The depth of each sand and bentonite pack were meticulously measured and recorded to ensure proper placement. A detailed method for the design, installation, and backfilling of the Westbay® multilevel systems can be found in the Meyer (2016) technical report. All MLSs were developed in April 2016 by removing 250 ml to 1L at a time until 2 consecutive litres were clear of suspended sediment.

The 6 existing pond holes previously had open tube Waterloo MLSs installed within the unconsolidated sediment and bedrock. Monitoring zones and seals were created using backfilling techniques. Sand packs varied between 0.6 m to 1.2 m in length and were separated by bentonite seals that ranged from 0.3 m to 2.4 m in length (see Swanson et al. 2005 for more details).
3.2.7 Hydraulic Head Profiles

Hydraulic head was measured in each Westbay® system in August, September, and December 2015. Head profiles were also measured in MP-19U, MP-25U, and MP-28U in April and July 2016. Unfortunately MP-27U developed an impassible restriction high in the Westbay® MLS; and therefore, head profiles were not measured in that MLS after December 2015. Head profiles for MP-23U were measured in April 2016 but not in July 2016 due to inaccessibility related to industrial activities on site.

Head profile measurements were made using the Westbay® sampling probe. Westbay® systems allow for very accurate measurements of in situ formation pressures using a MOSDAX™ sampling probe and MAGI interface. The system is designed so that the probe physically connects with the measurement ports and creates a seal around the opening of the port for direct measurements of shut in formation fluid pressure with a resolution of 0.01 psi. Pressure measurements at surface and within each measurement port were recorded. In field QA/QC was completed by comparing pressure measurements to previous measurements to ensure the correct zone was measured.

Pressure measurements were combined with port elevation data to compute a hydraulic head for each hole as per methods described by Meyer et al. (2014). Head profiles were used to calculate the vertical component of hydraulic gradient (vertical gradient) between adjacent monitoring zones as per Meyer et al. (2014). Contrasts in head between adjacent monitoring zones less than 2 cm were considered to be within the limits of the error of the probe and potential depth errors and not resolvable; therefore, vertical gradients were assumed to be zero for these zones. Vertical hydraulic gradients were defined as the following: resolvable, where the head difference was greater than 2 cm between adjacent ports in all profiles from a specific hole; sometimes resolvable, where the head difference was greater than 2 cm between adjacent ports at least once when heads were measured; and unresolvable, where head differences greater than 2 cm were never identified between adjacent measurement ports.

Head profiles within the Waterloo systems have been measured quarterly since their initial installation in 2004. Head profiles from July, September, and December 2015 are presented here for MP-10, MP-11, MP-12, MP-13R, and MP-14. The hydraulic head profiles for MP-9 are incomplete as some ports within the MLS were not able to be measured due to the narrow
sampling tube diameters compared to the coaxial water level tape; as a result, these profiles are not included.

Head profile measurements were made using a co-axial water level tape, which advances down a ¼ inch (inner diameter) Teflon tube from ground surface to each port. The water level is recorded as the location where the tape sounds and is measured multiple times to a consistent and known depth reference. The accuracy of this measurement within a Waterloo system depends on several sources of error: i) error in elevation of depth reference, ii) error in depth of port, iii) twisting of the Waterloo system tubing that creates a positive bias, iv) false positives from water clinging to the tubing, v) accuracy of the water level tape, and vi) personnel reading errors. The combination of these errors may be upwards of 10 cm. Since the magnitude of error within these systems has not been formally quantified, a more conservative 5 cm contrast in head between adjacent monitoring zones is considered within the range of error for this study. Similar to Westbay® head measurements, Waterloo system head profiles were checked in the field at the time of measurement (quality assured and quality controlled (QA/QC)) by comparing the shape of the head profile to previously measured profiles, since the shape of head profiles has been shown to be consistent through time (Parker et al. 2006; Meyer et al. 2014; Meyer et al. 2016). This comparison was completed in order to eliminate mis-reading and transcript errors.

3.2.8 Surface Geophysics

Surface electrical resistivity surveys were completed by Colby Steelman in 2012, 2013, and 2014 to gather insight on the shallow bedrock and unconsolidated sediments on site. Electrical resistivity measurements were collected with a multi-core 96 channel Syscal Pro Switch resistivity meter with a collinear Wenner-Schlumberger array (Steelman 2015). This equipment measures the potential difference at different locations due to an applied DC electrical current (Steelman 2015).

Measured resistivity data was not constrained with geologic core logs due to lateral offset of these holes from the geophysical lines, the inherent heterogeneous nature of Quaternary sediments, and the variable detail and accuracy of the existing on-site geologic logs. Instead, prior to inversion with RES2DINV v.3.58 and v.3.59, resistivity data was manually filtered to remove erroneous data points and retain an unbiased geophysical subsurface model (Steelman 2015). Effects of large surface resistivity variations were suppressed by setting the model cell
width to half the electrode spacing. Resistivity data was visualized and plotted using Geosoft Oasis software. Topography was incorporated using a 3 m by 3 m digital elevation model of the site.

3.3 Laboratory Methods

3.3.1 Volatile Organic Compounds and Moisture Content Analysis

VOC samples were analyzed by the G360 Centre for Applied Groundwater Research at the University of Guelph using the shake-flask then purge and trap extraction method (EPA method 8260B). The movement of VOCs from the unconsolidated sediment to the methanol was assisted by the shake-flask method, where samples are disaggregated to encourage contaminant movement into the methanol by agitation for one hour per week for 5 to 6 weeks. Contaminants within the methanol were delivered into the gas chromatograph using the purge and trap method. Thirty-five analytes are detected using this method with detection limits ranging from 0.2 to 2 µg analyte per litre methanol extractant.

All VOC concentrations were converted from µg/L methanol to µg/g wet sediment using the following equation.

\[
\frac{\text{µg analyte}}{\text{g wet sediment}} = \left( \frac{\text{µg analyte/Litre Methanol}}{V_{\text{Methanol/sample}}} \right) \frac{V_{\text{Methanol/sample}}}{M_{\text{wet sediment}}} \quad \text{(Eq. 3.2)}
\]

where, µg analyte per litre methanol is the analytical result, \( V_{\text{Methanol/sample}} \) is the volume of methanol before analysis, and \( M_{\text{wet sediment}} \) is the field measured sample weight (wet weight of sample) as determined by the following equation.

\[
M_{\text{wet sediment}} = M_{\text{vial}} - M_{\text{MeOH+vial}} - M_{\text{MeOH+vial+wet sediment}} \quad \text{(Eq. 3.3)}
\]

Moisture content samples were weighed in the field the day of sampling to ensure moisture losses during storage were minimal. All moisture content samples were placed into a 40°C oven to dry for approximately 1 month. Thirty percent of samples were weighed 2-3 times a week to monitor drying. Once the weight of these samples changed by less than 0.2%, the samples were declared dry and a final mass was taken.
Moisture content (mass of water per sample) was calculated as the difference in the mass of the dried sample and the initial mass in the field (Eq. 4).

\[ MC = \text{wet mass} - \text{dry mass} \quad (\text{Eq. 3.4}) \]

### 3.3.2 Grain Size Distribution Analysis

Grain size distribution analysis was completed on a subset of samples (58/210) in January 2016. Samples were selected to ensure all unique geological units were analyzed, to investigate the heterogeneity of similar units laterally between cores and vertically within the same core, and to calibrate field estimates of grain size. Nine samples out of the 58 grain size samples were field duplicates to ensure accuracy of analysis, whereas five of the 58 samples were analyzed twice for laboratory duplicates. Based on these duplicates, comparison of field samples indicated an error typically less than 4% whereas laboratory duplicates indicated an error less than 2% (see Appendix A.3.1 for details).

Grain size analysis was completed with a combined sieve and hydrometer analysis method adapted from Kroetsche and Wang (2008) (Figure 3.8). Selected samples were put through a riffle box to obtain approximately 100 g for analysis. Each subsample was carefully crushed using a mortar and pestle to separate the sample into its smallest particles. All gravels greater than 2 cm were removed from analysis prior to crushing. An up-down motion was used to avoid grinding the sediment into smaller sizes. Each sample was then dried overnight at 104°C to remove all moisture and weighed to an accuracy of 0.01 g after returning to room temperature (~10 min).

All samples except 8 (HC-MP23U-GS-0026, HC-MP23U-GS-0025, HC-MP23U-GS-0021, HC-MP23U-GS-0030, HC-MP23U-GS-0023, HC-MP27U-GS-0029, HC-MP27U-GS-0051, HC-MP19U-GS-0012) were then soaked in 100 mL of 50 g/L sodium hexametaphosphate overnight to de-flocculate any clay particles in preparation for wet sieving. The 8 samples that were not soaked were determined to contain no clay after looking under a microscope and based on field descriptions. Wet sieving involves mixing each soaked sample with 250 mL of deionized (DI) water in a milkshake mixer for 5 min then sieving through the No. 325, 45 µm, until the water coming through was clear. All silt and clay washed out during wet sieving was placed into a
1000 mL graduated cylinder for the hydrometer experiment and the remaining sediment was washed into a weigh tray and dried overnight at 104°C.

Figure 3.8: Grain size distribution analysis via sieve and hydrometer. A) riffle box used to split sample; B) ~100g of sample dried overnight at 104°C; C) Sample soaked in 100 ml of 50 g/L sodium hexametaphosphate; D) Sample mixed for 5 min to deflocculate clays; E) sample wet-sieved to remove mud (< 45 µm); F) sieve stack and shaker used to measure distribution of sand-size particles; G) sieve being weighed before and after; H) hydrometers used to measure distribution of fine grained materials.

Samples were weighed after drying and placed in the sieve stack to be shaken for 10 min using a Ro-Tap shaker. Each sieve was weighed prior to and after shaking to obtain the mass of particles at each grain size interval. Percentages of each grain size were determined using equation 3.5:

\[
\% \text{ by mass} = \frac{\text{sieve with sediment} - \text{empty sieve mass}}{\text{total sample mass} - \text{mass of gravels}} \quad \text{(Eq. 3.5)}
\]

All sediment captured by the No. 325 (45 µm) sieve and bottom tray of the sieve stack were transferred into the graduated cylinder for hydrometer analysis. Hydrometers were topped up to 1L using DI water and mixed thoroughly using a plunger. Measurements were taken after 40 seconds (\(R_{40}\)) and 7 hours (\(R_7\)) to determine the percentage of silt and clay within the samples using equations 3.6 to 3.7 For accuracy, the 40 second measurements were taken in triplicate and averaged. A blank 1000 mL cylinder containing 100 mL of the sodium hexametaphosphate
and DI water was measured (RL) to obtain the influence of the sodium hexametaphosphate on hydrometer readings. Data were then used to calculate % silt and clay as follows:

\[
\%Clay = 100 \times \frac{R_L - RL_{dry\ sample\ mass}}{dry\ sample\ mass} \quad (Eq. \ 3.6)
\]

\[
\%Silt = 100 \times \frac{Mud\ mass - (R_L - RL_{dry\ sample\ mass})}{dry\ sample\ mass} \quad (Eq. \ 3.7)
\]

Where the mass of mud includes both silt and clay, and is determined from equation 3.8.

\[
Mud = total\ dry\ mass - gravel\ mass - sand\ mass + mud\ from\ sieves \quad (Eq. \ 3.8)
\]

For the full methodology please refer to Appendix A.3 and for full results see Appendix B.3.

### 3.3.3 Calculating Hydraulic Conductivity From Grain Size Analysis

Grain size analysis results were used to estimate saturated hydraulic conductivities of the matrix of each sample with the Kozeny-Carman equation (Eq. 3.9), obtained from Odong (2008), Lu and Xu (2014), and Rosas et al. (2014). This equation has been found to be the best estimator for a range of different sediments and for sediments with variable grain size distributions (Odong 2008; Lu and Xu 2014; Atkinson et al. 2014). Kozeny-Carman is also the most widely accepted equation to use when estimating hydraulic conductivities from grain size (Odong 2008; Atkinson et al. 2014). The Kozeny-Carman equation has been found to be most appropriate for silt, sand, and gravelly sand with a d_{10} (grain size diameter where 10% of the sample, by weight, is smaller than this size) less than 3 mm and not for clayey sediments (Atkinson et al. 2014). Therefore, the Kozeny-Carman equation (Eq. 3.9) was used to estimate hydraulic conductivities for all samples with a d_{10} less than 3 mm and with less than 10% clay.

\[
K = \frac{d}{v} \times 8.3 \times 10^{-3} \times \left[\frac{\pi n^3}{(1-n)^2}\right] d_{10}^2 \quad (Eq. \ 3.9)
\]

Where \( g \) is acceleration due to gravity (9.8 m/s\(^2\)), \( v \) is the kinematic viscosity of water (1.004 \times 10^{-6} \text{ m}^2\text{s}^{-1} \text{ at } 20\degree\text{C}), \( n \) is porosity as determined by Equations 3.10 and 3.11 (Odong 2008), and \( d_{10} \) is the grain size where 10% of the sample, by weight, is smaller than this grain size (i.e. is passing; as determined from grain size distribution analysis and Equation 3.12 to 3.14).
\[ n = 0.255(1 + 0.83^{Cu}) \] (Eq. 3.10)

Where, \( Cu \) is the coefficient of uniformity defined by:

\[ Cu = \frac{d_{60}}{d_{10}} \] (Eq. 3.11)

\[ d_{10} = 10^{\frac{10-b}{m}} \] (Eq. 3.12)

Where \( b \) and \( m \) can be calculated from Equations 3.13 and 3.14 respectively.

\[ b = x_2 - (m \cdot \text{LOG} y_2) \] (Eq. 3.13)

\[ m = \frac{y_2 - y_1}{\text{LOG} \left( \frac{x_2}{x_1} \right)} \] (Eq. 3.14)

Where, \( d_{60} \) is the grain size where 60% of the sample, by weight, is smaller than this size.

The Sauerbrei equation (Eq. 3.15) was used to estimate hydraulic conductivity of samples with more than 10% clay since this equation is good for sand and sandy clay (Rosas et al. 2014). The Sauerbrei equation is the same as the Kozeny-Carman equation except the effective grain size is \( d_{17} \) instead of \( d_{10} \) and the constant is 3.75x10^{-3} instead of 8.3x10^{-3}.

\[ K = \frac{g}{v} 3.75 \times 10^{-3} \left[ \frac{n^3}{(1-n)^2} \right] d_{17}^2 \] (Eq. 3.15)

Therefore, equations 3.9 to 3.14 used above were also used for Sauerbrei with \( d_{17} \) instead of \( d_{10} \).

Estimates of \( d_{10}, d_{17}, \) and \( d_{60} \) from grain size distribution analysis were calculated using a logarithmic interpolation between two known data points as shown in equations 3.12 to 3.14. Grain size distribution analysis was conducted on the matrix sediments and therefore estimates of hydraulic conductivity using the Kozeny-Carman equation provide the hydraulic conductivity of these sediments and may not accurately represent \textit{in situ} hydraulic conductivities as it does.
not take into account the abundance and size distribution of > 2mm particles in the sample and its impact on sorting or the nature of consolidation/packing of the in situ sample.

### 3.3.4 Falling Head Permeameter Analysis

Falling head permeameter analysis was completed on a small subset of samples (n=6) in July 2016. All samples selected for analysis had to have a corresponding grain size sample, which was analyzed, so as to determine the percentage of mud (silt and clay content).

Methods were modified from Sudicky (1986) and Gilmore (2010) and only completed for samples with less than 12% mud as samples with greater than 12% mud would not let water pass through them and into the reservoir. (Figure 3.9; Gilmore 2010). A subsample of approximately 50 g was separated using a riffle box, dried in an oven at 104°C overnight, and weighed again. Each sample was continuously poured into a sample column, with No. 200 mesh (75 µm), which was gently tapped in order to allow for even and natural consolidation of the sample. A modification from Sudicky (1986) and Gilmore (2010), due to equipment limitations, was the method for sample saturation; before analysis, each sample was slowly saturated from below in a DI water bath instead of using carbon dioxide to remove air from samples. During saturation, approximately 1 cm of water was added each day until the water level reached the top of the sample within the column.

Deionized water was de-aired by boiling for a minimum of 2 hours until flat. The de-aired water was added to the system by slowly pumping up through the sample and into the reservoir, ensuring the sample remained saturated. The reservoir was filled until 1.3 m of head was achieved between the outflow manifold and the water surface. The filled reservoir, with 1.3 m of head, was then allowed to flow freely through the sample and the time it took to fall to 0.3 m above the outflow manifold was recorded. Each test was repeated three times and averaged.

Hydraulic conductivity from the falling head permeameter results was calculated using the following equation:

\[
K = \frac{aL}{At} \ln \left( \frac{h_1}{h_2} \right) \quad \text{(Eq. 3.16)}
\]
Where \( a \) is the cross-sectional area of the reservoir, \( L \) is the length of the sample, \( A \) is the cross-sectional area of the sample \((3.81 \times 10^{-4} \text{ m}^2)\), and \( t \) is time for water to fall from 1.3 m \((h_1)\) to 0.3 m \((h_2)\) above the outflow.

The maximum quantifiable hydraulic conductivity that the system can test with the equipment set up was found to be approximately \(6 \times 10^{-4} \text{ m/s}\) (Gilmore 2010). Therefore, hydraulic conductivities above this value are considered not representative of the sediment. Please refer to Appendix A.4 for full methodology.

Figure 3.9: Falling head permeameter methods. A) sample columns with loaded sample in water bath for sample saturation, B) de-aired water with pump for introduction to column through bottom of sample, C) sample and sample column on outflow manifold in foreground and water reservoirs for analysis in background, D) sample and outflow manifold in foreground and reservoirs in background.
4.0 Results

Five complementary data sets were collected and analyzed for improvement of the site conceptual model of the study site. The following sections will present and discuss the results of each of these data sets independently as follows: the geologic facies and the sediment heterogeneity identified from core (Section 4.1); the surface geophysics electrical resistivity surveys and the sediment geometries they reveal (Section 4.2); the geologic description (Section 4.3.1) and interpretation (Section 4.3.2) of stratigraphic units (SU) identified within the cross section and the geologic framework developed from SU interpretations (Section 4.3.3); hydraulic conductivity estimates from grain size and falling head permeameter analysis (Section 4.4); hydraulic head profiles and vertical hydraulic gradients and identified hydraulically significant geologic features (Section 4.5); and the contaminant distribution within cores (Section 4.6).

4.1 Geologic Facies Descriptions

The dominant sediment types found within the five 2015 cores are diamict and sand, with significantly less gravel and silt and clay (Figure 4.1 and 4.2). Each of these sediment types, within and between cores, display variability based on primary grain size, percent gravel, percent silt, colour, clast characteristics, and sedimentary structures. These variabilities result in stacked beds with sharp or gradational contacts. Most sediment within the cores are loose, but an observable increase in compaction occurs with depth, except in the drumlin core (MP-27U), which contains compacted sediment for the entire length of the core. Although not quantitatively measured in this study, none of the sediments are overconsolidated based on their minimal penetrative resistance, as reported by Benn and Evans (1998).

Based on field observations, sand and diamict beds are very similar, with sandy diamict throughout the core. This similarity is also seen from grain size distribution analysis (see appendix B.3 and B.4). Although sand and diamict are different, with different sorting and different \( d_{10} \) and \( d_{90} \) values (Table 4.1), they share similarities. Both diamict and sand beds have similar sand content and similar \( d_{60} \). The sand content is very similar for each facies above the \( d_{30} \) (30% of grains, by weight, are smaller than this grains size; Figure B.12) with variation in the grain size curves clearly seen in the finer grain sizes. The \( d_{60} \) for most sand and diamict facies is medium sand, with the exception of intermediate diamict (fine sand \( d_{60} \)) and gravelly sand...
Figure 4.1: Geologic logs collected from 2015 cores including interpreted stratigraphic units (as determined in Figure 4.8) and MLS designs with water table levels interpreted from blended head in the open borehole. Grain size is shown on x-axis as clay (cl), silt (s), very fine sand (vf), fine sand (f), medium sand (m), coarse sand (c), very coarse sand (vc), granules (g), and pebbles (p). Red boxes indicate locations of interbedded diamict. Logs are offset based on surface elevation. Letters indicate locations where sediment pictures are shown in Figure 4.2. Inset map shows location of boreholes relative to the industrial facility (red box), man-made pond and nearby trail. For full geologic data set per core refer to Appendix B.1.
Figure 4.2: Facies observed within the 5 cores. A-C) variability within diamict (A - clast poor intermediate diamict, B - clast poor sandy diamict, C - clast rich sandy diamict). D) mud. E-G) variability within sand (E - moderately sorted sand, F - gravelly sand, G - very well sorted sand). H) sandy gravel. Locations of each photo are marked on the geologic logs of Figure 4.1 with the corresponding letter. Each photos shows between approximately 15 cm to 30 cm of sediment.

(coarse sand $d_{60}$; Table 4.1). Intermediate diamict is expected to have a lower $d_{60}$ since it is defined by its higher mud content (Hambrey and Glasser 2003). The sandy diamict facies grain size distributions have a similar curve and slope to the sand facies (Appendix B.4). Only the intermediate diamict, with more mud content, shows significant differences in the grain size curves.

Diamict within all cores is very sandy and primarily massive, poorly to very poorly sorted, non-plastic (clay poor), medium to coarse grained sand with variable gravel and silt content. The majority of diamict facies within the study site are either clast poor intermediate diamict or clast
poor/rich sandy diamict (Figure 4.2). Grain size distribution analysis agreed with field interpretations (Appendix B.1). Diamict samples identified as intermediate diamict have mud percentages varying from 19% to 45% silt and approximately 13% clay (total 22% to 51.7% mud), whereas sandy diamict samples have mud percentages varying from 9% to 24% silt and 1% to 11% clay (total 12% to 45% mud; Table 4.1). Matrix grain size distribution of all diamict samples contained between 48% to 89% sand, which is consistent with previous studies of the Horicon Till in Dane County Wisconsin (Mickelson 1983; Rayne et al. 1996; Clayton and Attig 1997b; Syverson et al. 2011).

Table 4.1: Average $d_{10}$, $d_{50}$, and $d_{90}$ as determined from grain size distribution analysis for each facies. See appendix B.3 for full grain size distribution analysis results and appendix B.4 for grain size distribution curves.

<table>
<thead>
<tr>
<th>Facies</th>
<th>$d_{10}$ (mm)*</th>
<th>$d_{50}$ (mm)</th>
<th>$d_{90}$ (mm)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clast poor intermediate diamict</td>
<td>0.00467 (silt)</td>
<td>0.164 (fine sand)</td>
<td>0.477 (coarse sand)</td>
</tr>
<tr>
<td>Clast poor sandy diamict</td>
<td>0.00949 (silt)</td>
<td>0.247 (medium sand)</td>
<td>0.552 (coarse sand)</td>
</tr>
<tr>
<td>Clast rich sandy diamict</td>
<td>0.0167 (silt)</td>
<td>0.293 (medium sand)</td>
<td>0.767 (very coarse sand)</td>
</tr>
<tr>
<td>Gravelly sand</td>
<td>0.121 (fine sand)</td>
<td>0.397 (coarse sand)</td>
<td>0.892 (very coarse sand)</td>
</tr>
<tr>
<td>Sand</td>
<td>0.164 (fine sand)</td>
<td>0.305 (medium sand)</td>
<td>0.470 (coarse sand)</td>
</tr>
</tbody>
</table>

*d$_{10}$ represents the grain size (mm) that 10% of grains, by weight, are smaller than

** d$_{90}$ represents the grain size (mm) that 90% of the grains, by weight, are smaller than

Many diamict beds, observed in the 5 new cores, are identified based on very slight changes in colour (single value change in value or chroma), visual gravel percentage (1-3% change), silt content, moisture, and secondary grain size. Although slight changes in one or more properties were observed between diamict beds, these beds probably represent internal heterogeneities within a larger diamict unit rather than distinct diamict beds. This is expected as diamict beds typically range around 1 m to 6 m (Evans et al. 2012; Meriano and Eyles 2009; Ó Cofaigh et al. 2008) and many of the crude beds shown in Figure 2.1 are several centimeters to 10s of centimeters thick.

Sedimentary structures are uncommon within most diamict with the exception of an occasional bed containing continuous or discontinuous horizontal laminations or slight grading. The lack of sedimentary structure is possibly a result of vibrations from rotosonic drilling; Determining the
degree of structure loss due to specific rotosonic coring techniques is not possible without a comparable high-quality log at the same location and drilled using a different technique. Horizontal lamination are typically identified due to colour differences and occasionally recognized as silty or coarse-grained sand laminations. Visual estimate of gravel content within diamict varies from 1% to 40% (see Appendix B.1) and are typically rounded clasts of carbonate or sandstone, consistent with previous studies (Mickelson 1983; Clayton and Attig 1997b). Angular clasts are present, but mostly isolated to diamict beds at the top of MP-27U. Chert and igneous clasts are also present but typically less than 1% of the total gravel content. Igneous clasts are typically found scattered within diamict beds and often weathered; whereas chert clasts are less widely dispersed and concentrated to specific stratigraphic units and mostly within sand facies (see Appendix B.1 for location of chert clasts).

In addition to the crudely bedded diamict, there are 7 locations of thinly interbedded diamict (Figure 4.1). These beds vary from ~3 cm to 28 cm thick and the whole interbedded package varies from 36 cm to a maximum of 132 cm thick. The interbedded diamict are characterized by diamict beds with the matrix alternating between either fine and medium or medium and coarse sand. It is this alternating back and forth between two different primary grain sizes on a small scale that characterizes the interbedded diamict. Therefore, crudely bedded diamict beds with changes defined by other characteristics besides primary grain size were not considered interbedded diamict. In addition, a change in the primary grain size of diamict beds without the alternating aspect were not considered interbedded diamicts but more likely represent a fining upward or coarsening upwards sequence. Interbedded diamict is only found within the till plain cores of MP-23U, MP-25U, and MP-27U and seem to be associated with stratigraphic unit (SU) boundaries, which are discussed in Section 4.3.

Sand facies are variable within all cores and range from massive, very well to poorly sorted, fine to coarse grained, muddy to gravelly sand (Figure 4.2). Sand facies show more variability than diamict facies; although, contacts between sand beds tend to be gradational rather than sharp. The sand facies within the study site include muddy sand, sand, and gravelly sand. Grain size distributions agree well with field interpretations of sand facies (Appendix B.1) and provide a quantitative basis for these observation-based logs. Muddy sand samples contained from 32.4% to 34.1% mud (silt and clay) whereas the matrix of sand and gravelly sand samples contained from 0.2% to 11.5% mud (Table 4.1; see appendix B.3 and B.4 for full grain size distribution analysis results).
Similar to diamict facies, sand facies are typically massive but have some continuous and discontinuous horizontal laminations or grading. Horizontal laminations are typically due to coarser or finer sand but are also found to be rhythmically laminated coarser sand with silt and clay, thick laminations of clay, or laminations due to colour variations. Visual gravel content within gravelly sand beds range from 1% to 35% and are typically rounded to subrounded carbonate and sandstone clasts. Similar to diamict facies, chert and igneous clasts are also found within gravelly sand facies, but to a larger extent than diamict facies, making up to 40% of the total gravel. Between all facies, chert clasts are most commonly found within sand facies of MP-28U and MP-19U. The higher chert content within MP-19U may be due to the underlying Prairie du Chien bedrock, which contains significant chert, suggesting the sediment source may be local.

Two sand layers within the till plain cores (MP-23U and MP-25U) were found to be contaminated. The contaminated sand bed within MP-23U is between ~256.9 to 256.6 masl (~13.1 and 13.4 mbgs) and is a very well sorted medium sand with fine sand grains and ~3mm thick coarse sand laminations overlying a very well sorted medium sand with coarse and fine sand grains, which is not as contaminated. The presence of contamination was obvious within this sand bed during geologic logging due to a distinctive sediment colour (2.5Y %) and noticeable volatile organic compound (VOC) smell (Figure 4.3). The contaminated sand bed within MP-25U is between ~252.2 to 252.1 masl (~ 21.2 and 21.3 mbgs) and contains vertical staining as seen in Figure 4.4.

Mud and sandy mud facies within all cores are massive or laminated, moderately to very well sorted silt and clay (Figure 4.1 and 4.2). Grain size distribution analysis of two mud samples indicated between 33.9% to 70.1% silt, 25.7% to 27.6% clay, and 2.3% to 41.1% sand. Mud laminations are a result of colour changes or rhythmically laminated with sand. Mud facies are typically isolated to deposits at the top of each core but also exist as beds at depth with thicknesses ranging from 0.8 cm to 43 cm. Thicker mud beds (10-43 cm) tend to be associated with sand facies, whereas thinner beds/laminations (0.8-3 cm) are found within diamict beds and interbedded with diamict beds. An exception is the two thick mud beds (19.2 cm and 10.1 cm) within MP-23U (16.52 mbgs and 17.26 mbgs respectively). In addition, there is a thick deposit of clay in MP-27U that is rhythmically laminated with silt and sand (24.60-27.43 mbgs).
Gravel clasts are sometimes associated with mud facies, but when present are typically less than 1%.

Gravel facies within the five cores are very limited, but when present they are massive, very poorly to poorly sorted, visually between 60% to 80% pebbles and granules, and matrix supported with a matrix of fine to coarse grained sand (Figures 4.1 and 4.2). Matrix composition of gravel facies, based on grain size distribution analysis of two samples, is between 81.6% to 98.3% sand, 2.2% to 16.8% silt, and 0% to 1.6% clay. Clasts are rounded to subrounded except at the weathered bedrock interface where clasts are angular. Clasts are primarily carbonate and sandstone with isolated igneous clasts and occasional chert clasts.

Figure 4.3: Sand bed with distinctive colour (2.5Y %) and odour (VOC smell) between ~13.1 and 13.4 mbgs (~256.9 to 256.6 masl) in MP-23U. Sand bed is primarily medium sand with some fine sand and ~3mm coarse sand laminations. This bed is associated with contaminant concentration peak seen in Figure 4.17 for MP-23U in Section 4.7.
Figure 4.4: Sediment stains in MP-25U between ~ 21.2 and 21.3 mbgs (~252.2 to 252.1 masl). Colour is similar to contaminated sand bed in MP-23U, 2.5Y ⅚ (Figure 4.3).

Similar to the 2015 cores described above, the six 2004 pond cores contain diamict and sand but unlike the 2015 cores, most are dominated by sand (Figure 4.5). Each of these sediment types display variability within and between holes based on primary grain size and sorting; however, the lower quality logging, due to coarser spatial resolution (10’s of cm scale versus cm scale resolution) and un-guided textural descriptions limited to dominant grain size, rather than full suite of sedimentary characteristics shown in figure 3.3, collected for these cores makes it difficult to define subtle changes in sedimentary characteristics such as percent gravel, percent silt, clast characteristics, sedimentary structures, as well as contact characteristics.

Diamict within the pond cores are typically identified as fine to coarse sand with gravel and mud although some diamict beds were described as primarily clay with sand and gravel. Gravel percentage within diamict beds ranges from 5 to 10%. No sedimentary structures or crude bedding was identified within the cores. Sand within the pond cores range from sand to gravelly sand to muddy sand. The primary grain size varies from fine to coarse sand with well sorted sand beds having fine to medium sand, muddy sand typically having fine or medium sand, and gravelly sand typically having medium to coarse sand. Gravelly sand contains between 5 to 15% gravel. Mud beds within the pond cores are more prevalent than within the 2015 cores and can contain between 5 to 10% gravel or sometimes sand.
Figure 4.5: Geologic logs for 6 pond study holes drilled in 2004-2005 (Swanson et al. 2005). Originally logged by B. Swanson and revisited and modified as outlined in the methods section. Inset shows location of cores relative to the man-made pond (see Figure 2.1 for location relative to other cores). Grain size is shown on x-axis as clay (cl), silt (s), very fine sand (vf), fine sand (f), medium sand (m), coarse sand (c), very coarse sand (vc), granules (g), and pebbles (p).
4.2 Surface Geophysics: Electrical Resistivity Tomography

Each of the five 2015 holes and 5 of the 6 pond holes were located on or near seven surface geophysical resistivity lines (Figure 2.1, refer to Appendix B.2 for all geophysical lines reported by Steelman (2015)). Four of these lines are primarily within the till plain whereas two are mostly within the glaciofluvial physiographic element and one extends over all three elements. Of the seven lines, three were found to represent the majority of the electrical resistivity characteristics of the unconsolidated sediments (Figure 2.1); these three lines will be focused on here.

Comparison of the electrical resistivity signal with the MP-25U stratigraphic core log reveals that the upper diamict facies (above ~ 260 masl) are more electrically resistive than the lower sand facies (Figure 4.6). Comparison of the electrical resistivity signal to the stratigraphic core log for MP-19U reveals good correlation (Figure 4.6), with moderately resistive sediment at depth corresponding to the lower sand and diamict facies within the core and low resistivity sediment at the surface corresponding to the large, 0.72 m thick, surface deposit of silt and clay. From these comparisons, it can be seen that the geophysical signal reveals the approximate location of general sediment package boundaries but cannot always differentiate between diamict and sand. This is expected since the diamict and sand sediments on site have similar grain size distributions. However, it may also be a scale issue as thinner diamict or sand beds are not always resolved, whereas contacts between larger diamict and sand packages are. In addition, other factors might be at play as solutions to geophysical data analysis are non-unique and different combinations of grain size, clay content, porosity, water content, and fluid conductance can produce a similar signal (Van Dan 2012; Loke et al. 2013).

Similarly, comparison of the electrical resistivity signal to the MP-27U stratigraphic core log again shows the ability of the signal to differentiate between the two main packages, the lower diamict and sand package versus the upper sand and mud package (Figure 4.6). The unexpected higher resistivity of mud sediments (between ~266.5 and 263.5 masl) could be a result of the lower water content due to their location above the water table. On the other hand, the higher resistivity signal may also be associated with different sediment considering the large offset between MP-27U and the survey line (109m).
Figure 4.6: Slice of electrical resistivity survey next to stratigraphic units and core log. Resistivity signals from ERT0015 and ERT0023 (Figure 4.7a,b). In general the contact between sand and diamict is expected to create a different resistivity signal however some of these boundaries were not identified within the geophysics (Locations of disagreement) and may be due to similarity of diamict and sand sediments, offset between core and survey line, water content as well as scale of measurement. Offset of cores from resistivity surveys is shown in meters.
Although the electrical resistivity survey cannot always distinguish between diamict and sand, in general the lower resistivity sediments can be considered mud, moderately resistive sediments can be considered sand or diamict, and highly resistive sediments can be considered sand and gravelly sand or unsaturated sediment.

In general the glaciolacustrine sediments are less resistive than the till plain sediments, which in turn seem to be less resistive than the glaciofluvial sediments (Figure 4.7). This can be explained by the expected decrease in clay-rich facies between the three physiographic elements, with the highest clay content in the glaciolacustrine element and lowest in the glaciofluvial element. In addition, the low to moderately electrically resistive sediments at depth, tend to be laterally continuous, whereas the upper sediments show more lateral heterogeneity within the site (~700 m).

Specifically, line ERT0015 (Figure 4.7a) extends west to east and is primarily within the till plain but traverses over the drumlin and into the glaciofluvial sediments to the east. In the west, this line is characteristic of the electrical resistivity signal of the till plain: continuous, low to moderately resistive sediment at depth (~250 masl), lenses of moderately to highly resistive sediment at mid depth (~261 masl), and low resistivity sediment interspersed with moderately resistive sediment at surface. The moderately and highly resistive materials are characteristic of sand, while the low resistivity materials are characteristic of mud, specifically clay-rich sediments. Occasionally at depth, localized very low resistivity signature is observed. These low resistivity features tend to occur at approximately the same elevation as a similar signal directly under the drumlin, suggesting they may have been deposited at a similar time.

Figure 4.7: Surface geophysical resistivity lines with associated surface physiographic elements and locations of nearby boreholes. Top of rock interpreted from seismic refraction surveys (ERT0023 and ERT0033) and geologic logs (ERT0015; Steelman 2015). A: ERT0015 with 5 m electrode spacing, Absolute error = 1.0%. B: ERT0023 with 3 m electrode spacing, Absolute error = 2.3%. Signal surrounding the culvert on the west side of the survey line is expected to be a relic of the culvert itself. C: ERT0033 with 2 m electrode spacing, Absolute error = 1.9%. Location where ERT023 and ERT0033 cross indicated in both lines (B and C).
Based on the ERT0015 resistivity line there is a distinct change in signal between the sediments underlying the till plain element and the sediments underlying the glaciofluvial element. The primary difference between these elements is that the moderately to highly resistive sediment, at mid depth (~261 masl; Figure 4.7a), within the till plain element do not extend into the glaciofluvial element in the east. In addition, sediments in the glaciofluvial element in general seem to be less resistive than the till plain element. However, the electrical resistivity signal at depth, above top of rock, from each physiographic element is similar and seems to be laterally continuous across the transect.

Line ERT0023 (Figure 4.7b) extends west to east and is primarily within the glaciofluvial element with the west quarter extending into the till plain. This line is characteristic of the electrical resistivity signal from glaciofluvial sediments on site: fairly continuous moderately resistive at depth (~250 masl), lenses of highly resistive sediments mid depth (~259 masl), and moderately to highly resistive sediment with isolated low resistivity zones at surface. In contrast to the till plain, few of these signals are laterally extensive but instead show spatial heterogeneity, which may suggest lateral facies changes. Similar to ERT0015, within the till plain, ERT0023 shows a change in signal between the till plain and outwash sediments, except at the very base of the unconsolidated sediments, which are laterally continuous.

A second line within the glaciofluvial sediments, ERT0033 (Figure 4.7c), extends south to north with glaciolacustrine sediments represented in the south. This line shows similar characteristics to ERT0023 but the signals are more laterally continuous: laterally continuous low to moderately resistive sediments at depth (~250 masl), laterally extensive lenses of highly resistive sediments mid depth (~262 masl), and low resistivity sediments at surface. Line ERT0033 also provides insight into the glaciolacustrine sediments and shows that they typically have a low resistivity.

Comparison of ERT0023 and ERT0033 (Figure 4.7b,c) shows the variability of glaciofluvial sediments with orientation. When both lines are considered together, the surveys suggest the presence of north-south trending glaciofluvial channels, which helps to better understand the 3-dimensional geometry of the sediments. The channel orientation is supported by the orientation of surficial glaciofluvial units mapped in Dane County by Clayton and Attig (1997a) and the direction of flow of the Green Bay Lobe.
4.3 Stratigraphic Units

4.3.1 Description of Stratigraphic Units

Eight stratigraphic units were distinguished within the unconsolidated sediment based on core logs from 2015 and 2004 and surface geophysical surveys (Figure 4.8 and 4.9). Stratigraphic units were first delineated using the 2015 cores. The higher quality of the 2015 cores allowed for the use of facies analysis. The 2004 cores were then similarly delineated based on the defined geologic framework. Integration of core logs and surface geophysical surveys were important to provide both a high-resolution stratigraphic understanding (core, z-direction) and lateral heterogeneity (geophysics, y-z direction) of the unconsolidated sediment at the site.

The first stratigraphic unit (SU1; varying from 0.7 m to 4m thick; Figure 4.8) is the basal diamict with sand interbeds that appears to be laterally continuous across the study site (~700 m), based on geologic core logs (Figure 4.1 and 4.5) and surface geophysical signals (Figure 4.7). SU1 is composed of diamict facies associated with mud interbeds and relatively thick interbeds of well sorted sand. The sedimentary characteristics of different diamict beds within SU1 are relatively similar. Mud interbeds are typically isolated to individual cores and not found in adjacent core, except within the pond transect between MP-12 and MP-11 (Figure 4.5). SU1 within the pond cores shows similar characteristics, with diamict containing sand and mud interbeds; however, these interbeds are thicker and more common within the pond holes (Figure 4.9). In addition, SU1 was found to be locally eroded from MP-9.
The second SU (SU2; varying from 2.3 m to 9m thick) overlies SU1 and is a succession of vertically variable sand (Figure 4.8). SU2 is characterized by thin stacked heterogeneous sand and gravelly sand facies with variable sorting and primary grain sizes. In general, SU2 tends to be more well sorted towards the northeast and more fine grained towards the south. Within SU2, the sand and gravelly sand facies have an occasional interbed of diamict or mud (Figure 4.1). Diamict interbeds are typically thin, maximum 20.4 cm thick, and do not extend between cores, whereas mud interbeds are only found within MP-27U. SU2 within the pond cores is also composed of well sorted sand (Figure 4.9) but within these cores interbeds of diamict and mud are not found (Figure 4.5).

Lithological differentiation of SU3, SU4, SU5 and SU6 is difficult as they are all dominated by diamict with very similar characteristics. Differentiation of different till units within Dane County
has proven difficult due to the similarity of the lithology; previous identification has only been accomplished based on stratigraphic position and cross-cutting relationships (Whittecar and Mickelson 1977; Clayton and Attig 1997b). These four stratigraphic units are composed of diamict beds with relatively similar sedimentary characteristics and crudely stacked beds with the occasional interbed of sand. These units are distinct from SU1 since they have fewer sand interbeds and contain crudely bedded diamict. Differentiation of these four stratigraphic units was done using several subtle lithologic clues from the 2015 cores. Pond holes lack adequate detail to aid in differentiation of diamict-dominated stratigraphic units; therefore, high resolution (centimeter scale) geologic investigations are critical for full reconstruction of the stratigraphic sequence and glacial history.

Differentiation of SU3 from SU4 was achieved as a result of a slight change in sediment compaction that occurred at approximately 261.4 meters above sea level (masl) in MP-23U and at approximately 261.2 masl in MP-25U. In addition, SU4 is laterally associated with mud and gravelly sand, whereas SU3 appears to be a relatively continuous diamict (Figure 4.1). Differentiation of SU4 from SU6 was achieved since the diamict beds within SU6 had more similar sedimentary characteristics (grain size distribution) and less interbeds of sand compared to SU4; as well, the lateral association of the diamict in SU4 with mud and gravelly sand indicates the diamict units of SU4 and SU6 are separate. The change to SU6 diamict occurred at approximately the same elevation within MP-23U (266.7 masl) and MP-25U (267.3 masl), providing more confidence in the division between SU4 and SU6. SU6 was differentiated from SU5, similar to SU4, due to the more homogeneous grain size distribution of SU6 and the lack of sand interbeds. In addition, SU5 was differentiated based on the higher plasticity and abundance of angular gravel clasts not found within other stratigraphic units.

SU3 (varying from 0 m to 7.3 m in thickness) is composed of thin crudely bedded diamict (less than 0.3 m thick) and thicker diamict beds (maximum 1.3 m thick) with a matrix that ranges from fine to medium sand and the occasional sand interbed. This unit may be bounded by the interbedded diamict feature described in Section 4.1 (Figure 4.1) and is interpreted to extend across the entire site due to the presence of diamict facies within MP-28U and MP-19U at approximately the same elevation and stratigraphically above SU2. However, within the north-south pond transect (Figure 4.9) SU3 is locally eroded, probably as a result of glaciofluvial erosion.
Figure 4.9: Reinterpretation of the pond transect from Casado 2012 (his figure 1.4.3) in context of geologic framework and stratigraphic units defined in this study (Figure 4.8). Location of boreholes can be seen in Figure 2.1. The geologic log from MP-10, located east of the pond has a similar sequence of stratigraphic units as those found in MP-13R and MP-12 (Figure 4.5). Mbr-Member, Grp-Group.

In contrast, SU4 (varying from 3.2 m to 5.5 m thick) shows a facies association of diamict in the west (MP-23U and MP-25U), mud and sand within the drumlin (MP-27U and MP-9), and gravelly sand within the east (MP-28U, MP-19U, MP-10, MP-11, MP-12, MP-13R, and MP-14; Figures 4.1 and 4.5). The lateral facies changes within SU4 are supported by surface resistivity surveys (Figure 4.7). The mud and sand of SU4, within the drumlin cores (MP-27U and MP-9), is characterized by a sequence of muddy sand and mud facies (Figure 4.10). Mud content within all facies is high and the muddy sand contains dispersed mud as well as clay clasts whereas the mud facies contain rhythmically laminated clay with silt and sand (~2 to 5 mm thick). The mud and sand facies typically overlie SU3 within the till plain element; however, SU3 may be locally eroded (MP-10, MP12, MP13R) and in some cases the mud and sand facies overlie bedrock (MP-9) where SU1, SU2 and SU3 have been eroded (Figure 4.1 and 4.5). The
gravelly sand within SU4 is only found within the glaciofluvial element (MP-10, MP-11, MP-19U, MP-28U) and within the till plain element where the cores are very close to the adjacent glaciofluvial element (MP-12, MP-13R, MP-14; Figures 2.2, 4.7 and 4.8). The gravelly sand is well sorted with the occasional interbed of mud within MP-19U. Sand beds within this unit are distinguished by sharp or gradational changes in primary grain size or gravel content but in general have similar sedimentary characteristics (based on grain size distribution).

Similar to SU3 and the diamict in SU4, SU5 is characterized by crudely bedded diamict with thin sand interbeds. However, the diamict within SU5 typically has higher plasticity and more angular gravel clasts than other units. In addition, the lower half of SU5 contains diamict with a matrix dominated by fine sand, which is finer than found in SU3 and SU4 (Figure 4.10). SU5 is only found within the drumlin holes (MP-27U and MP-9; Figure 4.10) and was likely eroded from the other profiles during drumlin formation. This stratigraphic unit is hypothesized to define the lower extent of the drumlin feature.

The final diamict stratigraphic unit, SU6 is relatively homogeneous medium sand diamict with less crude bedding and minimal sand interbeds. SU6 is found to be fairly extensive across the site but is eroded in the east from the pond holes and MP-19U (Figures 4.7 and 4.8).

SU7 is only found within or at the boundary of the glaciofluvial and glaciolacustrine elements (Figure 4.8). No lithologic descriptions are available for this unit because it was interpreted from the surface electrical resistivity lines, which indicated that the surficial mud deposits (SU8), within the 2015 and 2004 holes (Figure 4.7 and Figure B.10 in Appendix B.2), were not laterally continuous (varying from 18 m to 160 m in lateral extent; Figure 4.7). It is unclear if SU7 is composed mostly of sand or diamict as the electrical resistivity signal for these two sediment types are very similar. SU7 was hypothesized to be sand due to a slightly higher resistivity signal than within the till plain (Figure 4.7a). However, further field investigations with core recovery and detailed logging are required to determine the exact nature of the sediment of SU7.

The final stratigraphic unit on site (SU8) is characterized by surficial mud deposits (varying from 18 m to 160 m in lateral extent and from 1.7 to 2.8 m thick; Figure 4.8 and 4.9). These mud deposits are weakly laminated and can contain diamict interbeds at the base (Figure 4.1).
Surface geophysical investigations identified that SU8 is not laterally extensive (Figure 4.7). SU8 within the pond cores is mostly clay but can be associated with organics and gravels.

At a similar stratigraphic position to the muds of SU8 are glaciofluvial channel deposits identified by surface electrical resistivity surveys (Figure 4.7b,c). No core intersected these deposits, but they were distinctly more resistive than surrounding sediments of SU7 and oriented in a northeast-southwest direction similar to glaciofluvial deposits identified by (Clayton and Attig 1997b).
Figure 4.10: Comparison of drumlin holes MP-27U (2015) and MP-9 (2004) with interpreted stratigraphic units as determined in Figure 4.8. Distance between MP-27U and MP-9 is ~ 89 m and their relative location can be seen in Figure 2.1. Grain size is shown on x-axis as clay (cl), silt (s), very fine sand (vf), fine sand (f), medium sand (m), coarse sand (c), very coarse sand (vc), granules (g), and pebbles (p).
4.3.2 Interpretation of Stratigraphic Units

As mentioned previously, the origin of diamict is sometimes difficult to establish as several processes can result in similar sedimentary characteristics. There is minimal diagnostic evidence to identify the specific origin of the diamict-dominated stratigraphic units (SU1, SU3, SU4, SU5, and SU6). Diagnostic evidence to suggest till versus diamict can include rafts of underlying sediments, overconsolidation, lateral continuity, boulder pavements, sand lenses and stringers etc., striated or faceted clasts, and deformation (Boyce and Eyles 2000; Kessler et al. 2012; Eyles et al. 2015). Many of these diagnostic criteria were not found likely due to the limited horizontal view of the sediment that core logging provides as well as the possible loss of evidence from rotosonic drilling disturbance. The absence of these criteria does not mean they are not glacial deposits or that there is no till on site. In the absence of these diagnostic sedimentary characteristics, the succession is constrained by the detailed sedimentology, that can help identify subtle difference, and the regional stratigraphic framework.

These diamict-dominated units may represent several different events related to the regional stratigraphic framework, which indicates there were 3-4 glacial advances within Dane County, but only 2 or 3 overriding the site (Clayton and Attig 1997b). Since glacial ice overrode the study site, several of the diamict-dominated stratigraphic units are expected to be subglacial till. The Horicon Till is historically interpreted as subglacial (Clayton and Attig 1997b). However, given the ice marginal location of the site and the glacial history of the area, it is also possible that some of the diamict-dominated stratigraphic units record sediment instability and reworking by debris flows in a supraglacial or ice proximal setting.

The diamict of SU1 may be interpreted as either subglacial till or ice marginal debris flows. The lateral continuity and similar sedimentary characteristics of the diamict within SU1, as seen in the geologic core logs (Figure 4.1) and geophysics (Figure 4.7), may suggest deposition as subglacial till (Eyles et al. 2015). However, the high number and thickness of sand beds suggest the diamict more likely formed as ice marginal debris flows, which are expected to have more and thicker sand lenses than basal tills (Kessler et al. 2012). Although individual debris flows are not typically considered laterally extensive, successive debris flows can be over 10 m thick and can cover 1000s to 10,000s of square metres in area (Benn and Evans 2010). In addition, multiple debris flows can be preserved interspersed with sand interbeds that record minor reworking by glacial meltwater in an ice marginal setting; this is consistent with the way many of the diamict units within SU1 cannot individually be correlated from one core to the next (Figure
4.1. Rather, the lateral continuity of SU1 is based on this association of diamict and sand interbed. Therefore, SU1 is hypothesized to be an ice marginal facies association due to the association of diamict and sand and the number and thickness of sand beds. This hypothesis can be tested further with recovery of additional cores in the area, and potentially with the collection of clast fabric data that can help with the interpretation of the diamict facies (Kessler et al. 2012).

In contrast to SU1, SU3 and SU5 are interpreted to be deposited as subglacial till. Although there is some uncertainty in the origin of these units, it is likely that they are subglacial till for the following reasons: i) the diamict beds within each stratigraphic unit have similar grain size distributions, which could indicate homogenization through subglacial deformation (Benn and Evans 1996; Evans et al. 2006; Kessler et al. 2012), ii) they have few thin sand interbeds (Kessler et al. 2012), and iii) they are laterally continuous across the site.

Although the diamict within SU4 is similar to SU3 and SU5, it is not laterally extensive and is associated laterally with thick mud and sand and gravelly sand facies. Based on this facies association, SU4 is primarily considered to represent ice marginal conditions and the diamict facies in the west of SU4 are considered debris flow deposits. The mud and sand facies of SU4 are thought to be of glaciolacustrine origin based on their similarity to glaciolacustrine deposits within the county (Clayton and Attig 1997b) and the low resistivity and shape of these deposits within the surface electrical resistivity surveys. The sand and gravel facies of SU4 are thought to record deposition by glacial meltwater draining the ice margin.

The diamict facies within SU6 is thought to be a till carapace deposited as a thin meltout or ablation till over the entire study area during glacial retreat, based on its stratigraphic position and its association with the drumlinized till plain. This is consistent with other drumlins within Dane County that are capped by a till carapace (Mickelson 1983).

Glaciofluvial processes likely deposited SU2 during glacial retreat. The thin stacked sand and gravelly sand facies within SU2 are consistent with other glaciofluvial deposits (Slomka and Eyles 2013). Although they lack cross-bedding, typically found in glaciofluvial successions, this may be due to the rotosonic vibrations during drilling. Similarly, the degree of sorting and lack of mud within the sand facies agrees with other glaciofluvial deposits within Dane County (Mickelson and McCartney 1979).
Thin patchy lake sediments and discontinuous loess covered much of Dane County (Clayton and Attig 1997b). The high clay content and presence of silt and clay laminations within SU8 makes the glaciolacustrine interpretation most likely.

Comparison of the stratigraphic units underneath the till plain versus glaciofluvial or glaciolacustrine elements identified two unique sedimentation styles: till plain sediments are dominated by diamict, whereas glaciofluvial and glaciolacustrine elements tend to have more sand and more lateral and vertical variability of units. Therefore, glacial sediments mapped at surface as different physiographic elements (e.g. till plain or glaciofluvial) may be used to predict the nature of the subsurface sediments. This is particularly useful for advancing the understanding of the current site conceptual model in areas offsite that have limited subsurface geologic data. However, inferences must be made with caution at boundaries between physiographic elements as there may be some error associated with the exact location of the boundary: this was shown to be the case with the pond holes that are mapped within the till plain element but show similar sediments to those of the glaciofluvial element (Figure 4.5). This is expected due to the scale of mapping and low resolution of these surficial maps. The sedimentation style under these physiographic elements may vary offsite as this study only investigated a small ~ 700 m wide site, but also due to site specific variations in the degree of glacial and glaciofluvial erosion. Further high-resolution geologic logs are recommended to better constrain the heterogeneity within each physiographic element in the area.

4.3.3 Geological Framework

Based on the stratigraphic units (SU) described in Section 4.3 the following sequence of events is interpreted from the available data (Figure 4.11) in the context of the regional stratigraphic framework. In general these stratigraphic units suggest deposition by 4 glacial advances and associated retreats (Brooklyn, Johnstown, Milton, and Lake Mills Phases). It is important to note that the paleoenvironmental reconstruction presented here is based on the best available data at this time and its analysis within the established regional geological framework, which has limited radiometric constraints on timing of deposition. Radiometric dating is recommended to strengthen the temporal constraints on this geological framework.

Little evidence of glaciations older than the Wisconsinan Glaciation are present in Dane County (Mickelson 1983; Clayton and Attig 1997b); therefore the basal diamict and sand facies of SU1
is interpreted as an ice marginal facies association recording glacial retreat during the Brooklyn Phases of the Green Bay Lobe of the Wisconsinan Glaciation (Figure 4.11a). The extent and thickness of the sand facies of SU2 suggests deposition during the interglacial period between the Brooklyn and Johnstown Phases (Figure 4.11b; Kessler et al. 2012).

The Johnstown Phase was characterized by multiple advances and retreats and was the most temporally dominant phase that overrode the Cottage Grove area, lasting approximately 4000 years (Clayton and Attig 1997b). Therefore stratigraphic units SU3, SU4, and SU5 were all likely deposited during this phase. The diamict facies of SU3 were likely deposited during an
intermediate advance of the Johnstown Phase (Figure 4.11c), whereas SU4 was likely deposited as laterally heterogeneous ice marginal sediments during a minor glacial retreat with deposition of debris flow (diamict), ponded sediments (mud), and glaciofluvial sediments (sand and gravel; Figure 4.11d).

The last advance at the site from the Johnstown phase is recorded by the diamict facies of SU5, which was then subsequently eroded into a drumlin form (Figure 4.11e and 4.10f; Clayton and Attig 1997b). More Johnstown or Milton Phase advances and retreats may have occurred; however, sedimentary records of these may have been eroded.

Following the formation of the drumlin, a thin meltout or ablation till carapace was deposited over the existing sediment (Figure 4.11f; Mickelson 1983; Stokes et al. 2011; Eyles et al. 2016). The till carapace was likely deposited during glacial retreat of the Milton phase. As the glacier continued to retreat during the Lake Mills Phase, glaciofluvial processes dominated and deposited glaciofluvial sand (SU7; Figure 4.11g) followed by more channelized outwash sediments and glaciolacustrine deposits (SU8; Figure 4.11h).

4.4 Hydraulic Conductivity Estimates

Hydraulic conductivity estimates for the unconsolidated sediments were made using grain size distribution analysis and falling head permeameter analysis. Grain size distribution results were used to estimate hydraulic conductivities (K) based on the empirical equations of Kozeny-Carman (Odong 2008; Lu and Xu 2014; Rosas et al. 2014) and Sauerbrei (Rosas et al. 2014), plotted in Figure 4.12. These calculations indicated that the diamict facies samples ranged from $3.0 \times 10^{-8}$ m/s to $6.0 \times 10^{-6}$ m/s (n=33), with a geometric mean of $1.9 \times 10^{-7}$ m/s. Similarly, the muddy sand facies ranged from $2.3 \times 10^{-8}$ m/s to $2.1 \times 10^{-7}$ m/s, with a geometric mean of $6.4 \times 10^{-8}$ m/s (n=4; Figure 4.12). In contrast, sand and gravelly sand facies had hydraulic conductivities ranging from $1.7 \times 10^{-8}$ m/s to $2.1 \times 10^{-3}$ m/s (n=17), with a geometric mean of $2.3 \times 10^{-4}$ m/s. Hydraulic conductivity, estimated based on falling head permeameter measurements, agreed well with the range of hydraulic conductivities estimated from grain size distributions (Figure 4.12; Appendix B.3).
Although hydraulic conductivity estimates show little difference between diamict and muddy sand facies, there are significant differences between diamict and sand or gravelly sand, even though the grain size distributions of diamict and sand facies are considered to be fairly similar (See Section 4.1). The key difference between the sand and diamict facies is the d10 value, which explains the differences in K estimate, as d10 is a critical variable in the equation used to calculate K.

Figure 4.12: Calculated hydraulic conductivity estimates using Kozeny-Carman and Sauerbrei equations and measured hydraulic conductivity values from falling head permeameter. Note depth scales are not all the same. mbgs-metres below ground surface.
Previous estimates of K within Cottage Grove, Dane County show similar ranges in K to the results presented here, $10^{-9}$ m/s to $10^{-4}$ m/s (for all sediment types; Oelkers 1995) and $10^{-7}$ to $10^{-5}$ m/s (for the Horicon Till; Rayne et al. 1996), but have higher geometric means than this study. Oelkers (1995) found the K geometric mean for diamict and glaciolacustrine to be $10^{-6}$ m/s and $10^{-5}$ m/s for glaciofluvial sediment whereas this study found a geometric mean of approximately $10^{-7}$ m/s for diamict and $10^{-4}$ m/s for glaciofluvial sands. However, as is often the case, the wide range of K found on site makes it difficult to use these estimates to predict the magnitude of K based on lithologic descriptions. Therefore further investigations of in situ hydraulic properties are required for a better understanding of the hydraulic behaviour of these sediments.

4.5 Hydraulic Head Profiles

Hydraulic head profiles for each 2015 hole were found to have very little to no change in head with depth showing minor hydraulic contrasts and little resistance to vertical flow throughout and a downward component of vertical gradient confirming the potential for recharge in all but one hole (MP-28U). Upward gradients were also observed by Casado (2012) within the pond transect (MP-11, MP-12, MP-13R, and MP-14).

On average, over the five periods that heads were measured, the total head difference across each of the profiles ranged from 0.10 m to 0.41 m within the 2015 holes (Table 4.2 and Figure 4.13). The minimal change in hydraulic head across each of the profiles may be explained by the similar grain size distribution of the diamict matrix and sand facies (see Figure B.11 and B.12 and Section 4.1) and the relatively flat topographic profile of the area, which makes it difficult to generate a large vertical head differential. This low hydraulic contrast and hydraulic similarity between sand and diamict is also evident from the low water table in the drumlin hole (MP-27U). The deep water table, which is not affected by the higher topography of the drumlin, indicates that the drumlin sediments have relatively high permeability. Due to the similarity of the unconsolidated sediments, and the timing of measurements with recent precipitation events, many vertical hydraulic gradients within the profiles are transient with time (sometimes resolvable; Freeze and Witherspoon 1967; Ostendorf et al. 2015).
Table 4.2: Average total change in head within each MLS system for the five periods heads were measured. Maximum length indicated the total length over which the change in head was measured, from the bottom of the deepest measurement zone to the top of shallowest measurement zone.

<table>
<thead>
<tr>
<th></th>
<th>Total head change (m)</th>
<th>Maximum length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP-23U</td>
<td>-0.11</td>
<td>16.95</td>
</tr>
<tr>
<td>MP-25U</td>
<td>-0.41</td>
<td>21.18</td>
</tr>
<tr>
<td>MP-27U</td>
<td>-0.10</td>
<td>17.95</td>
</tr>
<tr>
<td>MP-28U</td>
<td>0.20</td>
<td>17.68</td>
</tr>
<tr>
<td>MP-19U</td>
<td>-0.21</td>
<td>14.94</td>
</tr>
</tbody>
</table>

*negative head valued indicate downward vertical flow

In the 2015 holes, only 6 of the vertical gradients are always resolvable (Figure 4.13), with 16 being 'sometimes resolvable’, as measured in 5 measurement events over the one year period. The 'always resolvable' vertical gradients ranged in magnitude from 0.02 m/m to 0.22 m/m at the site over the measurement period, whereas the 'sometimes resolvable’ vertical gradients ranged from 0.01 m/m to 0.23 m/m.

Of the 6 'always resolvable’ gradients, 2 occur at top of rock (TOR) contacts, 3 occur between sand and diamict, and one occurs as a result of interbedded diamict (Figure 4.1). These three geologic features (TOR, sand-diamict contact, and interbedded diamict) are also responsible for 12 of the 16 ‘sometimes resolvable’ vertical gradients seen within the holes, implying that these geologic features are hydraulically significant. However, the presence of these geologic features does not guarantee the presence of a vertical gradient, except in the case of interbedded diamict. This may be due to the lateral discontinuity of some units and lateral heterogeneity within the sediments.

The TOR contact was found to produce a vertical gradient within 3 of the 5 holes. Where present, these vertical gradients are due to a contrast in $K_v$. This contrast may be a result of an erosional surface inhibiting vertical connectivity between pores, a lack of vertical fractures in the top of rock, or a change in geologic material. The underlying bedrock lithology is not a unique characteristic for determining the location of vertical gradients. For example, the TOR contact between diamict and the sandstone of the Tonti Member in MP-28U produced a gradient, but it did not produce one in MP-23U (Figure 4.13). The exact explanation for this inconsistency is unknown but may be related to the lateral variability of the Quaternary sediments, bedrock.
Figure 4.13: Geologic logs, hydraulic head profiles, and location of vertical gradients within Westbay® multilevel systems of the 2015 holes. Head profiles for each hole from August, September, and December 2015 and April and July 2016. Head profiles in April and July 2016 were not measured for MP-27U and July 2016 heads were not measured for MP-23U. Vertical hydraulic gradients shown are from August 2015. Resolvable gradients were measured in all measurement campaigns from 2015-2016, while 'sometimes resolvable' were measured only in one or two measurement campaigns during 2015-2016 and unresolvable gradients were never measured in any of the measurement campaigns. Note: that the head profile scale of MP-25U spans 2 m instead of 1 m due to the large change in head magnitude over the course of the year. Refer to Figure 4.1 for detailed stratigraphic log legend.
fracture network, variable degree or nature of weathering at the TOR contact or lateral facies changes within the same bedrock unit. In general, this inconsistency represents the lateral variability in hydraulic connectivity at the Quaternary sediment and bedrock contact, which is not predicted by bedrock lithostratigraphy.

Similar to the TOR contact, the contact between sand and diamict was not found to create vertical gradients in all locations. However, K estimates based on grain size distributions indicate that the location of vertical gradients are associated with a contrast in estimated K between the sand and diamict of 3 orders of magnitude or more. This implies that in the groundwater flow system a contrast in K greater than 3 orders of magnitude may be hydraulically significant, assuming the units are reasonably laterally extensive.

The influence of the interbedded diamict on vertical hydraulic properties may be a result of the differences in the primary sand grain size between adjacent diamict beds that then result in more closely packed particles and lower porosity at the interface (Thomson 2004). The similarity of the grain size distribution of diamict beds makes it unlikely that there are large contrasts in K creating the vertical gradients.

Only 4 vertical gradients are not associated with the 3 geologic features described above. Two of these gradients are associated with thin mud beds found within MP-23U (Figure 4.13) and the final two gradients are associated with interbedded sand in MP-25U and with gravelly sand beds in MP-28U (Figure 4.13).

Mud beds within MP-23U are expected to cause a vertical gradient due to their lower K and higher contrast in \( K_v \) between the mud and surrounding sediment. Although these mud beds are not continuous across the site, if they extend almost to the location of MP-25U they may be upwards of ~ 100 m in lateral extent. In contrast, other mud beds do not produce vertical gradients and are therefore hypothesized to be small mud lenses that are not extensive enough to affect the hydraulic system.

Similar to the 2015 hole profiles, hydraulic head profiles for the 2004 pond cores were found to have very little to no change in head with depth, indicating minor hydraulic contrast within the system (Figures 4.14 and 4.15). The average total head difference across each of the profiles ranged from 0.13 m to 0.39 m. In contrast to the 2015 holes, all pond holes except MP-10 and
MP-9 have upward gradients. In addition, 9 of the 25 vertical gradients within the pond holes were always resolvable. The location of these vertical gradients indicates that similar geologic features as those found in the 2015 cores are responsible for most of the hydraulic contrast at the pond transect.

Of the 9 'always resolvable' vertical gradients in the pond holes, 3 occur at TOR, 3 occur between sand and diamict, and 3 occur as a result of mud beds (Figures 4.13 and 4.14). These three geologic features are also responsible for 10 of the 16 'sometimes resolvable' gradients. It is unknown what geologic features are responsible for the 6 remaining 'sometimes resolvable' vertical gradients. These gradients may be a result of geologic features not captured in these lower resolution core logs; also making it impossible to identify locations of interbedded diamict and to further investigate their hydraulic significance.

Identification of these hydraulically significant geologic features emphasizes the importance of combining high-resolution geologic logs with high-resolution hydraulic head profiles; since, low-resolution data sets would be incapable of isolating a depth at which the vertical gradient occurred and identifying a geologic feature responsible for the hydraulic contrast. In addition, it is important to consider the 3-dimensional and complex nature of these systems since hydraulically significant features may not be captured by the cores or 2D geophysical surveys.

High-resolution hydraulic head profiles were very useful for understanding hydraulic behaviour below the water table but above the watertable there is limited hydraulic data. Hydraulic conductivity estimates from grain size analysis can provide some insight into the hydraulic properties of the unconsolidated sediments above the watertable (See Section 4.4). In addition, moisture content data analysis can be used to help fill in data gaps above the watertable by providing insight on the retention capacity and therefore pore size of the sediment (Hu-nan and Ling-wei 2010). Below the watertable, moisture content differences may represent differential compaction and packing.

Figure 4.14: Geologic logs, hydraulic head profiles, and location of vertical gradients within Waterloo™ multilevel systems of the pond holes. The interval from 254.15 masl to 248.06 masl in the core log of MP-13R is inferred using the laterally adjacent log of MP-13, as no core was recovered in MP-13R over that interval. Grain size is shown on x-axis of core log as clay (cl), silt (s), very fine sand (vf), fine sand (f), medium sand (m), coarse sand (c), very coarse sand (vc), granules (g), and pebbles (p)
Figure 4.15: Geologic log, hydraulic head profile, and location of vertical gradients within the modified Waterloo™ multilevel system of MP-10, glaciofluvial element (see Parker et al. (2006) and Swanson et al. (2005)). Grain size is shown on x-axis of core log as clay (cl), silt (s), very fine sand (vf), fine sand (f), medium sand (m), coarse sand (c), very coarse sand (vc), granules (g), and pebbles (p).
Above the watertable similar moisture content is seen within the sediment from the five 2015 holes and likely indicates similar retention capacities. Although there are similarities in the moisture content several trends can be observed (Figure 4.16): i) mud beds have higher moisture content indicating higher retention capacity, as expected; and ii) sand beds within the diamict of MP-27U show a slight decrease in moisture content indicating a slightly lower retention capacity. The slightly lower moisture content of the sand facies than the diamict facies show that there is a contrast between the two facies, likely due to the deviation of the grain size distribution within the fine sediment fraction (Figure B.12). However, the very slight decrease in moisture content between the sand and diamict within MP-27U and the similarity of the moisture content of sand and diamict in other holes suggests that these sediments have similar unsaturated hydraulic behaviour.

Below the watertable few trends are observed from the moisture content data. Sand and diamict facies cannot readily be distinguished with this data set, further indicating their similarity. An exception is within MP-19U, the moisture content samples from this core show a slight pattern of increasing and decreasing moisture content that corresponds with both facies changes between sand and diamict and locations where vertical gradients were measured. This may be explained by the very well sorted sand within this hole and the larger contrast in K seen between the diamict and sand beds (Figure 4.12). However, the exact reasoning for this pattern of moisture content is unknown and requires further investigations into grain size distribution, packing, and other sedimentary characteristics that affect the hydraulic properties.
Figure 4.16: Moisture content profiles from the five 2015 holes. Red boxes indicate locations of slightly lower moisture content as a result of sand beds above the watertable within MP-27U. Refer to Figure 4.15 for stratigraphic unit legend and grain size axis abbreviations. Inset map shows location of cores relative to industrial facility, man-made pond and nearby trail.
4.5.1 Hydraulic Head Profiles through Time

Comparison of hydraulic head profiles of individual holes measured in August, September, and December 2015 and April and July 2016 have very similar shapes but variable magnitudes. Hydraulic heads tend to increase from August 2015 to April 2016 in most holes.

Although head measurements tend to increase from August 2015 to April 2016, head profiles in MP-28U have similar magnitudes regardless of season. There are several plausible explanations for this behaviour; i) MP-28U is composed mainly of well sorted sand that may re-equilibrate faster to recharge events and translate recharge laterally; ii) MP-28U has less mud at surface to store/retard recharge and support higher heads for longer periods of time; iii) there is the potential for upward vertical gradients and groundwater discharge at MP-28U that would limit the effects of recharge on the system. The exact cause of the similar head profiles for MP-28U is difficult to determine due to the lack of understanding of the distribution of recharge within the site and the temporal connection between recharge and the response of the watertable.

4.6 Contaminant Profiles

Numerous depth-discrete sediment samples from 4 core locations (MP-23U, MP-25U, MP-27U, and MP-19U) were collected for VOC analyses and preliminary evaluation of these sample results indicate detectable concentrations at various depths in 3 of the 4 cores, with non-detects in MP-19U (Figure 4.17). MP-23U contains the highest total VOC (TVOC) concentrations at any specific depth with a maximum concentration of 63.99 ug/g of wet sediment. This is expected since MP-23U is located closest to where it is expected that the contaminants were released into the subsurface and concentration peaks are likely to decrease with distance from this source (Guilbeault et al. 2005). VOCs were also detectable in MP-25U, with a maximum of 4.03 ug/g wet sediment, and MP-27U, with a maximum of 2.81 ug/g wet sediment. Of the 35 chemical compounds analyzed, 21 were detected in the MP-23U profile, 13 in MP-25U, and 17 in MP-27U.

Figure 4.17: Total volatile organic compound (VOC) profiles represented as ug/g of wet sediment for MP-23U, MP-25U, and MP-27U. Grain size is shown on x-axis of core log as clay (cl), silt (s), very fine sand (vf), fine sand (f), medium sand (m), coarse sand (c), very coarse sand (vc), granules (g), and pebbles (p). Refer to figure 4.15 for stratigraphic unit (SU) legend.
The highest concentrations of individual compounds in one sample within each core were reviewed to find the top 5 constituents within the contaminant mass (Table 4.3). In general, similar to previous research on site by Swanson et al. (2005) and Casado (2012), most detectable VOC concentrations are confined to the lower sediment and tend to accumulate at the TOR contact (Figure 4.17). Swanson et al. (2005) and Casado (2012) also found that not only was there a horizontal component (from the source zone) to contaminant migration at the pond transect, but also a vertical component from bedrock through top of rock and into the unconsolidated sediment.

Table 4.3: Top 5 compounds within contaminant profiles of MP-23U, MP-25U, and MP-27U as seen in Figure 4.17. Concentrations represent maximum concentrations from one peak within the contaminant profile.

<table>
<thead>
<tr>
<th>Compound Name</th>
<th>Maximum Concentration (ug/g wet sediment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cis-1,2-dichloroethene</td>
<td>18.96</td>
</tr>
<tr>
<td>Trichloroethene</td>
<td>8.95</td>
</tr>
<tr>
<td>Toluene</td>
<td>7.71</td>
</tr>
<tr>
<td>1,1,1-trichloroethane</td>
<td>6.29</td>
</tr>
<tr>
<td>4-methyl-2-pentanone</td>
<td>4.04</td>
</tr>
<tr>
<td>Acetone</td>
<td>2.87</td>
</tr>
<tr>
<td>Toluene</td>
<td>1.81</td>
</tr>
<tr>
<td>m,p-xylenes</td>
<td>0.65</td>
</tr>
<tr>
<td>4-methyl-2-pentanone</td>
<td>0.40</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>0.40</td>
</tr>
<tr>
<td>Trans-1,2-dichlorothene</td>
<td>1.08</td>
</tr>
<tr>
<td>Toluene</td>
<td>1.06</td>
</tr>
<tr>
<td>Trichloroethene</td>
<td>1.01</td>
</tr>
<tr>
<td>Acetone</td>
<td>0.87</td>
</tr>
<tr>
<td>Dibromochloromethane</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Total VOC concentrations in MP-23U are confined to the bottom of the profile in SU1 and SU2 within the unconsolidated sediment (Figure 4.17). Although the concentration profile is heterogeneous, several concentration peaks are associated with two hydraulically significant geologic features identified in Section 4.6; TOR contact and mud beds. The accumulation of contaminants above these boundaries may be a result of the higher hydraulic contrast between
the sediment; indicated by the sometimes resolvable vertical gradients in Figure 4.13. Guilbeault et al. (2005) and Phillips et al. (2007) found similar concentration peaks associated with clay beds, which likely act as a barrier to downward migration of VOCs and facilitate pooling and horizontal or lateral migration along the adjacent higher K units. Similarly, previous research on site using groundwater contaminant data identified that higher VOC concentrations associated with a mud bed was likely the result of diffusion into the silt and clay matrix over long time periods (Swanson et al. 2005; Casado 2012).

Some concentration peaks are not associated with vertical gradients and the 4 hydraulically significant geologic features (Figure 4.13). For example, there is a concentration peak associated with a sand bed within SU2 at ~256.9 masl (MP-23U; Figures 4.3 and 4.17). The higher concentrations within this sand bed may be a result of preferential contaminant migration pathways through thin coarse sand laminations within this sand bed (Phillips et al. 2007), as evidenced by the physical observation of contaminants and coarse sand laminations in this layer during drilling (Figure 4.3).

Similar to MP-23U, total VOC concentrations in MP-25U are confined to SU1 and SU2 (Figure 4.8) and are associated with 2 hydraulically significant geologic features, identified in Section 4.6; TOR contact and sand-diamict contact (Figure 4.17). A third concentration peak occurs within the sand of SU2 and is not associated with a specific lithological control. Unlike MP-23U, the main concentration peak within SU2 in MP-25U (~251.3 masl) was not visually obvious within the core, though vertical staining at ~ 252.2 masl corresponds to the depth where total VOC concentrations start to increase in MP-25U. The lack of contaminant mass high in these profiles may suggest these locations are away from surface spills and migration has occurred laterally away from them, primarily along relatively more permeable beds or that contaminant migration was primarily vertical within the upper sediments with limited accumulation of contaminant mass.

Total VOC concentrations within MP-27U show 4 individual peaks with an elevation above MP-23U and MP-25U and a maximum concentration zone associated with TOR contact (Figure 4.17). The 4 peaks suspended higher in the profile are associated with geologic features such as sand, sand lenses, and coarser diamict. These coarser layers, likely with higher K than adjacent beds, may have preferentially transported higher concentrations of VOCs away from
the source zone by acting as pathways for lateral contaminant migration as observed by Phillips et al. (2007).

The elevated position of the MP-27U peaks, compared to MP-23U and MP-25U, are not clearly associated with the on-site source area, but currently there is no evidence that these peaks should be disregarded based on analytical and field quality assurance and quality control. The isolated nature of these peaks makes it difficult to determine if and how they are related to the rest of the contamination. It is important to note that the results presented here have been compared to but not validated against field blanks; however, these field blanks were generally clean.

The local variability of contaminant concentrations results in a spikey total VOC profile within all three holes that likely reflects an aged, spatially variable source zone (Guilbeault et al. 2005) enhanced by the heterogeneous character of the unconsolidated sediment deposit. It is likely that contaminant distribution is affected by more subtle changes within unconsolidated sediments compared to groundwater flow since many concentration peaks are not associated with vertical hydraulic gradients and hydraulically significant geologic features identified from head profiles. The importance of subsurface heterogeneity has been shown by Blasting and Hinchey (1993) and Guilbeault et al. (2005) and confirms the need for more detailed geologic and hydraulic investigations at DNAPL contaminated sites. Given the complex nature of the contaminant distribution and the influence of small geologic heterogeneities on peak concentrations, it is crucial that studies of contaminated sites complete high-resolution geologic and hydraulic investigations in order to understand contaminant distribution.

### 5.0 Revised Hydrogeologic Site Conceptual Model

Historically, the unconsolidated sediment of the Horicon Member was geologically and hydrogeologically differentiated into two units. More recently, subsurface mapping identified 6 geologic units, using lower quality geologic logs over a ~ 275 km² area that were typically limited to textural descriptions (Matrix Solutions Inc. 2014). These 6 geologic units were used as a proxy to define 6 hydrostratigraphic units (HSUs) that were defined as hydraulically similar sediment due to consistent lithologic and structural characteristics (Aquaresources 2013). Geologically, the surface HSU is described as variable diamict, wetland, or glaciolacustrine sediments whereas the underlying unconsolidated sediments are a simple pattern of repeating
glaciofluvial and diamict sediments defined as aquifers and aquitards, respectively, that may be discontinuous (Aquaresrouce 2013). This previous interpretation of the unconsolidated sediment has a similar number of glaciofluvial deposits (3), as defined in Section 4.3.1, but lacks the differentiation of the diamict sediments and identification of ice marginal facies associations present in SU1 and SU4. The subsurface mapping work conducted in 2013/14 also assumed diamict sediments will act as aquitard materials, whereas the current study has shown diamict and sand sediments to behave similarly in terms of hydraulics, likely not creating aquitard conditions. Although the current study is completed at the plume scale compared to the regional scale of the existing geologic model, it can be used to inform the larger scale model by providing insight into the glacial history and lateral heterogeneity of the unconsolidated sediment. This will allow for more accurate subdivision of the sediments based on the sequence of glacial events. A combination of existing data and the current data collected in 2015, can now be used to update the existing site conceptual model of the unconsolidated sediment.

Although the unconsolidated sediments show minimal hydraulic contrast, the location of most vertical hydraulic gradients tend to be associated with geologic features (top of rock (TOR) contact, sand-diamict contact, or interbedded diamict) and tend to occur at stratigraphic unit boundaries (Figure 5.1). Several of these boundaries seem to be both geologically and hydrologically laterally continuous across the site: the boundary of SU1 and TOR, SU1 and SU2, SU2 and SU3, and SU3 and SU4.

Stratigraphic unit 1 (SU1), primarily diamict with sand and mud interbeds, is found to be both geologically and hydraulically more heterogeneous than other diamict dominated stratigraphic units. Geologically, this unit can contain both mud and sand interbeds and hydrogeologically, it can contain vertical hydraulic gradients both at its upper (sand-diamict contact) and lower (TOR contact) bounding surfaces and within the stratigraphic unit across mud beds.

Stratigraphic unit 2 (SU2), primarily sand facies, is also found to be geologically and hydraulically heterogeneous. Although this unit is mostly sand, it has variable gravel and mud content and can contain interbeds of diamict. Vertical hydraulic gradients associated with SU2 can be found at its bounding surfaces and within. Vertical hydraulic gradients at the boundaries of SU2 are a result of sand-diamict contact and sometimes interbedded diamict at the upper boundary when overlain by SU3. However, SU3 can be locally eroded, especially within the glaciofluvial or glaciolacustrine physiographic elements. Where SU3 is eroded, SU2 is typically
Figure 5.1: Site conceptual model showing geological framework, current understanding of variable peak contaminant concentrations within the unconsolidated sediments, and vertical and horizontal components of groundwater flow in the unconsolidated sediments on site. 6x vertical exaggeration. Stratigraphic log offset from transect is shown as o (into the page) and x (out of the page). Although each stratigraphic unit has different sediment assemblages or facies associations, sand and diamict have similar grain size distributions and low K contrasts, resulting in relatively low hydraulic contrasts throughout. No stratigraphic unit on site should be considered an aquitard. Recharge occurs over the whole site except at the pond and north of the pond at MP-28U; the patchy distribution of the mud at surface will likely affect the distribution of recharge. Refer to Figure 2.1 for planar view of hole location. MP-28U geologic log is not shown due to the large offset from the transect.
overlain by the gravelly sand of SU4. The boundary between SU2 and the gravelly sand of SU4 does not typically produce a vertical hydraulic gradient, likely due to the similarities of the sand grain size distribution and layering (Figure 4.14).

Stratigraphic unit 3 (SU3) is less heterogeneous than SU1 and SU2 since it is composed of diamic beds with very similar grain size distributions, fewer interbeds of sand, and was not found to contain vertical hydraulic gradients within the unit. Vertical hydraulic gradients at the boundaries of SU3 are typically a result of interbedded diamic or sand-diamic contact. Stratigraphic units four to eight cannot be hydraulically defined since they are either partially or entirely above the watertable.

Stratigraphic units SU2 and SU3 are relatively laterally continuous at the site and are therefore expected to be found off site, except where locally eroded. SU1 is also laterally continuous across the site and may be found off site; however, its interpretation as an ice marginal facies association indicates that it may be laterally associated with other ice marginal deposits such as in SU4, including mud that may provide more significant hydraulic gradients than is currently observed in most of the profiles presented here. If SU1, SU2, and SU3 are laterally continuous off site, future studies may expect vertical hydraulic gradients at the boundaries of the three units as well as associated with any internal mud beds within SU1.

Most of the persistent (‘always resolvable’) vertical hydraulic gradients seem to be concentrated at depth in the sediment. The largest most consistent gradients seem to be associated with TOR and SU1 as well as SU1 and SU2. These larger more consistent vertical gradients are likely a result of larger hydraulic contrast in vertical hydraulic conductivity ($K_v$) between the sediments.

The existing hydrostratigraphic framework for the site defined 6 hydrostratigraphic units that are categorized as either aquifers or aquitards (Matrix Solutions Inc. 2014). However, based on stratigraphic logs, a lack of major inflections within the head profiles, and the limited lateral extent of lower K units, no aquitards are defined within the study site. In addition, defining aquitards and aquifers at this site based on texture and a layer-cake framework is difficult since a) there are lateral facies changes across the site; b) there are interbeds of sand within diamic that may act as preferential flow paths if connected (Meriano and Eyles 2009); and c) the grain
size distributions of diamict and sand are similar, thus making diamict units behave much more like sandy aquifers than aquitards as is typically assumed.

Defining hydrogeologic units (HGUs) based on lithological units with contrasting hydraulic properties is difficult in glacial settings due to the lateral variability and complex geometry of the deposits. At this site, the similarity between the grain size distributions of sand and sandy diamict sediments makes it even more difficult to identify HGUs since hydraulically these sediments seem to behave similarly and it is unclear if the contrasts in hydraulic properties identified are enough to justify defining separate HGUs. No HGUs have yet been identified on site; additional data off site should be collected to test the lateral continuity of SU1, SU2, and SU3 and the hydraulic significance of their bounding surfaces prior to defining HGUs.

The higher VOC concentrations at depth, mostly within SU1 and SU2, likely reflect the larger more consistent vertical hydraulic gradients found at depth within the sediment and at the top of rock contact. These larger gradients likely cause more vertical resistance to groundwater flow and contaminant migration possibly allowing contaminants to accumulate at these locations. Given the isotropic nature of subsurface materials the resistance to vertical flow likely allows lateral migration of the contaminants within the system. Contaminant distribution on site was also shown to be affected by subtle geologic features, such as coarse sand or diamict beds, that are not related to vertical hydraulic gradients. Therefore, vertical hydraulic gradients and subtle geologic features both affect contaminant distribution on site. Additional studies should look at the relative importance of other factors expected to affect contaminant distribution including both vertical and horizontal hydraulic conductivities and the physical, chemical, and microbial properties of the unconsolidated sediment.

6.0 Discussion

This thesis aimed to better understand the relationship between the geology and hydrogeology of the unconsolidated sediments in an ice marginal environment and how a detailed geologic investigation, on a centimeter scale, integrated with other high-resolution data sets might be used to inform the hydrogeology of the site as relevant to plume scale investigations. This was achieved through the collection and integration of multiple independent and high-resolution data sets including; 1-dimensional sedimentological core logs, grain size analysis, in situ hydraulic head profiles, and sediment VOC concentrations as well as 2-dimensional surface geophysical...
surveys used to extend from the 1-dimensional profiles into 2-dimensional interpretations and site conceptual model. This study demonstrates i) the value of the facies approach, ii) importance of integrating data sets, and iii) the usefulness of the hydraulic head profile approach and the challenges with delineating hydrogeologic units (HGUs) in an ice marginal environment.

6.1 Value of Facies Analysis

Historically groundwater studies have used limited geologic data to guide hydrogeologic investigations. However, many studies have emphasized the importance of using the facies analysis approach in groundwater investigations for a more complete understanding of the heterogeneity and geometries of the unconsolidated sediment (Anderson 1989; Klingbeil et al. 1999; Heinz and Aigner 2003; Atkinson et al. 2014). Many hydrogeologic investigations of unconsolidated sediment that use facies analysis have focused on one depositional environment (e.g. glaciofluvial, glaciolacustrine, subglacial); in contrast, this study demonstrates the importance and value of using facies analysis for hydrogeologic investigations in ice marginal settings where multiple depositional environments are encountered. Similar to this study, Atkinson et al. (2014) investigated the hydrogeology of an ice marginal environment on a kilometer-scale and found that many ice marginal deposits may be laterally extensive at this scale, but internally heterogeneous on a smaller scale. This study made use of facies analysis, on a smaller scale (~700 m) relevant for plume scale studies and highlights the nature of the heterogeneity at this smaller scale.

In this study, the facies analysis method, which includes high resolution (cm scale) sedimentological logging of cores, was particularly critical for developing a comprehensive site conceptual geologic framework from one-dimensional geologic logs. By identifying depositional environments and developing a stratigraphic framework, facies analysis allows us to better understand the subsurface heterogeneity and predict what sediments may exist onsite and at offsite locations with minimal or no geologic data. For example, the sediments deposited in a more laterally extensive environment, such as the interglacial glaciofluvial deposits (SU2) and subglacial deposits (SU3), are more likely to be found offsite, whereas sediments deposited at the ice margin (SU4) are expected to be laterally variable and more difficult to predict offsite.
The facies analysis approach also revealed two distinct sedimentation styles between the till plain element and the glaciofluvial and glaciolacustrine elements. Identification of these sedimentation styles will allow improved characterization of the ice marginal environment through the use of surficial physiographic elements to guide geologic interpretations where geologic data is unavailable. However, it should be noted that the exact stratigraphic sequence preserved in these settings is likely to vary depending on the magnitude and duration of erosional events at various sites. This may be more variable underneath the glaciofluvial element, though this requires further testing with additional cores to get a better sense of the full range of variability. No distinct sedimentation style was identified between the glaciofluvial and glaciolacustrine elements, which may be explained by several possibilities: 1) the two elements may have a similar subsurface stratigraphic sequence as they are associated with the ice retreat phase; or 2) the current study may not have had adequate detail for the glaciolacustrine physiographic elements to define a specific subsurface sedimentation style as only one hole was located in this element. To confirm the sedimentation style of the glaciolacustrine element additional cores should be drilled into this physiographic element for facies analysis.

6.2 Importance of Integrated Data Sets

Integration of multiple data sets is important for providing a comprehensive understanding the groundwater flow system. Geologic data and facies analysis are critical components in these investigations but should not be used alone to understand the hydraulic behaviour of the glacial system. Many studies have shown the importance of integrating data sets such as surface and downhole geophysics, hydraulic conductivity estimates, piezometer or multilevel well installations, in situ hydraulic tests such as hydraulic head measurements or pumping tests, and groundwater sampling with geologic data for an improved understanding (Klingbeil et al. 1999; Gerber et al. 2001; Heinz and Aigner 2003; Guilbeault et al. 2005; Parker et al. 2006; Phillips et al. 2007; Atkinson et al. 2014; Best et al. 2015).

This study also emphasizes the need for integrating multiple data sets but uses a combination and number of data sets not seen in other studies. This combination of data sets was particularly useful for plume scale studies and predicting sediment geometries with more evidence. Specifically, many hydrogeologic investigations do not incorporate the high-resolution geologic data set for facies analysis that was obtained in this study. In addition, surface geophysics was integrated in this study for improved understanding of the lateral distribution...
and geometry of the sediment; this is not always utilized in other studies (Guilbeault et al. 2005; Parker et al. 2006; Phillips et al. 2006; Best et al. 2015). Finally, *in situ* hydraulic data has been recognized as very important in groundwater studies but tend to be lacking (Heinz and Aigner 2003). Multilevel systems (MLS) provided high-resolution depth-discrete in situ hydraulic data to hydraulically calibrate the geologic data instead of relying on lithologic units to define hydrogeologic units (Figure 2.5). Compared to many previous studies that only utilize low-resolution piezometers (Figure 2.6; Fortin et al. 1991; Gerber et al. 2001; Phillips et al. 2007; Cuthbert et al. 2010), the high-resolution MLSs used here helped to identify specific geologic features responsible for hydraulic contrasts in the system. By calibrating geologic data with in situ hydraulic data, hydraulic interpretations of the unconsolidated sediment were not blindly based on lithologic units. Had the standard method (Figure 2.5) of using lithologic units as a proxy for hydrogeologic units been used then the hydraulic understanding of the site would have erroneously assumed there were at least 6 contrasting hydrogeologic units at the site, where in reality there is minimal hydraulic contrast within the system.

In this study, the integration of high-resolution (cm scale) facies analysis of geologic logs with depth-discrete hydraulic head profiles revealed specific small-scale geologic features that are responsible for most vertical hydraulic gradients and are therefore important in the groundwater flow system (Section 4.5). The identification of these hydraulically significant geologic features may be used to inform the hydraulic behaviour of the unconsolidated sediments in locations without adequate hydraulic data to help better understand the system. In addition, these geologic features can be used in the future to guide MLS design at the site for more targeted and hydraulically informed depth-discrete monitoring zone locations.

With only 4 geologic features recognized as hydraulically significant in a highly heterogeneous geologic system, it is believed that the hydrogeologic system at this site is less heterogeneous than the geologic system. This may be a result of the similarity of the grain size distributions of the diamict and sand facies. The diamict sediments within the study site are very sandy and show limited or no hydraulic contrast at the contact with sand units. In comparison, a more clay rich diamict (clayey till) was shown by Phillips et al. (2007) to be hydraulically different compared to the sand lenses at their study site, with a 3 m drop in head at the boundary of these units, whereas in this study the maximum drop in head across a sand-diamict contact was 12 cm and a maximum of ~40 cm over the whole profile.
The integration of geologic and hydraulic data sets with VOC data revealed that other geologic features, beyond those recognized from the hydraulic head profiles, are important for contaminant migration (Thomson 2004). The identification of additional significant geologic heterogeneities may indicate that the hydraulic head profiles are not sensitive enough to capture all hydraulic contrasts within the unconsolidated sediments or that contaminant migration is more susceptible to subtle geologic heterogeneities that may not affect groundwater flow. Regardless, these results confirm the need for centimeter scale geologic resolution and the integration of geophysical, hydraulic, and geochemical investigations for plume scale studies.

6.3 Usefulness of Hydraulic Head Profile Approach for Delineating Hydrogeologic Units

The 4 hydraulically significant geologic features were recognized using the method described by Meyer et al. 2016, by integrating high-resolution geologic logs with depth-discrete high-resolution hydraulic head profiles. This method is proven here to be useful for ice marginal environments to identify possible locations of hydraulic contrast and the hydraulic behaviour of the sediments. However, an outcome of using that method is to delineate HGU boundaries (Meyer et al. 2016). Meyer et al. (2016) were able to define HGU boundaries as many of the hydraulic contrasts occurred at lithological boundaries that corresponded to the regional sequence stratigraphic framework. In contrast to the relatively undeformed, subhorizontal, and laterally extensive fractured sedimentary bedrock units of Southern Wisconsin (Meyer et al. 2016), the overlying unconsolidated sediments of the current study have more lateral variability and complex geometries. This is a result of their geologic origin; the fracture sedimentary bedrock units within Southern Wisconsin were deposited as part of a broad shallow shelf of an inland sea that deposited laterally extensive units across not only Southern Wisconsin but also parts of many surrounding States (Runkel et al. 2007), whereas the unconsolidated sediments were deposited near the ice margin of the Green Bay Lobe with multiple depositional environments and consequently rapid lateral facies changes. In addition, lithological bounding surfaces in the marine environment of the fractured sedimentary rock result from relative sea level changes that have predictable basin wide effects and that can be mapped out using sequence stratigraphy (Runkel et al. 2007; Meyer et al. 2016). In contrast, bounding surfaces in glacial depositional environments are a function of relatively more localized erosional and depositional processes (Slomka and Eyles 2015). As such, the heterogeneity of this ice marginal environment hampers the definition of HGUs using the Meyer et al 2016 approach.
The lateral complexity of the unconsolidated sediments and their bounding surfaces may explain why ‘always resolvable’ gradients occurred less frequently than ‘sometimes resolvable’ gradients within the unconsolidated sediments than within the lower fractured sedimentary bedrock.

The transient nature of many of the vertical hydraulic gradients (‘sometimes resolvable’) within the unconsolidated sediments makes it more difficult to confidently delineate HGUs and identify where their boundaries likely exist. This difficulty may be due to the low total vertical head differential of the unconsolidated sediment at the site, a lack of vertical hydraulic conductivity contrast, as well as the lateral variability of the sediments. As described by Meyer et al. 2016, the total vertical head differential and the number and length of monitoring intervals will affect the resolution of the hydraulic head profile. Therefore, a smaller total vertical head differentiation, as seen in this study, results in less well defined profiles and makes it more difficult to differentiate small differences in head and delineate HGUs. Furthermore, the ‘sometimes resolvable’ gradients likely indicate low contrast in the vertical hydraulic conductivity of the sediments, which is likely due to the similarity of the grain size distributions of sand and diamict. In sum, the Meyer et al. 2016 method is useful in this ice marginal setting, though the lack of contrast between diamict and sand and the lateral variability and complex geometry make it more challenging to define HGUs in this dynamic environment.

7.0 Conclusions

7.1 Summary of Key Findings

Integration of multiple high-resolution and independent data sets, combined from 11 locations, helped to improve our understanding of the relationship between the geology and hydrogeology of unconsolidated sediments in an ice marginal environment as relevant to plume scale investigations. This was accomplished using integrated and high-resolution 1-dimensional and 2-dimensional data sets including: stratigraphic logs from continuous cores; surface geophysical electrical resistivity surveys; lithology and facies-specific grain size distributions; high spatial resolution hydraulic head and vertical gradient profiles; and depth-discrete VOC contaminant concentration profiles. In addition, this study helped to refine our understanding of the spatial distribution and hydraulic properties of unconsolidated Quaternary sediment within the site.
conceptual model of the contaminated site in South Central Wisconsin. The 5 new core locations were selected based on reasonably well informed Pleistocene geology maps and existing data from conventional contaminated site investigations (1985 to present) and were intended to represent the range of sediments that underlie the surface physiographic elements common to the study site and nearby glaciated region.

From the stratigraphic logs and electrical resistivity surveys, a geologic framework was developed using facies analysis and analysis of these one and two-dimensional data sets. The geologic framework identifies 8 stratigraphic units deposited as subglacial till, interglacial glaciofluvial sediment, and ice marginal sediment (debris flow, glaciofluvial, and glaciolacustrine) associated with four main glacial advances of the Green Bay Lobe. Sediment within these deposits were dominated by crudely bedded sandy and intermediate diamict and sand. Diamict and sand sediments were found to have similar grain size distributions and are difficult to distinguish in core and with geophysics. The subtle grain size variability was not only found within facies associations but also between facies associations representing different depositional environments.

Surface geophysics were able to constrain the 2-dimensional lateral distribution of the unconsolidated sediments and identify geologic features missed by 1-dimensional core logs. The integration of these data sets identified the lower sediments (SU1, SU2, and SU3) to be relatively continuous across the site, with localized erosion as determined from MP-9, MP-13R, and MP-12. In addition, surface geophysics identified the surficial glaciolacustrine deposits to be discontinuous on site and have established the presence of north-south trending glaciofluvial channels within the glaciofluvial physiographic element. Although surface mapped physiographic elements (ie. till plain, glaciofluvial, or glaciolacustrine) cannot be adequately relied on for subsurface interpretations, the glaciofluvial and glaciolacustrine elements, in this study site, were found to have a subsurface stratigraphy that is distinct from the till plain sediments. The glaciofluvial and glaciolacustrine ice marginal physiographic elements were found to have fewer diamict units and more sand units whereas the till plain element is dominated by diamict units. Identification of specific sedimentation style for these physiographic element will help guide geologic interpretations offsite where geologic data is limited or unavailable.
Hydraulic properties of the sediment were investigated and hydraulic conductivities ranged from $10^{-8}$ to $10^{-3}$ m/s with sand having a geometric mean of $2.3 \times 10^{-4}$ m/s and diamict having a geometric mean of $1.9 \times 10^{-7}$ m/s. Although hydraulic conductivity ($K$) estimates showed variability between the diamict and sand, there were minor hydraulic contrasts within the unconsolidated sediment system as shown by nearly constant head with depth (small total head loss over unconsolidated sediments), indicating the sand and diamict sediments behave similarly in terms of hydraulics. Most vertical hydraulic gradients are small and are likely a result of the low hydraulic contrast between sediment that is possibly due to the similar grain size distributions between sand and diamict. In addition, most of the observed vertical hydraulic gradients are only sometimes apparent due to timing of recharge events and measurements. However, where vertical gradients are found, 4 hydraulically significant geologic feature are observed to be primarily responsible: top of rock contact; sand-diamict contact (where the two lithologies have hydraulic conductivities that are 3 orders of magnitude different or more); interbedded diamict; and mud beds. However, only the interbedded diamict feature consistently creates a vertical gradient whenever it is observed. Identification of these 4 hydraulically significant geologic features is important since they can be used to inform the hydraulic properties of the sediment where hydraulic information is absent. In addition, these features can be used to improve MLS design at the site for more targeted and informed monitoring zones.

Investigations of the contaminant distribution on site show most total VOC concentrations to be confined to stratigraphic units 1 and 2 and at the bedrock contact. Concentrations seem to decrease with distance from the source zone except for at the pond where contaminants migrate through the bedrock and up into the unconsolidated sediment. Concentration peaks seems to be associated primarily with the locations of vertical hydraulic gradients, such as due to top of rock or mud beds, but are also found associated with sand layers showing no vertical gradient. Therefore, VOC concentrations are shown to be affected by both hydraulically significant geologic features and subtle changes in sedimentary characteristics. The influence of subtle geologic heterogeneities on contaminant distribution emphasizes the need for centimeter scale geologic investigations for plume scale studies.

Quaternary geologic core logs and hydraulic head profiles from 2004 agree with conclusions made in the current study (2015-2016). Combining these two data sets allows for an increased understanding of the unconsolidated sediment on site and have helped improve the site conceptual model by providing additional geologic and hydrogeologic data for the
unconsolidated sediments. This model shows that most vertical hydraulic gradients occur at the boundaries of the stratigraphic units: specifically SU1, SU2, and SU3. Hydraulically, stratigraphic units can be internally homogeneous or can contain heterogeneities where vertical hydraulic gradients occur within the unit. The lateral continuity of SU1, SU2, and SU3 needs to be confirmed with further investigations, and if found to be laterally extensive these units may be use offsite and in future studies to identify possible locations of vertical hydraulic gradients at their boundaries and as a result of mud beds in SU1, without direct hydraulic data.

Although vertical hydraulic gradients are present within the unconsolidated sediments, there is minimal vertical hydraulic contrast within the system. None of the identified stratigraphic units can be defined as aquitards given the moderate range of K values for the diamict units as a result of their high sand content and no units have the characteristic inflection within the hydraulic head profile that identifies low K zones.

The Meyer et al. 2016 hydraulic head profile approach was critical for understanding the hydraulic behaviour of the unconsolidated sediments and identifying the 4 hydraulically significant geologic features. However, the low total head differential of a system with subtle hydraulic contrasts, due to texturally similar sand and diamict units, makes it difficult to utilize the full potential of the Meyer et al. 2016 approach for delineating hydrogeologic units within an ice marginal environment. Therefore, the Meyer et al. 2016 approach may be more suited to defining HGUs in environments with more sedimentologically distinct and laterally continuous sediments.

At a plume scale, it is critical that subsurface investigations for groundwater studies incorporate four primary high-resolution data sets, geologic logs for facies analysis, surface geophysics, in situ hydrogeologic data, and geochemical data. The integration of these one and two-dimensional data sets can provide a well informed and constrained site conceptual model of both the subsurface geologic and hydrogeologic systems, which can be used offsite to inform locations with limited or absent data. For hydrogeologic investigations it is particularly important to hydraulically calibrate the geologic data with in situ hydraulic data, as geologic heterogeneity does not directly transfer to hydrogeologic heterogeneity. In addition, for contaminant investigations centimeter scale resolution is critical as smaller scale geologic heterogeneities, that do not influence groundwater flow, are likely important for contaminant transport. These
methods will aid in the characterization of complex Quaternary ice marginal sediments and can be adapted for other sites in similarly complex ice marginal settings.

7.2 Future Work

Given the highly heterogeneous nature of ice marginal environments, further research at this site and in the surrounding region is needed to help further constrain groundwater flow models. More high-resolution core logs are required to improve our understanding of the heterogeneity within each physiographic element as well as to provide ground truthing of the surface geophysical surveys. Specifically additional holes within the till plain element to further investigate the lateral continuity of the stratigraphic units, within the glaciolacustrine element to identify a sedimentation style, and within the glaciofluvial element to target SU7 (which was only identified by geophysics) will further improve the geologic model. Given rotosonic drilling techniques may disturb subtle geologic structures, a method comparison between mud rotary and rotosonic, would be useful to investigate data limitations due to core disturbance and to obtain further information to delineate stratigraphic units at a larger scale. The Meyer et al. 2016 method provided important in situ vertical hydraulic data; however, our understanding of the horizontal hydraulic behaviour of the sediments is still limited. The horizontal hydraulic information is particularly important as the total vertical head differential at the site is minimal and may indicate primarily horizontal flow. Therefore, additional in situ hydraulic tests, such as slug tests, are required to gather a better understanding of the horizontal hydraulic properties of the unconsolidated sediments and to determine if the sand and diamict units also behave similarly in this direction. These in situ tests can be compared to hydraulic conductivity estimates from grain size and falling head permeameter analysis to investigate their range and accuracy. Infiltration tests at surface would also provide useful hydraulic information for informing local recharge into the unconsolidated sediments considering the less extensive glaciolacustrine sediments at surface.

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Appendix A: Methods

A.1 Drilling details and Samples

Once cores were recovered (Table A.1) volatile organic compound, moisture content, grain size, and falling head permeameter samples were collected from each core (Table A.2). High-resolution sampling was completed along the entire length of each core in order to capture small changes in unconsolidated sediment properties (Figures A.1 to A.3).

Table A.1: Drilling completion details

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Ground Surface Elevation (masl)</th>
<th>Depth Drilled (mbgs)</th>
<th>Top of Rock (mbgs)</th>
<th>Surficial Unit</th>
<th>Bedrock Unit</th>
<th>Estimated Watertable depth (mbgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP-19U</td>
<td>263.72</td>
<td>16.46</td>
<td>13.96</td>
<td>Glaciofluvial</td>
<td>Prairie du Chien Grp.</td>
<td>0.82</td>
</tr>
<tr>
<td>MP-23U</td>
<td>269.96</td>
<td>22.25</td>
<td>18.93</td>
<td>Till Plain</td>
<td>Tonti Mbr.</td>
<td>5.49</td>
</tr>
<tr>
<td>MP-25U</td>
<td>273.38</td>
<td>28.65</td>
<td>26.7</td>
<td>Till Plain</td>
<td>Readstown Mbr.</td>
<td>8.56</td>
</tr>
<tr>
<td>MP-27U</td>
<td>290.89</td>
<td>45.42</td>
<td>42.67</td>
<td>Till Plain (Drumlin)</td>
<td>Readstown Mbr.</td>
<td>27.43</td>
</tr>
<tr>
<td>MP-28U</td>
<td>266.1</td>
<td>19.81</td>
<td>14.26</td>
<td>Glaciolacustrine</td>
<td>Tonti Mbr.</td>
<td>1.83</td>
</tr>
</tbody>
</table>

Grp. – Group, mbgs – meters below ground surface, Mbr. – Member, masl-meters above sea level

Table A.2: Total number of samples collected from each core, the total number of samples analyzed and the sampling frequency, represented as number of samples per meter.

<table>
<thead>
<tr>
<th>Station ID</th>
<th>VOC Samples</th>
<th>Moisture Content</th>
<th>Grain Size Samples</th>
<th>Falling Head Permeameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total #</td>
<td>Sample frequency</td>
<td>Total #</td>
<td>Sample frequency</td>
</tr>
<tr>
<td>MP-19U</td>
<td>57</td>
<td>3.46</td>
<td>57</td>
<td>3.46</td>
</tr>
<tr>
<td>MP-23U</td>
<td>102</td>
<td>4.58</td>
<td>102</td>
<td>4.58</td>
</tr>
<tr>
<td>MP-25U</td>
<td>108</td>
<td>3.77</td>
<td>108</td>
<td>3.77</td>
</tr>
<tr>
<td>MP-27U</td>
<td>170</td>
<td>3.74</td>
<td>170</td>
<td>3.74</td>
</tr>
<tr>
<td>MP-28U</td>
<td>0</td>
<td>0</td>
<td>24</td>
<td>1.21</td>
</tr>
</tbody>
</table>
Figure A.1: Stratigraphic log legend for figures A.2 and A.3. Grp. – Group. Mbr. - Member
Figure A.2: Sample locations for Mp19U, MP-23U, MP-25U, and MP-28U. See Figure A.3 for MP-27U. Moisture content sample locations correspond to VOC sample locations except in MP-28U where only moisture content samples were collected. Refer to Figure A.1 for stratigraphic log legend.
Figure A.3: Sample locations for MP-27U. Refer to Figure A.1 for stratigraphic log legend.
A.2 Westbay® Multilevel System Design

Monitoring zones and seal locations were carefully selected to minimize blending of potential hydrogeologic units, within the constraints of the system. The monitoring zone rationale can be found in Figure A.5 to A.9. All unmonitored areas were sealed with bentonite. After designing each MLS, a completion report containing the as built MLS design was created (Table A.3; Figure A.10 to Figure A.15) and each Westbay® component was carefully laid out and checked by several personal for quality control. During installation, the zero reference was checked frequently during backfilling and end shifts of each system were noted (Table A.4).

Table A.3 - Number of monitoring zones and pumping ports in each MLS.

<table>
<thead>
<tr>
<th>Location</th>
<th># of Monitoring zones</th>
<th># of zones with pumping ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP-19U</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>MP-23U</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>MP-25U</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>MP-27U</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>MP-28U</td>
<td>8</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure A.4: Legend for MLS design figures (Figures A.5 to A.9; figures drafted by Jessica Meyer).
Figure A.5: MP-19U data sets and MLS design rationale. Refer to Figure A.4 for legend. Figure drafted by Jessica Meyer.
Figure A.6: MP-23U data sets and MLS design rationale. Refer to Figure A.4 for legend. Figure drafted by Jessica Meyer.
Figure A.7: MP-25U data sets and MLS design rationale. Refer to Figure A.4 for legend. Figure drafted by Jessica Meyer.
Figure A.8: MP-27U data sets and MLS design rationale. Refer to Figure A.4 for legend. Figure drafted by Jessica Meyer.
Figure A.9: MP-28U data sets and MLS design rationale. Refer to Figure A.4 for legend. Figure drafted by Jessica Meyer.
Figure A.10 - Legend for Westbay® Multilevel systems as built diagrams; Figures A.11 to A.15 (Meyer 2015).
Figure A.11 – Westbay® Multilevel system as built report for MP-19U. For legend please refer to Figure A.10. Depths in ft from ground surface (Meyer 2015).
Figure A.12 – Westbay® Multilevel system as built report for MP-23U. For legend please refer to Figure A.10. Depths in ft from ground surface (Meyer 2015).
Figure A.13 – Westbay® Multilevel system as built report for MP-25U. For legend please refer to Figure A.10. Depths in ft from ground surface (Meyer 2015).
Figure A.14 – Westbay® Multilevel system as built report for MP-27U. For legend please refer to Figure A.10. Depths in ft from ground surface (Meyer 2015).
Figure A.15 – Westbay® Multilevel system as built report for MP-28U. For legend please refer to Figure A.10. Depths in ft from ground surface (Meyer 2015).
A.3 Grain Size Distribution Analysis


1. Air-dry samples in a fumehood to volatilize VOCs.
2. Crush samples with mortar and pestle using up and down motion
3. Remove visible gravel
4. Pre-weigh trays (one per sample)
5. Riffle sample for ~100 g. Slightly less sample (between 80-100 g) was selected for samples suspected to have large amounts of silt and or clay while slightly more sample (between 120-150 g) was selected for samples with lots of gravels.
6. Dry sample at 104°C overnight in pre-weighed tray
7. Soak overnight in 100 ml of 50g/L sodium hexametaphosphate – Calgon
8. In electric mixer add sample and 250 ml DI water (3/4 full) and mix for 5 min on low
9. Wash content of mixer through 45 µm sieve (No. 325) into a 1000 ml cylinder using a funnel.
10. Wash sieve with DI until water running out is clear. To aid in process manually shake sieve, be careful not to lose sediment during shaking.
11. Rinse mixer and funnel and add water to cylinder. Be sure to leave some space to later add sediments less than 63 µm from the dry-sieving process.

**NOTE:** If sample is particularly muddy and requires more than 1000 ml of DI water to washout mud then use a second 1000 ml cylinder with 100 ml of 50 g/L sodium hexametaphosphate.

12. Rinse sand from sieve into pre-weighed large tray
13. Determine grain size distribution of sand fraction using sieves and shaker
   a. Dry over night at 104°C and weigh again.
   b. Clean and check sieves for tears using microscope. Clean sieves from bottom side.
   c. Weigh each empty sieve
   d. Add sample to sieve stack (Table A.4) and shake for 10 min
   e. Weigh each sieve with sand fraction obtained. Redo if >2% discrepancy between total sand mass before and after shaking.
   f. Weigh gravels to remove from total mass
   g. Weigh then add any additional silt/clay (less than 63 µm) to 1000 ml cylinder
h. Calculate sand fraction

\[
\% \text{ sand} = 100 \times \frac{\text{mass sieve with sand} - \text{mass clean sieve}}{\text{total dry sample mass} - \text{gravel mass}}
\]

14. Determine mud fraction via hydrometer

a. Top up water in cylinder to 1000 ml with DI water

b. Set up blank cylinder
   i. 100 ml of 50 g/L sodium metaphosphate and 900 ml of DI water
   ii. Mix well with plunger and allow temperature to equilibrate with room temperature then take reading (Rₗ)

c. Allow sample and water to equilibrate to room temperature, ~5min.

d. Mix sediment sample with plunger using an up and down and twist motion. To dislodge sediments use a strong upward stroke near bottom of cylinder and/or spinning the plunger just above the sediment. At the end finish with two-three smooth slow strokes.

e. Record time when plunger is removed

f. Take a reading after 40 seconds. Repeat 3 times and take the average of these values (R₄₀). Record time of third 40s reading for calculation of the 7-hour reading.

g. Take a reading after 7 hours to 0.1 g/L (R₇)

h. Take a measurement from the blank cylinder at the same time
   i. Calculate clay and silt content

\[
\% \text{ clay} = 100 \times \frac{R₇ - Rₗ}{\text{total dry sample mass} - \text{gravel mass}}
\]

\[
\text{Mud} = \text{silt} + \text{clay mass}
\]

\[
\text{Mud} = \frac{\text{total dry sample mass} - \text{gravel mass} - \text{sand mass}}{\text{mud mass from sieves}}
\]

\[
\% \text{ Silt} = 100 \times \frac{\text{mud mass} - (R₇ - Rₗ)}{\text{total dry sample mass} - \text{gravel mass}}
\]

**NOTE:** if sample was split into two cylinders need to add results from both cylinders for final silt and clay content analysis.
Table A.4 - grain size divisions for the coarse sieve stack and fine sieve stack used for grain size analysis

<table>
<thead>
<tr>
<th>Sieve Number</th>
<th>Sieve Diameter (mm)</th>
<th>Sieve Diameter (Phi)</th>
<th>Wentworth Size Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.75</td>
<td>-2.0</td>
<td>Larger than granules</td>
</tr>
<tr>
<td>7</td>
<td>2.80</td>
<td>-1.5</td>
<td>Granules +</td>
</tr>
<tr>
<td>10</td>
<td>2.00</td>
<td>-1.0</td>
<td>Granules</td>
</tr>
<tr>
<td>14</td>
<td>1.40</td>
<td>-0.5</td>
<td>Very coarse sand</td>
</tr>
<tr>
<td>18</td>
<td>1.00</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.710</td>
<td>0.5</td>
<td>Coarse sand</td>
</tr>
<tr>
<td>35</td>
<td>0.500</td>
<td>1.0</td>
<td>Medium sand</td>
</tr>
<tr>
<td>45</td>
<td>0.355</td>
<td>1.5</td>
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A.3.1 Grain Size Error Analysis

Nine field and five laboratory duplicates were analyzed to investigate the error associated with sampling bias and sediment loss during laboratory analysis. Error was calculated as percentage of total sample mass.

For field duplicates the similarity in weight of the different grain size fractions of the two separate samples was of concern. Therefore, the error between each grain size fraction was calculated using equation A.1.

\[
Error = (\%GrainSize_{n})_{Sample\ 1} - (\%GrainSize_{n})_{Sample\ 2} \quad \text{Eq. A.1}
\]
where, n is the grain size fraction from clay to very coarse sand.

For laboratory duplicates the loss of fine sediment was the primary concern during laboratory analysis error. Therefore, the error between the total sand and mud content of the sample, by weight, was calculated using equation A.2.

\[
Error = \left(\%Sand_{Lab\,dup1}\right) - \left(\%Sand_{Lab\,dup2}\right) \quad \text{Eq. A.2}
\]

A.4 Falling Head Permeameter

Falling head permeameter methods adapted from Sudicky 1986 and Gilmore 2010

1. Select samples with less than 12% mud
2. Crush sample as per grain size distribution methods (Appendix A.3)
3. Use riffle box to obtain 50 g of sample and place in pre-weighed tray
4. Dry sample overnight at 104°C and weigh again next day
5. Assemble sample containment column and add No. 200 mesh size to top and bottom
6. Pour sample into sample column while tapping sides to ensure even consolidation
7. Measure sample height within column
8. Close sample containment column
9. Saturate sample from bottom in basin of DI water using positive head differential and capillary rise. Slowly place sample in basin with water to base of sample, ensure no air in sample column below sample. Allow sample to saturate naturally by adding 0.5 to 1 cm of water per day until the water level is even with the top of the sample and there is a sheen on the water surface.
10. The day before, de-air water by boiling it for a minimum of 2 hours until it is flat.
11. Place lid on pot and cool water to room temperature overnight
12. Load saturated sample and sample column upright onto valve and outflow manifold. Use aluminum tray to ensure no water is lost from bottom of sample during transport.
13. Select a reservoir for the falling head test. For finer grained samples use a smaller diameter column
14. Fill reservoir by very slowly pumping de-aired water up through sample. This will dislodge final air within sample.
15. Fill reservoir until 1 m of head is achieved between outflow valve and surface of water.
16. Once reservoir is filled open valve and start timer.
17. Measure time for head to fall from $h_1$ (1 m) to $h_2$ (0.3 m)
18. Repeat measurement 3 times and average the tests
19. Calculate hydraulic conductivity

$$K = \frac{aL}{At} \ln \left( \frac{h_1}{h_2} \right)$$

where, $a =$ area of reservoir (cm$^2$), $L =$ length of sample (cm), $A =$ area of sample = 3.81 cm$^2$, $t =$ time (sec)
Appendix B: Full Datasets

B.1 Downhole Data Sets

Several downhole data sets were collected during the field program including geologic data sets (stratigraphic log, visual % gravel, and visual sorting), laboratory data sets (grain size distribution, moisture content), natural gamma radiation, and hydraulic data sets (MLS designs, hydraulic head profiles, vertical hydraulic gradients). A composite of these data sets for each hole can be found in Figure B.1 to Figure B.6.

![Geologic Legend](image)

![Quaternary Facies Associations](image)

![MLS Legend](image)

![Head Legend](image)

![Vert. Grad. Legend](image)

Figure B.1: Legends for figures B.2.

Figure B.2: Down hole data sets for MP-19U, MP-23U, MP-25U, MP-27U, and MP-28U including; multilevel system (MLS) design, head profiles, vertical hydraulic gradient locations (Vert. Grad.), moisture content, VOC concentrations where available, stratigraphic log, matrix grain size distribution, visual % gravel, sediment sorting established using standard diagrams for visual estimates, and natural gamma. Natural gamma logs give insight to clay content, with increased clay content corresponding to higher counts per second (cps). Refer to figure B.1 for legends. Grain size is shown on x-axis of core log as clay (cl), silt (s), very fine sand (vf), fine sand (f), medium sand (m), coarse sand (c), very coarse sand (vc), granules (g), and pebbles (p).
B.2 All Existing Surface Geophysical Lines

Existing surface geophysics resistivity lines were collected by Colby Steelman between 2012 and 2014. All lines that cross the 5 new unconsolidated holes and 4 existing pond transect holes are included in Figures B.3 to B.10.

Figure B.3: Legend for resistivity surveys (Figure B.4 to B.10). Fm. – Formation. Grp. – Group. Mbr. – Member.
Figure B.4: Surface electrical resistivity survey ERT1436 within the till plain setting and passing through several boreholes. MP-25U and MP-23U are in approximately same location as MP-25S and MP-23S respectively. For exact location on site see Figure 2.1. $o$ indicates offset distance out of page and $x$ indicates offset distance into page. Courtesy of Colby Steelman.
Figure B.5: Surface electrical resistivity survey ERT1435 within the till plain setting and passing through MP-26S near MP-27U (at ~300 m east location). For exact location on site see Figure 2.1. o indicates offset distance out of page and x indicates offset distance into page. Courtesy of Colby Steelman.
Figure B.6: Surface electrical resistivity survey ERT0025 within the till plain setting and passing through several boreholes and near MP-27U (at approximately 400 m position). For exact location on site see Figure 2.1. o indicates offset distance out of page and x indicates offset distance into page.Courtesy of Colby Steelman.
Figure B.7: Surface electrical resistivity survey ERT0015 within the till plain setting and passing through several boreholes and near MP-25U. For exact location on site see Figure 2.1. o indicates offset distance out of page and x indicates offset distance into page. Courtesy of Colby Steelman.
Figure B.8: Surface electrical resistivity survey ERT0023 within the till plain and glaciofluvial setting and passing through several boreholes and near MP-19U (at approximately same location as MP-19SD). For exact location on site see Figure 2.1. o indicates offset distance out of page and x indicates offset distance into page. Courtesy of Colby Steelman.
Figure B.9: Surface electrical resistivity survey ERT0033 within the glaciofluvial setting and passing through several boreholes and near MP-19U (at approximately same location as MP-19D). For exact location on site see Figure 2.1. o indicates offset distance out of page and x indicates offset distance into page. Courtesy of Colby Steelman.
Figure B.10: Surface electrical resistivity survey ERT0013 within the till plain, glaciofluvial, and glaciolacustrine setting and passing through several boreholes and near MP-28U (at approximately 475 m position). For exact location on site see Figure 2.1. o indicates offset distance out of page and x indicates offset distance into page. Courtesy of Colby Steelman.
B.3 Grain Size Distribution and Hydraulic Conductivity Estimates

Table B.1: Grain size distribution results and estimated hydraulic conductivities. A) Percentage by weight of each particle size from grain size distribution analyses for MP-27U and MP-28U, B) percentage by for MP-19U, MP-23U, and MP-25U, C) hydraulic conductivity estimates from Kozeny-Carman and Sauebrei equations and falling head permeameter analysis as well as facies classification based on Hambrey and Glasser (2003) for MP-27U and MP-28U, D) hydraulic conductivity estimates and facies classification based on Hambrey and Glasser (2003) for MP-19U, MP-23U, and MP-25U. Analysis was completed in January and February 2016 for grain size distribution analysis and June/July 2016 for falling head permeameter analysis. Discrepancies from 100% are due to loss or gain of sediment during laboratory analysis. mbgs – meters below ground surface.

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B.4 Grain Size Distribution Curves

Figure B.11: Grain size distribution curves for each facies analyzed (sand n=8, gravelly sand n=9, clast poor sandy diamict n=17, clast rich sandy diamict n=9, and clast poor intermediate diamict n=9). Black curves show results from sieve analysis and grey curves show results from hydrometer analysis of mud content. % passing indicated the percentage by mass of grains smaller than that grain size.
Figure B.12: Comparison of representative grain size distribution curves for each facies analyzed (sand, gravelly sand, clast poor sandy diamict, clast rich sandy diamict, and clast poor intermediate diamict). One curve from each facies in Figure B.11 was chosen as the representative curve. This representative curve was a curve in the middle of the distribution.