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GEOPHYSICAL MAPPING OF SEPTIC EFFLUENT AND THE EFFLUENT AND THE EVALUATION OF PERFORMANCE OF MOUNDED SEPTIC LEACH FIELDS

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Research Report

Geophysical mapping of septic effluent and the evaluation of performance of mounded septic leach fields

by

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ABSTRACT

In rural and suburban areas, many people are served by private wells and septic systems. The proximity of septic systems to private wells and sensitive surface water bodies presents a potential for contamination with human pathogens and excessive nutrients. This study uses geophysical methods to investigate how mounded soil absorption systems function in practice at two sites, a single-family residence and a small county park. Direct current electrical resistivity, capacitive-coupled electrical resistivity, electromagnetic induction, self-potential and ground penetrating radar were used to monitor displacements and concentration changes in the effluent plumes. Geophysical surveys were supplemented with Geoprobe™ investigations in which soil and groundwater samples taken to groundtruth the collected geophysical data.

All of the geophysical methods with the exception of ground penetrating radar were successful in imaging the septic effluent plumes at both sites as a low-resistivity anomaly. Borehole to borehole GPR was successfully used to image heterogeneities in the soil and the depth to the water table and capillary fringe. The plume at both sites was imaged in 3 dimensions using capacitive-coupled electrical resistivity. EM induction and DC resistivity show good quantitative agreement between the geophysically measured resistivity and the modeled resistivity of direct groundwater samples. SP is useful as a means of identify the general location and shape of the effluent plume but does not provide the resolution to accurately define the boundaries of the plume.

Both plumes remained approximately the same size and in roughly the same position. The concentration of the plume showed a strong response to the precipitation at the site. When the precipitation was high relative to the effluent dosing the plume shrank slightly and became less resistive. However, when the dosing was large relative to the precipitation, either from low precipitation at the single-family residence or high usage at the county park, the plume became more concentrated and grew.

In all of the geophysical investigations at both sites, the plume was identified along only about half of the mound, showing effluent is being discharged from only approximately

50% of the leach field. This means that the soil is receiving roughly twice the contaminant loading that it was designed to.

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Chapter 1 Introduction

1.1 Motivation

Better monitoring and understanding of the transport and fate of septic effluent is necessary to protect public health and nearby water resources. According to the US Census Bureau, approximately 23% of the estimated 115 million homes in the United States are currently served by on-site wastewater treatment systems (OWTS), the most common of which are septic tanks with soil absorption systems (SAS) (USEPA, 2002). This means that roughly 60 million people in the United States rely on septic systems to treat their domestic wastewater, including residents of roughly 1/3 of new homes. In a report to congress the EPA stated that "*Adequately managed decentralized wastewater treatment systems are a cost-effective and long term option for meeting public health and water quality goals, particularly in less densely populated areas,"* showing that septic systems are a treatment system that will continue its widespread use (Beal et al., 2005).

A typical on-site system has a design life of 10 to 20 years (Lowe and Seigrist, 2008). The US Census survey found that of the septic systems currently in use, approximately half are 30 years old or older and that 10 to 20% of all septic systems fail (USEPA, 2002). The states that reported septic system failure rates to the EPA had a numerous definitions of failure, usually only considering a system to have failed if effluent had backed up into the residence or created "surfacing" near the leach field. Due to these relatively extreme definitions of failure, the reported failure rates do not reflect the number of sites that may have surface or groundwater contamination resulting from septic systems (USEPA, 2002). Septic effluent contains a number of potential contaminants. These include household chemicals, nutrients such as nitrates and phosphorus, as well as viruses and biological hazards (Yates et al., 1985; Borchardt et al., 2004; Wilcox et al., 2005).

In Wisconsin, septic systems are used by 28.3% of the population. With the population of Dane County increasing, 1.5% annually since 1990, new development has been widespread with approximately 7600 acres of land developed for residential use between 1980 and 2000, much of which is serviced by septic systems (Wilcox, 2003; Gleason, 2006). A study conducted on 50 private wells in 2003 found that 8% of those domestic wells were contaminated with viral pathogens, primarily the result of human waste (Borchardt et al., 2003). All contaminated wells tested by Borchardt et al. (2003) were located in residential subdivisions serviced with septic systems as opposed to agricultural sites using manure spreading. In response to concerns over uncontrolled residential development and the potential contamination of groundwater, Dane County issued a moratorium on the construction of new unsewered subdivisions in 1995 (Wilcox, 2003).

Traditionally, subsurface contaminants exiting septic leach fields have been monitored using wells. These monitoring wells provide direct groundwater samples that can be analyzed for contaminants, but measure the groundwater at a single point only and are relatively costly. The placement of monitoring wells in most studies depends on assumed regional and local groundwater flow systems and can miss the primary zone of contamination if not installed directly down gradient of the leach field or due to unexpected flow caused by heterogeneity in the subsurface. A study by Harmsen et al. (1991) found that four piezometers placed on the corners of subdivisions in the central sand plains of Wisconsin were not adequate to determine the groundwater flow direction at some of the houses within the subdivisions, showing the importance of plume-specific groundwater flow measurements to accurately place groundwater-monitoring wells. Furthermore, monitoring wells can disperse contaminants vertically through the well bore in subsurface soils, polluting a greater volume of soil and leading to erroneous conclusions on the mechanisms of contaminant transport (Knight, 2001; Guillen and Hertzog, 2004).

The goal of the research presented in this report is to show that geophysical methods can effectively monitor the extent of septic effluent plumes. All of the methods that have been selected are of electrical or electromagnetic nature, because these methods have responses that are directly related to the ionic concentration of the pore water (Auken et al., 2006). Ground penetrating radar (GPR), electromagnetic (EM) induction, direct current (DC) electrical resistivity tomography, capacitive-coupled electrical resistivity, and self-potential allow for the evaluation of subsurface soil properties that are used to qualitatively and in some cases quantitatively evaluate the contamination of groundwater due to septic effluent. Each of these methods is directly sensitive to changes in the ionic concentration of the pore-fluid in soils (McNeill, 1991; Daniels, 1996; Reynolds, 1997; Zonge et al., 2005; Kuras et al., 2006). Septic effluents have a nutrient and dissolved ion concentrations that are much higher than the surrounding groundwater, and the elevated ionic concentration is what was imaged using geophysics and subsequently confirmed with direct groundwater sampling.

1.2 Selection of Sites

Both of the sites for this research utilized mounded septic leach fields. In the state of Wisconsin, the base of the aggregate layer of a septic leach field must be 0.9 m above the "limiting layer", which is either the water table or an impervious layer (Converse et al., 1989). The required separation distance varies from 0.3 and 1.2 m in different states. Based on site limitations, including the separation distance to the limiting layer and the hydraulic conductivity of the soil, it has been estimated that 70% of the soils in the United States have characteristics that make them unsuitable or limit their use for on-site wastewater treatment systems (Morey and Amoozegar, 2004).

To achieve the required separation at sites that were otherwise unsuitable the Wisconsin Legislature approved the Wisconsin mound system in the 1970s. The Wisconsin mound system is an "above ground septic tank-soil absorption system, which relies on a selected fill to purify and to convey the treated septic effluent hydraulically away" (Converse and Tyler, 1985). Since its original acceptance for conservative site conditions, research by Converse and Tyler (1985) has expanded the use of the Wisconsin mound system to sites with more difficult site conditions. Wisconsin has also developed an at-grade soil absorption system for site conditions between those acceptable for a traditional SAS and the extreme conditions that require a mounded SAS (Converse et al., 1989).

1.2.1 *Sun Prairie site - Contamination of private wells*

The contaminants of highest concern to human health in septic effluent are bacteria and viruses. Viruses have potential to migrate large distances in the subsurface, with horizontal migrations of up to 408 m having been reported (Yates et al., 1985). Viruses are capable of persisting several months in soils and groundwater and are shed in extremely large quantities (10^9 to 10^{10} /g) in human waste (Borchardt et al., 2003). Borchardt et al. (2003)

also found that all of the wells in their study that tested positive for viruses were located in subdivisions served by septic systems and that all wells were constructed to code. Not only is the location of private wells in relation to septic systems important, but the density of septic systems must also be considered as in some subdivisions the wastewater applied to the soils by the combination of all the systems in the subdivision may be substantial in comparison to the precipitation (Morey and Amoozegar, 2004).

After the Dane County moratorium on unsewered subdivisions, county executives approved a pilot subdivision that would use alternative on-site wastewater treatment technologies (Wilcox, 2003). This subdivision, the Savannah Valley subdivision, is the residential field site for this research. Groundwater monitoring at the site began prior to development and was set to continue for 10 years after the end of construction. The field site for this research within the Savannah Valley subdivision is a single-family home serviced by a septic system with a mounded SAS and shallow well. At the down gradient edge of the property, there is a surface drainage channel. Geophysical monitoring was performed between 2006 and 2009 between the septic mound and the drainage channel using surface electrical resistivity, self-potential, and borehole ground penetrating radar.

1.2.2 *Collins Lake site – Surface water protection*

The possibility of septic effluent contamination affecting surface water bodies was investigated at Collins Lake County Park in Portage County, Wisconsin. The system at the site consisted of a septic tank with an above ground leach field encapsulated in a mound. The mound was constructed to 150% of the required size with the ultimate goal of increasing the number of visitors allowed at the park. Collins Lake County Park is located adjacent to the 42-acre Collins Lake.

Due to the close proximity of the lake and the absence of a water supply well, the principle constituents of concern for contamination are phosphate (PO_4^{3-}) and nitrate (NO^3 - Harman et al., 1996). Nitrogen and phosphorus that discharge to surface waters, either directly or through ground water flow can cause algal blooms and eventual eutrophication and depletion of dissolved oxygen in lakes (USEPA, 2002). Studies of excessive nutrient loading in lakes have found that near-by septic tanks can be a source of phosphorus (Harman et al., 1996). Common phosphorus concentrations of septic effluent (~5 to 20 mg/L) are significantly higher than those shown to promote algal growth (i.e., ~0.03 mg/L) and the majority of the phosphorus mass that enters the subsurface is ultimately mobile, although at a highly retarded rate (Robertson et al., 1998; Robertson and Harman, 1999).

1.3 Previous Studies

1.3.1 *Groundwater pollution associated with septic systems*

Contaminants associated with septic effluent can be grouped into two broad categories, those that negatively affect public health and those that have adverse impacts on surface and groundwater environments. The principle constituents of concern for public health are bacteria and viruses, while nitrates and phosphorus are the primary contaminants of surface water bodies. Contamination due to excessive nutrients of surface water bodies is widespread, and septic systems are only one of many sources of contaminants. As part of the Clean Water Act of 1998, states reported 4,773 water bodies contaminated by excessive nutrients (USEPA, 2002). The most common nutrient contamination is that from excessive nitrogen and phosphorus.

The primary form of nitrogen in septic tanks is ammonium (Beal et al., 2005). Ammonium, however, is commonly nitrified in the unsaturated zone between the septic leach field and the water table, leaving nitrate. Nitrate is much more persistent in the subsurface and is the form of nitrogen most commonly detected in septic effluent plumes (Beal et al., 2005). The Chesapeake Bay Program to study groundwater contamination from septic systems found that 55 to 85% of the nitrogen entering a SAS is discharged to the groundwater. Another study reported to the USEPA (2002) in Buttermilk Bay, Massachusetts found that 74% of all the nitrogen in the bay originated from septic systems. In addition to the potential negative environmental impacts, nitrates have also been linked to health problems in pregnant women and methemoglobinemia, also known as "blue baby syndrome" (Harman et al., 1996).

The constituent of septic effluent most often considered when discussing negative impacts to surface waters is phosphorus. Phosphorus can promote algal blooms at concentrations as low as 0.03 mg/L, much lower than the typical effluent concentration of 5 to 20 mg/L (Robertson et al., 1998). Algal blooms can lead to expedited eutrophication of lakes, which decreases the dissolved oxygen content and negatively affects aquatic animals. A number of studies have found phosphorus to be significantly attenuated after migration of only a few meters in the subsurface (Harman et al., 1996).

A study of a 44-year-old septic plume under "near worst-case" conditions was conducted by Harman et al. (1996). The septic plume considered is a highly studied plume of an elementary school located in an unconfined aquifer sand aquifer (Harman et al., 1996; Robertson et al., 1998; Robertson and Harman, 1999). The highly concentrated effluent combined with the fast groundwater velocity is what makes the site conditions a good scenario for the evaluation of solute transport in septic effluent under critical site conditions (Harman et al., 1996). Laboratory studies have shown that the transport of phosphates in the subsurface is highly retarded, which is generally attributed to adsorption of PO_4^{3-} to soil solids and the precipitation of solid phosphate minerals (Robertson and Harman, 1999; Robertson, 2008). The primary sorbing surfaces for PO_4^{3-} are $CaCO_3$, metal hydroxide soil coatings, and solid organic carbon present in the soil (Harman et al., 1996).

Harman et al. (1996) found that phosphate attenuation occurred in the unsaturated zone immediately below the septic leach field. By observing a PO_4^{3-}-P ratio at the water table that was constant and solid P concentrations, it was determined that the phosphate attenuation was being controlled by precipitation in a localized horizon where approximately 85% of the mass of phosphorus was retained. Robertson and Harman (1999) returned to the same site after the septic system had been decommissioned to determine if the removal of phosphates was irreversible once the sewage source was removed. Monitoring during the first year of decommissioning showed little change in the location and concentration of the PO_4^{3-} plume. It was determined that the constant phosphate plume was caused by dissolution of the phosphorus that had accumulated in the “phosphorus rapid transformation zone”, leading to the conclusion that PO_4^{3-} is little affected by irreversible sorption and that the majority of the phosphorus mass that enters the subsurface is ultimately mobile, although highly retarded (Robertson and Harman, 1999). It was further determined by Robertson

(2008) that a 20 m lake setback, typical in most areas, is insufficient for attenuation of phosphorus solely due to attenuation in the ground water zone.

1.3.2 *Geophysical mapping of groundwater contaminants*

The geophysical methods used in this research do not directly measure the presence of subsurface contaminants. Electrical and electromagnetic methods detect the surface effects produced by the electric current flow in the subsurface (Telford et al., 1990). In near-surface soils, the conduction of electrical current occurs due to the movement of hydrated ions in the pore fluid and surface conduction of clay minerals. Geophysical measurements using electrical resistivity, EM induction, and self-potential have been used successfully in environmental applications to detect changes in the subsurface electrical properties associated with environmental contaminants and subsurface features. Ground penetrating radar has also been widely used in hydrologic and environmental applications due to its sensitivity to changes in water content and pore fluid electrical resistivity (Davis and Annan, 1989; Knight, 2001; Hollinger et al., 2001; Alumbaugh et al., 2002; Kuroda et al., 2009).

Researchers often use multiple geophysical methods together to determine subsurface structure that can influence geotechnical and environmental applications. Hudyma et al. (2005) used five different geophysical techniques, including electrical resistivity, ground penetrating radar, and capacitive-coupled resistivity to identify sinkholes in a karst environment in Florida. In the shallow karstic environment, the geophysical methods gave results that agreed with and supplemented borings to determine the bedrock topography and identify sinkholes below the surface.

Geophysical methods have also been widely used in larger scale investigations into regional and aquifer-scale fluid properties. Using EM induction will coil spacing of 40 m, Santos et al. (2002) used a quasi-3D approach based on the cumulative response functions developed by McNeill (1980) to determine the source and extent of mineral-rich spring waters. The EM induction survey in the Santos et al. (2002) study was supplemented with a self-potential investigation. Both the EM and SP surveys were able to identify the more conductive mineral-rich spring water and SP was able to identify characteristics in the groundwater flow system that were controlled by an unseen fault (Santos et al., 2002). Structural features in the Blue Ridge province of Virginia were identified using surface electrical resistivity and borehole geophysics. Using these methods, Seaton and Burbey (2000) identified sand and clay layers that control flow systems as well as a fault. Changes in resistivity of individual sand layers were found to correspond with changes in the degree of saturation of the soil (Seaton and Burbey, 2000).

More precise instrumentation has lead to smaller scale investigations using geophysics to identify anomalies with smaller contrasts and smaller sizes. A combination of electromagnetic induction and GPR has been used at many sites to investigate preferential flow paths. In these studies, EM induction is used to identify areas of further interest because of the speed at which surveys are performed. These zones of interest are then investigated in more detail using GPR. Studies have shown that combining methods in this way minimizes the amount of time spent on data collection (Inman et al., 2002).

Witten and Culvert (1999) used this technique to investigate the development of solution channels beneath storage ponds at a sewage treatment center in Oklahoma.

Electromagnetic induction surveys using the highest frequency that instrument operated at (15 kHz) detected zones of high resistivity in the near-surface that were not identified by lower frequency surveys. GPR tomography on the high resistivity zones were performed because the EM data could not provide depth estimates of the features. Using GPR, channels as small as 0.4 m could be clearly imaged and the effect of smaller channels was also seen, but the exact sizes could not be determined (Witten and Culvert, 1999). Inman et al. (2002) used a similar methodology to locate preferential flow paths in a sand-alluvium formation. The apparent electrical resistivity was found to have a strong relationship to the percent sand, which was highest in the preferential flow paths (Inman et al., 2002). As with the Witten and Culvert (1999) study, EM induction was used to locate zones of interest for more in-depth GPR investigation. Using this method distinct electromagnetic regimes were identified that compared well to soil-type regimes identified using traditional sampling alongside GPR surveys (Inman et al., 2002).

Many groundwater pollutants have electrical properties that are significantly different from surrounding groundwater, which allows their presence to be identified using geophysical methods. Non-aqueous phase liquids (NAPLs) are one such contaminant. It is expected that the high electrical resistivity (ρ) and low relative dielectric permittivity (ε_r) compared to surrounding groundwater will make NAPLs identifiable using geophysics, particularly GPR (Sauck et al., 1998). Research on a LNAPL plume by Sauck et al, (1998) identified a zone of low resistivity using electrical resistivity and high GPR attenuation corresponding to a known hydrocarbon spill. It was expected that the LNAPL plume would result in a high resistivity contaminant plume, the unexpected presence of a low-resistivity plume was attributed to the results of biodegradation in the older plume (Sauck et al., 1998).

Geophysical mapping of contaminant plumes has often focused on landfill leachate plumes due to the high ionic content, and therefore low electrical resistivity of the plumes (Olofsson et al., 2006). An unlined landfill in Newfoundland, Canada was investigated using electromagnetic induction and ground penetrating radar by Miller and Guzzwell (1998) and later by Miller et al. (2002). In the first investigation of the site, electromagnetic induction was used to detect low resistivity anomalies concentrated in known bedrock channels (Miller and Guzzwell, 1998). In this survey, the analysis was made based entirely on apparent resistivity, in 2002, the data were revisited and inverted using a 3-layer model that confirmed the bedrock topography and showed a low resistivity plume located in the bedrock channels (Miller et al., 2002). The second survey also revisited GPR data collected in 1998 and identified signal attenuation that corresponded to the low resistivity plume similar to that observed by Sauck et al. (1998). Olofsson et al. (2006) also used a combination of EM induction and GPR to identify the source of a low-resistivity contaminant plume. By combining geophysics with chemical analysis researchers were able to identify the plume as having originated in a nearby landfill as opposed to from road salting, a competing hypothesis.

Most of the environmental applications of geophysics in the literature employ multiple geophysical methods. However, there are few examples where methods measuring the same method are quantitatively compared. One such study is that performed by Allred et al. (2006). In this study, electrical resistivity variations of an agricultural field are mapped using DC electrical resistivity, capacitive-coupled resistivity, and EM induction. Overall, Allred et al. (2006) found qualitatively results were similar between methods, showing the same overall spatial trends. However, quantitatively the methods did not show good agreement, especially between the DC and capacitive-coupled resistivity techniques (Allred et al., 2006). One of the research goals of this study is to quantitatively compare the electrical conductivities measured using different geophysical methods on the septic plume located at the Collins Lake field site.

Chapter 2 Systems and Study Methodology

2.1 Conventional Septic systems

A “conventional” septic system consists of a septic tank and soil absorption system. The septic tank provides primary treatment of household waste. After passing through the septic tank, waste is discharged into the soil using absorption fields in systems known as soil absorption systems (SAS) (USEPA, 2002). The use of septic tanks for the primary treatment of wastewater began in the late 1800s; subsurface drains (SAS) to discharge the effluent became common practice in the middle of the 20th century in rural and suburban areas (Kriessl, 2000). This “conventional” system has not changed significantly in areas where centralized sewage collection is not available.

2.1.1 *Theory of Operation*

The conventional SAS uses a septic tank to remove most settleable material and floatable material (USEPA 2002). The septic tank also acts as an anaerobic bioreactor to digest the waste (Beal et al., 2005). The remaining effluent still contains significant contaminants and is further treated by the SAS as it is directed into the soil through an underground diffuser. Multiple diffusers exist, including trenches, tile beds, or mounds (such as exist at both the Collins Lake and Sun Prairie sites). Effluent is treated as it flows through the soil pores in the unsaturated zone by filtration, sedimentation, chemical absorption, and biological reactions (Hu et al., 2007; Lowe and Siegrist 2008). Flow through the unsaturated zone is critical to create a properly functioning SAS. According to Beal et al. (2005), the unsaturated zone creates an environment comparable to a sand filter, such that it “promotes aerobic degradation of pathogen, prolonged retention time of effluent, and maximum contact with soil media." The majority of treatment in SAS systems occurs in the biomat or in the upper 50 cm of the unsaturated zone immediately below the biomat (Beal et al., 2005). The biomat is a biological zone or clogging layer that forms where the effluent enters the ground (Beal et al., 2005). This zone has been shown to have a low hydraulic conductivity that will maintain the unsaturated flow below it even if saturated conditions exist above the biomat, eventually developing a steady-state condition in mature systems (Beal et al., 2005).

The development of a biomat is critical to the in-soil treatment of septic effluent and to maintaining the region of unsaturated flow (Lowe and Seigrist, 2008). Lowe and Seigrist (2008) showed that after a certain operating period the ability of SAS to remove nutrients, especially nitrogen, decreases to almost zero. A typical system should be able to function properly receiving a hydraulic loading of 9 to 36 L/m^2 (Hu et al., 2007). Beal et al. (2005) found that at sites that receive only seasonal dosing, the development of the biomat can be either incomplete or absent. Other research has focused on the development of SAS systems that can provide adequate treatment without a biomat in order to increase the possible loading rate (Hu et al., 2007).

2.1.2 *Contaminants of concern*

Septic leach fields and mound systems in Wisconsin are required to be a minimum of 15.25 m (50 ft.) from domestic drinking water wells, however the density of systems is not constrained and the location with respect to groundwater flow direction is not considered (Borchardt et al., 2003; Wisconsin Administrative Code, 2006). Septic leach fields slowly release a number of potential contaminants into the subsurface, including household chemicals including nutrients such as nitrates and phosphorus, as well as viruses and biological hazards (Yates et al., 1985; Wilcox, 2003; Borchardt et al., 2004). A septic leach field transfers contaminants to the soil and groundwater through a series of perforated plastic pipes installed over a gravel base. Contaminants can be carried by groundwater, affecting the water quality of both groundwater and surface water far from the septic leach field.

The contaminants of concern depend on the location of the septic system. In residential developments where there is a potential for water supply contamination, viruses and bacteria will be the primary contaminants of concern and nutrients such as nitrate and phosphorus will be of secondary concern. At sites located close to sensitive surface waters, nutrient overloading of nitrates and phosphorus will be of primary concern.

A number of bacteria exist in septic effluent that can negatively affect human health including *E. coli*; however, the most common of the bacterial indicators is typically total coliform bacteria (Borchardt et al., 2003). Of greater concern are viruses in the groundwater. For 1997 and 1998, 80% of infectious outbreaks of waterborne illnesses were caused by contaminated well water (Borchardt et al., 2003). Of the outbreaks, viruses are thought to be responsible for a significant portion of the gastroenteritis outbreaks (Borchardt et al., 2004). Analyses by Borchardt et al. (2004) suggested 98,000 illnesses annually from public occur due to water systems that do not disinfect for viruses. These analyses do not include private wells, the majority of which have no disinfection system.

Enteric viruses can survive for up to 6 to 9 months in the subsurface and have been observed to migrate as far as approximately 400 m horizontally and 65 m vertically (Yates et al., 1985; Borchardt et al., 2004). There are a number of potential sources for virus contamination of the groundwater, including septic systems, leaking municipal sewage pipes, and spreading of manure as fertilizer (Yates et al., 1985). In rural areas, where municipal sewers do not exist, it has been found that septic systems are a more likely source of contamination than land application of manure (Borchardt et al., 2003). The distance that viruses have been observed to travel from the contaminant source is significantly greater than the 15.25 m (50 ft.) minimum separation between septic tanks and private wells required by the State of Wisconsin.

When human health is not the primary concern at a site, but rather the protection of nearby surface waters, the contaminants of greatest concern become phosphate (PO_4^{3-}) and nitrate (NO_3^- - Harman et al., 1996). Nitrogen and phosphorus that discharge to surface waters can cause algal blooms leading to accelerated eutrophication and low dissolved oxygen in lakes (USEPA, 2002). The effects of eutrophication can range from nuisance vegetation and odors to winter kills of marine species. Both nitrogen and phosphorus are typically removed in the unsaturated zone near septic leach fields; however, research by Lowe and Seigrist (2008) and Robertson and Harman (1999) suggest that over the long-term life of a system the majority of the nutrient mass will ultimately be mobile in the subsurface and can enter nearby surface waters.

2.2 Mounded septic systems

2.2.1 *Design*

The Wisconsin mound and at-grade SAS systems were designed to provide the necessary separation between septic leach fields and the underlying water table at sites where conventional in-ground SAS would not meet required site conditions (Converse and Tyler, 1985; Converse et al., 1989). Mound and at-grade system were originally developed for sites with: (1) low permeability soils, (2) shallow permeable soils over creviced or porous bedrock, or (3) permeable soils with a shallow water table (USEPA, 1980). Research by Converse and Tyler (1985) showed that the mound system could successfully be used on: (1) filled sites, (2) sites where water table seasonally is as shallow as 30 cm, (3) on steep slopes up to 21%, and (4) placed on top of older failed systems in addition to the already approved conditions, expanding the applicability of septic systems to a wider range of site conditions.

The Wisconsin mound system consists of a septic tank, a dosing chamber and the mound. A schematic of the Wisconsin mound system is shown in Figure 2-1. The septic tank performs the same functions as in a conventional SAS before passing the effluent to the dosing chamber, which distributes effluent under pressure to the network of small diameter distribution pipes located in the mound (Converse and Tyler, 2000). The soil in the mound and native soil beneath the mound then operate in the same manner as a conventional SAS.

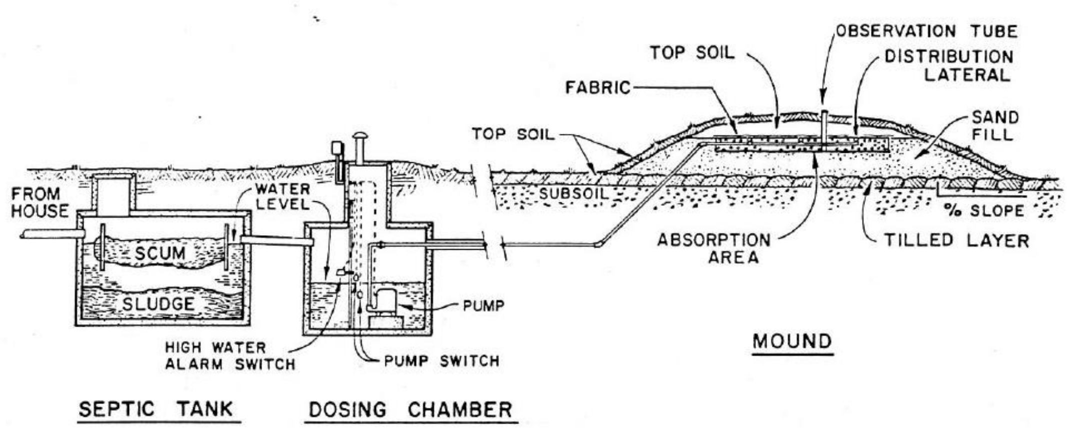


Figure 2-1: Schematic of the Wisconsin mound system showing septic tank, dosing chamber and mound. From Converse and Tyler, 2000.

At-grade soil absorption systems are very similar to the Wisconsin mound system, but are used in intermediate site conditions between those suitable for conventional systems and those that require a mounded SAS. A true mound system consists of a fill layer and aggregate above the surface encapsulated in a mound (Converse and Tyler, 2000). The at-grade soil absorption system places the aggregate layer directly on the tilled native soil without the fill layer present in the Wisconsin mound system (Converse et al., 1989). In Wisconsin, a separation of 0.90 m is required from the base of the infiltration network to the groundwater table (Converse et al., 1989). Thus, if the water table is greater than 1.2 m deep (0.9 m separation+ .3 m thick aggregate layer) a shallow in-ground system may be used. If the groundwater table is between 0.3 and 0.6 m, a mound system will be required to obtain the necessary separation. However, for groundwater depths of 0.6 to 0.9 m, an at-grade system is suitable (Converse et al., 1989). Figure 2-2 provides a schematic relationship of the four SAS types.

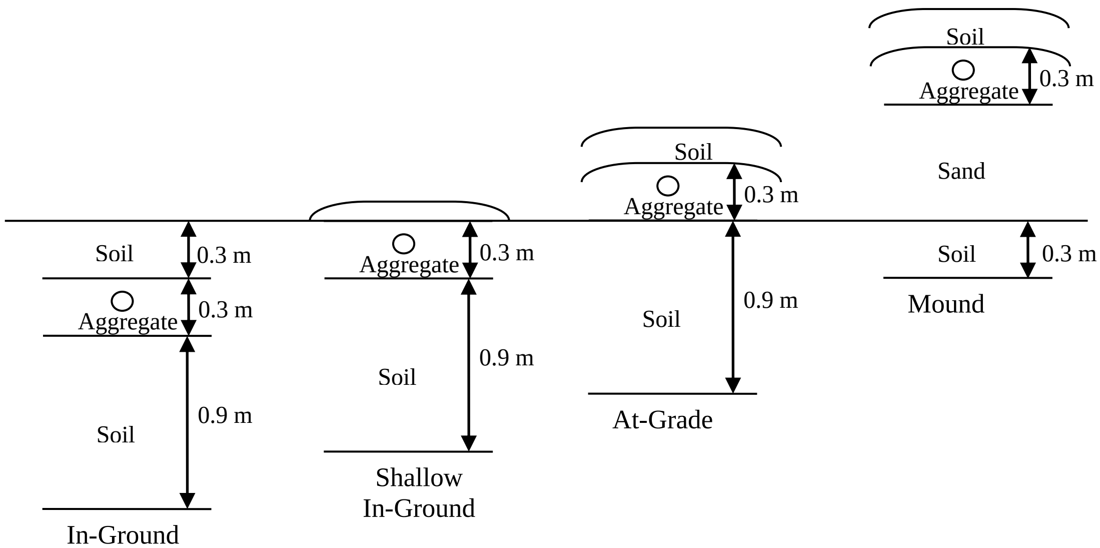


Figure 2-2: Cross-section of four soil absorption systems in relation to ground surface and water table. Adapted from Converse and Tyler (2000).

2.2.2 *Expected response of geophysical investigations*

Borchardt et al. (2003) found a high correlation between wells with high chloride concentrations and those contaminated by viruses. This was attributed to the high chloride concentration in human and household waste and its behavior as a conservative tracer identifying the extent of septic contaminant plumes (Borchardt et al., 2003). In a review of 10 sites, Robertson et al. (1998) showed that phosphorus had a high degree of retardation (~20 to 100) compared to conservative ions such as chloride (CL^-). The primary contaminants of concern in this study cannot be directly measured for using the electrical and electromagnetic geophysical methods employed in this study. However, the effects of other constituents of septic effluent, specifically chloride, can be detected using electrical and electromagnetic geophysical methods (Aaltonen and Olofsson, 2002).

The electrical conductivity of a medium is a measure of charge mobility in response to an applied electric field and the electrical resistivity is the inverse of conductivity (Klein and Santamarina, 2003). All of the geophysical methods used as a part of this research are sensitive to changes in the electrical resistivity of the subsurface. Electrical resistivity of soils is primarily the result of the movement of hydrated ions through a porous medium and surface conduction of clay particles (Klein and Santamarina, 2003). There are a number of soil parameters that affect the electrical resistivity of soils including electrolyte resistivity, porosity, and clay content (Tabbagh et al., 2000).

It is expected that in the effluent from septic mounds, the only change between contaminated soils and native soils will be in the chemistry of the pore water. As previously discussed, the septic effluent will have elevated levels of chloride that will behave as a conservative tracer of the effluent plume (Borchardt et al., 2003). Changes in the ionic concentration of the groundwater due to increased Cl^- concentrations will result in decreased electrical resistivity of the pore water and therefore decreased formation resistivity within the septic effluent plume. Using Archie's law, the fluid resistivity and formation resistivity of particulate media can be related (Archie, 1941). This relationship will be used to estimate the resistivity of the pore fluid based on the measurements of formation resistivity. Electrical methods have been used by Kemna et al. (2002) and Barker et al. (2001) to image solute transport and contaminant plumes by measuring the effects of conductive contaminants on the formation resistivity.

2.3 Direct current (DC) electrical resistivity

The primary geophysical survey technique used at the Stevens Point, WI site was DC electrical resistivity using the ABEM Terrameter. A dipole-dipole electrode array with 2 m unit electrode spacing was used for all surveys. DC resistivity is the most time consuming of all the methods used in this study, it does however, when performed with care provide the results with the least amount of noise. The excellent signal-to-noise ratio of electrical resistivity methods and the dipole-dipole electrode array in particular was also observed by Barker et al. (2001).

2.3.1 *Theory of electrical resistivity tomography*

Electrical resistivity is a fundamental and diagnostic material property that can be used to determine properties of the subsurface (Rhoades et al., 1976; Saarenketo, 1998; Klein and Santamarina, 2003; Attia et al. 2008). This method is especially suited to hydrogeologic applications, such as this research, because both the electrical and hydraulic response of the soil is controlled by pore fluid chemistry and pore structure (Aristodemou and Thomas-Betts, 2000). Electrical resistivity surveying is based on the principle that the distribution of electric potential around a current-carrying electrode depends on the resistivity and its distribution in the surrounding soil and rock (Zonge et al., 2005). Electric current in geo-materials is conducted by three mechanisms: electrolytic conduction, electronic conduction, and surface conduction (Tabbagh et al., 2000; Klein and Santamarina, 2003; Auken et al., 2006). In near-surface applications, electronic conduction is not important and can be ignored. Electrolytic conduction in the pore fluid will be the most important mechanism of conduction in the study of septic plumes as the soil properties at both sites due not vary significantly between the plume and surrounding area (Zonge et al., 2005).

The electrical resistivity of the pore fluid in sandy soils can be used to estimate the bulk resistivity using empirical relationships such as Archie's law (Archie, 1941). Archie's law is given by Equation 2-1.

$$\rho_{bulk} = a\phi^{-m} s^{-n} \rho_{fluid} \tag{2-1}$$

where ρ_{bulk} and ρ_{fluid} are the bulk formation and fluid resistivity respectively, ϕ is the porosity, s is the degree of saturation (i.e.1 for saturated material), and a, m, and n are empirically determined constants. Archie's law will be used to compare the quality of geophysically measured resistivity between methods and to measured pore water resistivity.

The electrical resistivity that is measured in the surveys is not the true resistivity, but instead a volumetric average of resistivity known as the apparent resistivity, ρ_a. The measured apparent resistivity values were inverted using Geotomo RES2DINV software to produce 2-dimensional profiles of electrical resistivity. The inversion routine used in the RES2DINV is based on the smoothness-constrained least-squares method described by deGroot-Hedlin and Constable (1990) and Sasaki (1992) (Geotomo, 2008).

2.3.2 *Dipole-dipole array*

All DC electrical resistivity data were collected using a dipole-dipole array. The dipole-dipole electrode array was selected due to its high signal to noise ratio and resolution in the shallow-subsurface (Barker et al., 2001). Another advantage of the dipole-dipole array is that only 2 electrodes need to be moved between successive measurements, making this array less labor intensive and time consuming than other electrical resistivity methods. The dipole-dipole array consists of two current electrodes separated by a distance (a) across which a known source current is applied and two potential electrodes separated by a distance (a) across which the voltage is measured. A schematic of the electrode array is shown in Figure 2-3.

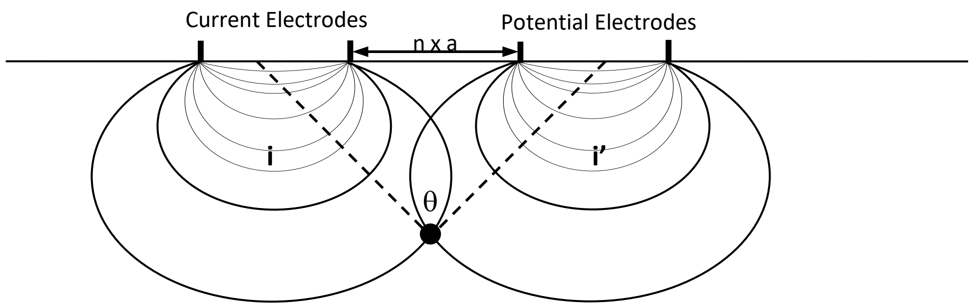


Figure 2-3: Schematic of the dipole-dipole array for DC electrical resistivity data collection.

The apparent resistivity (ρ_a) for the dipole-dipole configuration is calculated using Equation 2-2:

$$\rho_a = \pi a n(n+1)(n+2)\frac{\Delta V}{I} \tag{2-2}$$

where *a* is the dipole length, *n* is the separation factor between dipoles, ΔV is the measured voltage difference between the potential electrodes and I is the applied current. Although each apparent resistivity measurement is a volumetric response, in order to plot the collected apparent resistivity data and obtain a resistivity profile each measurement must be assigned to a single point in the subsurface (Figure 2-3).

To determine the point where this measurement is assigned, we can imagine the vector current fields **i** and **i'** between the current and potential electrodes respectively shown in Figure 2-3. The power in this system can be defined by the equation

$$Power = i \bullet i' = |i| \cdot |i'| \cos\theta \qquad (2\text{-}3)$$

Each measurement will be assigned to the point in the subsurface that has the maximum power given by Equation 2-3. Maximum power will occur when the vectors **i** and **i'** are perpendicular, which occurs at the center of the electrode array and at a depth equal to a(n+1)/2, as shown by the point in Figure 2-3.

2.4 Capacitive-coupled electrical resistivity

Capacitive-coupled electrical resistivity was used at both the Stevens Point and Sun Prairie field sites. At Sun Prairie, it was the primary method of investigation, whereas at Stevens Point it was only used in later surveys to supplement DC resistivity. The reason it was used more extensively at Sun Prairie was that the site is larger than the Stevens Point site and it would have been prohibitively time consuming to perform DC resistivity surveys at the Sun Prairie site.

The use of capacitive-coupled electrical resistivity has several advantages over DC electrical resistivity surveys. The system is dragged behind the operator and collects data at a rate of 1 Hz. This allows mapping of the subsurface as the operator walks, making it possible to perform relatively large surveys in a short period of time (approximately 1 to 2 hours to complete a survey at Sun Prairie and less than one hour at Stevens Point). One user can also operate the system easily, which is not feasible for DC surveys. All capacitive-coupled resistivity surveys were performed using the Geometrics OhmMapper.

2.4.1 *Theory*

The OhmMapper is a capacitive-coupled resistivity system. It consists of transmitting and receiving dipoles that are dragged behind the operator. The OhmMapper couples a 16.5 kHz alternating current to the earth, treating the coaxial cables of the transmitter dipole as one plate of a parallel-plate capacitor and the ground as the other plate (Geometrics, 2001; Kuras et al., 2006). The receiver works in the same manner, but records the AC voltage transferred from the ground, which is proportional to the earth's resistivity. The system operates in a dipole-dipole array, which was found to be the most favorable for capacitive-coupled resistivity measurements (Kuras et al., 2006).

Capacitive-coupled systems use antennas known as "capacitive-line antennas". This antenna type has an operating frequency range of 1.6 kHz to 25 kHz. The lower limit of this range is defined by the need to inject sufficient current into the subsurface to create a measurable response and the upper limit is the highest frequency that can be used while remaining in the low induction-number regime (Kuras et al, 2006). Capacitive-line antennas cannot be analyzed in the same was as DC dipole-dipole surveys because the antennae inject current into the subsurface over the entire length of the antenna, as opposed to at the 2 ends of the dipole as in the DC case. Kuras et al. (2006) gives modified geometric factors originally developed in unpublished work by Timofeev for the capacitive-coupled electrical resistivity dipole. Using the modified geometric factors, an "effective" dipole length can be calculated for the capacitive line dipole that is always longer than the corresponding DC dipole (Kuras et al, 2006).

2.4.2 *OhmMapper setup and operation*

The OhmMapper system uses a dipole-dipole configuration with dipole length (a) of 5 m and n values of 0.2, 0.4, 0.8, 1.2, 1.6, 2.0, and 2.8 corresponding to separations (n·a) of 1, 2, 4, 6, 8, 10, and 14 m between antennae. Figure 2-4 shows the OhmMapper setup, consisting of the transmitter dipole (back) separated from the receiver dipole (front) using a non-conductive rope.

Figure 2-4: The OhmMapper capacitive-coupled electrical resistivity system. From www.geometrics.com

OhmMapper surveys were performed by walking a pre-defined survey line oriented parallel to the septic mound. Each survey line was completed in both directions for every transmitter-receiver separation. These data sets were used to develop 2D profiles along each survey line and a 3D profile by combining all of the survey lines. The survey lines had a number of predetermined "marks" every 15 or 20 m along the line that were used to align each pass of the OhmMapper survey.

2.4.3 *Data processing and smoothing*

After completion of the survey, the OhmMapper data were imported to a computer using the MagMapper2000 software by Geometrics. This software package allows the user to use the "marks" recorded during data collection to align the data and place them on the grid that was used during data collection. The MagMapper2000 software assumes that the user walked at a constant pace during data collection and evenly distributes the data (collected at 1 Hz) between "marks". An attempt to maintain a constant walking speed was made, however vegetation at the sites made this difficult at times. The inversion software used required constant "unit electrode spacing". This was achieved by rounding the assigned position to the nearest 25 cm along the survey line in Excel. The "forward" and "backward" traces were then combined. Prior to inversion, high frequency noise was eliminated by applying a moving average of apparent resistivity readings where Excel showed the data to be noisy. Finally, the apparent resistivity data were exported to the RES3DINV software package by Geotomo Software for inversion. RES3DINV uses the same computational procedure as the RES2DINV software that was used to invert the DC electrical resistivity data.

2.5 Ground Penetrating Radar

2.5.1 *Reflection*

Reflection ground penetrating radar (GPR) surveys were performed at the Stevens Point filed site using GSSI 120 MHz and 500 MHz antennae. The system was used in a continuous collection reflection mode as it was dragged along the survey lines. GPR investigates the subsurface using the propagation of electromagnetic waves (Annan, 2005). The subsurface electromagnetic wave velocity and attenuation are dependant on the soil composition and water content, which control electromagnetic properties of the soil (Davis and Annan, 1989). The electromagnetic wave velocity is dependant on the speed of light in free space (0.3 m/ns), the relative dielectric permittivity (ε_r), and the relative magnetic permeability (μ_r) (Daniels, 1996). The attenuation coefficient, α, of the EM field is described by the equation

$$\alpha = \omega \sqrt{\frac{\mu\varepsilon}{2}\left[\left(1 + \frac{1}{\omega^2\rho^2\varepsilon^2}\right)^{\frac{1}{2}} - 1\right]} \qquad \text{(2-4)}$$

Equation 2-4 shows that the attenuation is not only a function of the dielectric permittivity and magnetic permeability of the medium but is also directly proportional to the frequency of the EM wave, ω, and the bulk resistivity of the subsurface, ρ (Knight, 2001). It was expected that the decreased electrical resistivity of the septic plume would result in increased attenuation of the reflected GPR signal with all other parameters remaining constant. Increased GPR attenuation has been observed in low-resistivity contaminant plumes (Sauck et al., 1998; Miller et al., 2002).

2.5.2 *Cross-hole*

Borehole to borehole ground penetrating radar surveys were performed at the Sun Prairie site using the 4 monitoring wells installed at the site. GPR surveys were performed using the PulseEKKO system manufactured by Sensors and Software, Inc. Both 100 MHz and 200 MHz antennae were used in zero-offset profiling (ZOP) and the 200 MHz antennae were used to obtain multi-offset gathers (MOG) and generate EM wave velocity and attenuation tomographic images.

Borehole to borehole GPR surveys can be used to monitor changes in the water content of the soil (Hollinger et al., 2001). The electromagnetic wave velocity is most directly affected by the dielectric permittivity, which is largely controlled by the volumetric water content (Kowalsky et al., 2005). The EM wave velocity, V_{EM}, for common geologic materials can be approximated under favorable conditions by

$$V_{EM} \approx \frac{c}{\sqrt{\kappa'}} \tag{2-5}$$

where c is the electromagnetic wave velocity in free space and κ' is the real relative dielectric permittivity (Kowalsky et al., 2005). The relative dielectric permittivity of water is much greater than that of most geologic materials, which allows the relative dielectric permittivity of a soil to be related to the volumetric water content, θ, by empirical relations such Equation 2-6, Topp’s equation (Topp et al., 1980).

$$\kappa' = 3.03 + 9.3\theta + 146.0\theta^2 - 76.7\theta^3 \tag{2-6}$$

The strength of GPR signal gathered in field scale studies depends on the electromagnetic properties of the soil, the frequency of excitation, the depth and electromagnetic contrast of the target (for reflection testing), and the separation between antennae (for borehole-to-borehole testing). The soil at the Sun Prairie site is glacial till containing gravel and a substantial amount of clay (anywhere between 12 and 50 % fines). Because GPR signals attenuate quickly in saturated clayey soils, the clay content will control the electromagnetic wave penetration and therefore the quality of the GPR survey.

The Radar Range Equation (RRE) was used to determine an appropriate separation between the boreholes to be used for GPR investigation (Annan and Davis, 1977). The RRE, first proposed by Ridenour (1947), is used to calculate the amount of power transferred from the transmitter to the receiver. The receiver antenna is able to detect an attenuated signal; however, a signal reaching the receiving antenna below the dynamic range of the GPR system will not be interpreted correctly if at all. Based on a conservative RRE calculation for soils collected at the Sun Prairie field site using a low frequency of 50 MHz and the parameters given in Table 2-1, an antenna separation of approximately 3 meters will provide sufficient signal strength to be interpreted accurately. The system performance factor is used to determine the quality or strength of the signal received by the receiver and is defined by the equation

$$Q = -\log\left(\frac{P_{\min}}{P_S}\right) \tag{2-7}$$

where P_{min} is the power received by the receiver and P_s is the source power. GPR performance is higher for lower Q factors. Davis and Annan (1989) give a range of acceptable Q factors from 120 dB to 160 dB. The Q factors calculated for a 3 m borehole separation were approximately 141.9 for 50 MHz antennae and 157.9 dB for 100 MHz antennae, falling within the acceptable range.

Table 2-1: Parameters and results of radar range equation analysis

Variable	Description of Variable	Units	Value
E_{TX}	Transmitter efficiency	-	0.1
E_{RX}	Receiver efficiency	-	0.1
G_{TX}	Transmitter gain	-	1
G_{RX}	Receiver gain	-	1
	Soil Properties		
z	Distance between antennae	m	3
ρ	Resistivity	Ωm	10
σ	Conductivity	mS/m	0.1
εr	Relative permittivity	-	20
e			1.77×10^{-10}
δ	Skin depth	m	237.47
mu			1.26×10^{-6}
ω			3.14×10^{8}
α	Attenuation coefficient	1/m	3.41
V	Velocity of medium	m/s	4.15×10^{7}
f	Signal frequency	1/s	5.00×10^{7}
tan(δ)	Loss Tangent	-	1.80
A	Effective antenna area	m^2	5.47×10^{-2}
P_S	Source power	W	400
P_1	Radiated power	W	40
P_2	Power radiated in target direction	W	40
P_3	Power reaching target	W	4.68×10^{-10}
P_4	Power at receiver	W	4.68×10^{-10}
P_5	Power received	W	2.56×10^{-11}
P_{RX}	Power to receiver electronics	W	2.56×10^{-12}
Q	System Performance	dB	141.9

Based on the RRE analysis, boreholes were conservatively drilled at a separation of approximately 2.5 meters. The 2.5 m separation guarantees that the signal will penetrate through the glacial till with enough strength to be visible at the receiver antenna. Using the same RRE parameters, Q factors of 125.6 dB, 139.4 dB, and 149.2 dB were calculated for a 2.5 m well separation for antennae of 50 MHz, 100 MHZ, and 200 MHz respectively, showing that for all off the antennae the performance factor will fall within the acceptable range. Placing the 4 wells in a single line allowed data to be collected across multiple wells (5.0 or 7.5 m separation) if the 2.5 m well separation was overly conservative.

2.6 Frequency Domain Electromagnetic Surveys

Frequency domain electromagnetic (FDEM) induction surveys were performed at the Stevens Point site to measure changes in the conductivity of the subsurface associated with septic effluent. The primary advantage of FDEM over other geophysical methods is the speed at which surveys can be performed. Due to the absence of any direct contact with the ground surface, a survey of the size used in this study can be performed in approximately 1 hour. The FDEM method also eliminates many of the near surface effects that cause noise in other methods because the response is a spatial average of a larger area (McNeill, 1991).

2.6.1 *EM 31 theory and operation*

Frequency domain electromagnetic (FDEM) surveys were performed using the Geonics EM31. This system has two co-planar coils with a fixed separation of 3.66 m, an operating frequency 9.8 kHz, and was used at a height of 1 m above the ground The system operates under the low-induction number principle, where the coil separation (s) divided by the skin depth (δ) is much less than one. The EM31 induces a time-varying electrical current in the earth, which in turn generates a time varying magnetic field. Under low-induction number conditions, the secondary magnetic field measured by the receiver (H_S) is directly proportional to the apparent conductivity (σ_a) of the subsurface (Telford et al., 1990):

$$\left(\frac{H_S}{H_P}\right) = \sigma_a \frac{\omega\mu_0 s^2}{4} \tag{2-8}$$

In Equation 2-8, H_P is the primary magnetic field, ω is the angular frequency ($\omega=2\pi f$), μ_0 is the magnetic permeability of free space, and *s* is the coils separation

The system was operated using the horizontal and vertical dipole configurations to develop a 2-layer model of the subsurface based on measurements averaging responses with different depths of penetration (McNeill, 1980). Figure 2-5 shows the relative sensitivities of the two dipole orientations of the EM31 with depth. The horizontal dipole is most sensitive to the conductivity in the very near surface, while the vertical dipole is most sensitive at a normalized depth of approximately 0.4 and is more sensitive at greater depths than the horizontal dipole.

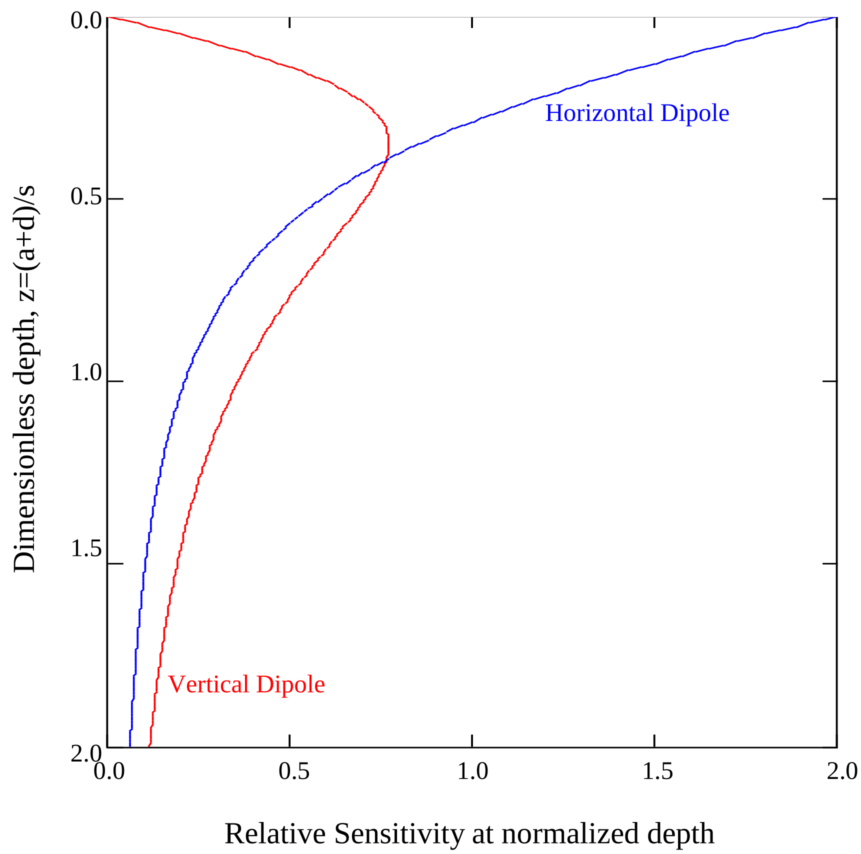


Figure 2-5: Relative sensitivity of EM31 operated in the vertical dipole configuration and horizontal dipole configuration with depth.

From the data collected using both dipole orientations, a simple two-layer model of the subsurface at the Stevens Point site was generated by assuming the boundary between layers was at 1.5 m below the surface and corresponded to the water table. The assumed water table depth was obtained from the DC resistivity data and supported by the Geoprobe investigation and ground penetrating radar reflection surveys performed at the same time as the EM31 investigation.

2.6.2 *2-layer model and expected response to septic plume*

Using the cumulative response functions for horizontal and vertical loop configurations, the response of the two layers in the simplified model was determined. McNeill (1980) gives the total contribution to the apparent conductivity below the normalized depths and are defined as:

$$R_H(z) = \sqrt{4z^2+1} - 2z \qquad \textit{horizontal loop cumulative response function} \tag{2-9}$$

$$R_V(z) = \frac{1}{\sqrt{4z^2+1}} \qquad \textit{vertical loop cumulative response function} \tag{2-10}$$

where z is the depth (including the 1 m above the ground) normalized by the intercoil spacing (3.66 m). The interface depth in this study was assumed to be the water table at a depth of 1.5 m. The cumulative response functions give. The conductivities of the two layers σ_1 and σ_2 were then calculated by solving the following system of equations:

$$\sigma_{aV} = \sigma_1[1 - R_V(z)] + \sigma_2 R_V(z) \tag{2-11}$$

$$\sigma_{aH} = \sigma_1[1 - R_H(z)] + \sigma_2 R_H(z) \tag{2-12}$$

From the modeled profile of the subsurface, the effluent plume from the septic mound was identified as an increase zone in conductivity (decrease in resistivity) below the groundwater table. Similar electromagnetic induction systems have been used to map the contamination caused by a failed septic system in Indiana (Taylor et al., 2002).

2.7 Self-potential

2.7.1 *Sources of self-potentials*

The self-potential (SP) method is a passive geophysical method in which the differences between natural ground potentials of any two points on the surface are measured. In order to measure self-potentials, two non-polarizing porous-pot electrodes are connected to a multi-meter. One electrode is fixed and the other moved along the survey line at the desired step distance. The non-polarizing electrodes used in this study are Cu-$CuSO_4$ porous-pot electrodes and are shown in Figure 2-6.

Figure 2-6: Non-polarizing Cu-CuSO4 porous pot electrode used in SP surveys

SP methods were originally developed to detect large ore bodies, however in recent years SP measurements have been used in groundwater investigations because it is sensitive to both groundwater chemistry and flow (Ernstson and Scherer, 1986; Maineult et al., 2005).

There are several sources of self-potentials, including electrokinetic, electrochemical, and mineral potentials (Telford, 1990). The anomaly of interest in this study is related to the septic plume in the shallow subsurface (<10 m) along survey lines of 50 to 100 m and therefore the self-potentials due to mineral potentials are not considered.

Electrokinetic self-potentials are caused by the flow of an electrolyte through a porous medium. When using SP to investigate the flow of an electrolyte, the self-potentials tend to become more positive in the direction of groundwater flow (Maineult et al., 2005). The other mechanism of interest in this study is electrochemical self-potentials. These potentials are caused by the difference in mobility of electrolytes of varying concentration in the subsurface (Reznik, 1990). In this study, electrochemical anomalies are important in identifying the septic effluent plume and electrokinetic anomalies will be used to identify the flow direction.

2.7.2 *Survey methodology and expected response to septic plume*

Self-potentials were measured using 2 non-polarizing porous pot Cu-$CuSO_4$ electrodes connected to the ABEM Terrameter to measure the voltage between electrodes. For all surveys in this study, the positive electrode was placed at the center of the septic mound. For each measurement, good contact with the ground was ensured by digging a small hole where necessary to eliminate interference from roots. To improve the quality of the data and reduce noise, readings were taken at each position until the change between successive readings was less than 5%.

With the positive electrode fixed at the center of the septic mound, it is expected that the measured self-potential will be small within the effluent plume and larger in the native groundwater. Since the positive electrode is fixed within the influence of the septic effluent (on the mound), the electrochemical potential difference between the mound and the plume will be less than between the mound and the native groundwater. Self-potential measurements at the Stevens Point site were also collected along the shoreline to identify the groundwater flow direction.

Chapter 3 Case Study: Sun Prairie Subdivision

3.1 Introduction

Geophysical investigations were performed down gradient of a mounded septic leach field serving a 6-year old single-family home in the recently developed Savannah Valley subdivision in Sun Prairie, WI. Construction of the Savannah Valley subdivision began in 2003 as part of the Dane County Subdivision project (Bardbury and Wilcox, 2003). As part of this project, 20 of the 30 lots in the subdivision will use alternative, new-technology Onsite Wastewater Treatment Systems (Wilcox, 2003).

3.1.1 *Contaminants of concern*

Because the Sun Prairie field site is located within a residential development, the groundwater contaminants of greatest concern are those that can have negative impacts on human health. A number of bacteria exist in septic effluent that can negatively affect human health including *E. coli*; however, the most common of the bacterial indicators is typically total coliform bacteria (Borchardt et al., 2003). Of greater concern than bacteria however, are viruses in the groundwater. Borchardt et al. (2004) calculated 98,000 illnesses annually result from viruses in public water systems. This analysis neglected private wells, the vast majority of which do not have any treatment for viruses in place.

Nutrients are a secondary concern at the Sun Prairie field site, specifically nitrates and phosphorus. While less of a threat to human health, nitrates in groundwater have been linked to methemoglobinemia (“blue baby syndrome”) in infants and other health problems in pregnant women and children (Harman et al., 1996).

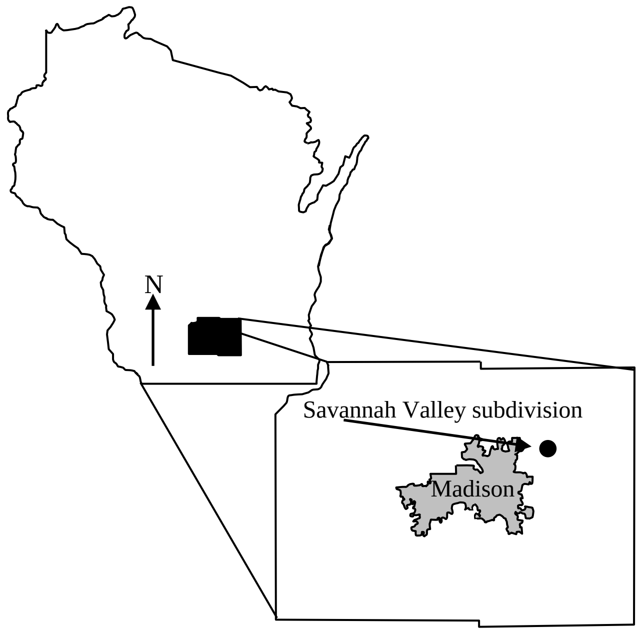
3.1.2 *Site specific goals*

All geophysical surveys at the Sun Prairie field site were performed down gradient of the septic leach field. Electrical resistivity data were collected in August 2006, October 2007, October 2008, and May 2009 and borehole-to-borehole GPR surveys performed in December 2006 and October 2007. Electrical resistivity surveys in 2008 and 2009 were supplemented with self-potential investigations. The results of the geophysical surveys were compared over time to understand how the properties of the soil near the septic tank have changed. Using the GPR data collected at different times, changes in the groundwater levels were identified between observation wells. The ERT provides data related to the porewater ionic concentration of subsurface soils; the data collected in the electrical resistivity surveys were used to identify changes in the size and concentration of the effluent plume over time. SP surveys were used as a fast method of identifying the location of the effluent plume and proved to be a useful method in addition to ERT but cannot provide the same detail.

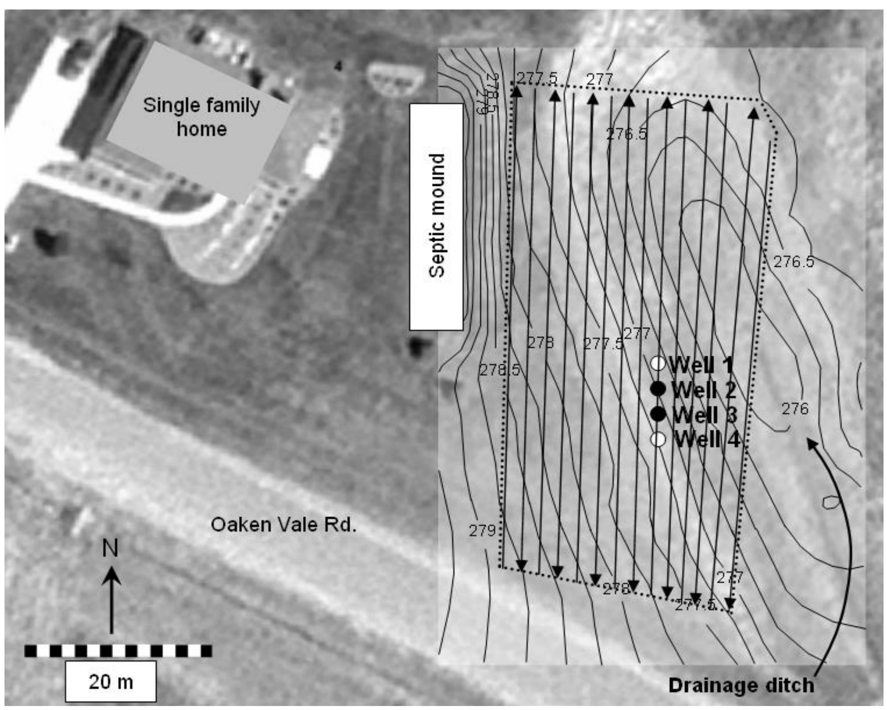
3.2 Site description

The Savannah Valley subdivision is located in Sun Prairie, WI approximately 22.5 km (15 miles) northeast of Madison, WI (Figure 3-1). Prior to development, the site consisted of farmland, wooded area, and a small wetland. The historical agricultural use of the site, which included the use of synthetic fertilizer and animal waste, may result in elevated nitrate levels associated with past agricultural use, not septic contamination (Wilcox, 2003). Improvements at the site began in September 2002 and the first homes were constructed in early 2003 (Wilcox et al., 2005).

All geophysical surveys were performed in the topographically low area east of the septic mound and west of the drainage ditch shown in Figure 1. Groundwater at the site flows east towards the drainage ditch based on water level measurements taken between 2002 and 2003 (Wilcox et al., 2005).



(a)



(b)

Figure 3-1: (a) Location of Sun Prairie field site. (b) Topographic contour map of the septic system and survey area (outlined with a dotted line) overlaid on an aerial photograph at the Savannah Valley subdivision in Sun Prairie, WI. Elevation is in meters above sea level, the contour interval is 0.25 m. Electrical resistivity survey lines, and GPR boreholes are shown on this map. The white boreholes are screened and the black boreholes are sealed (Aerial photograph source: http://dcimap.co.dane.wi.us).

3.2.1 *Geology of site*

The majority of soils in southern Wisconsin, including those at the Savannah Valley subdivision are glacial tills, well-graded soils containing gravel, sand, and clay. Particles range from several centimeters to less than 0.075 mm in size. A stratigraphic column of the soils in the Savannah Valley subdivision based on four monitoring wells drilled in 2006 is shown in Figure 3-2. Soil samples collected while drilling show grain sizes that range from coarse gravels to clayey sands. Sandy dolomite bedrock of the Prairie du Chien geologic group is encountered at depths between 6 and 20 m at the site (Wilcox et al., 2005). Within the study area, bedrock is 6 to 8 m below the surface.

Four monitoring wells were drilled to perform borehole-to-borehole ground penetrating radar (GPR) onsite. The location of these wells is shown in Figure 3-1. Wells 1 and 4 were screened so that water can be sampled and tested for conductivity (related to ionic concentration) and possible contaminants, while wells 2 and 3 are sealed from the ground to prevent infiltration of water and allow borehole-to-borehole GPR surveys to be performed in both water-filled and air-filled environments.

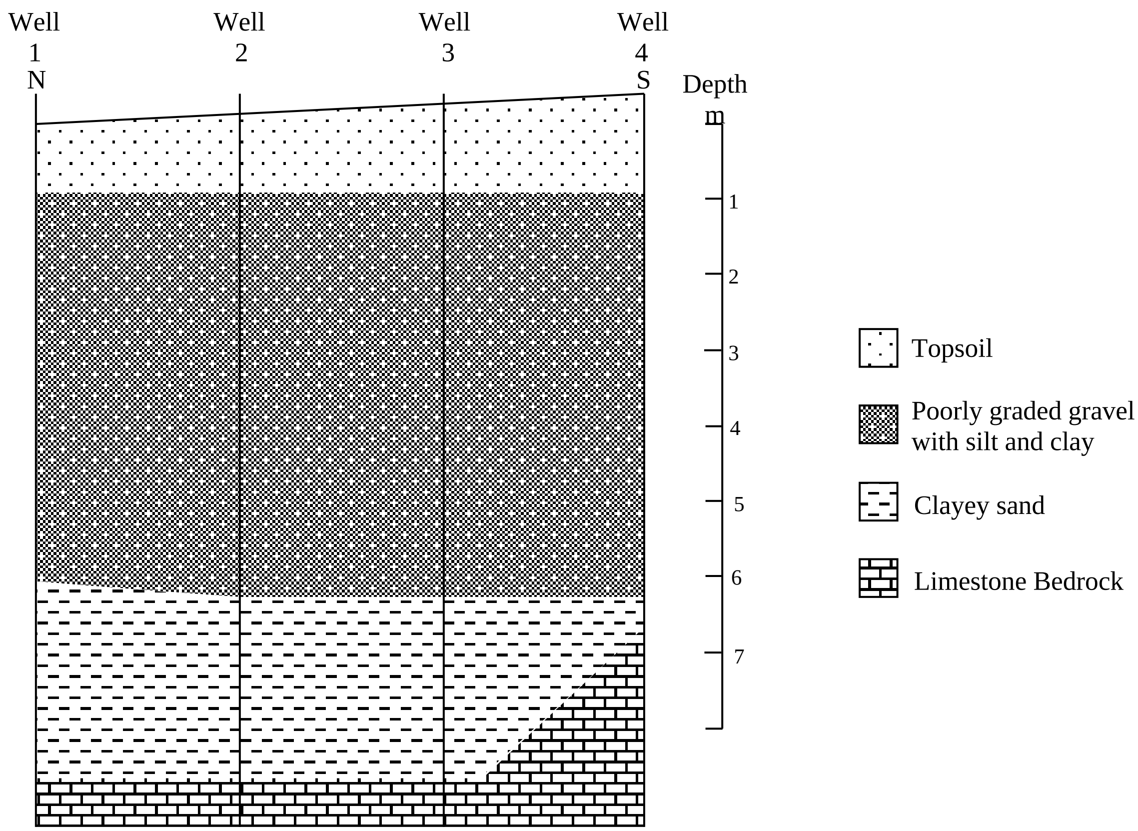


Figure 3-2: Stratigraphic column of subsurface conditions at the Savannah Valley subdivision based on four wells drilled in 2006.

3.2.2 *Hydrogeologic conditions*

A shallow aquifer in the glacial sediment is present at the Sun Prairie filed site. The groundwater in the shallow glacial till aquifer is approximately 4 m below the ground surface but changes seasonally. The subdivision-scale groundwater flow is from west to east with a horizontal flow velocity of 15 to 30 cm/day (Wilcox et al., 2005). On the scale of the single-home considered in this study, the groundwater will flow towards the drainage ditch located at the east side of the property.

Wilcox (2003) showed that the majority of recharge at the site occurs in the spring months and responds rapidly to precipitation, snowmelt, and ground thaw. After the spring recharge, the groundwater level was observed to declines the rest of the year. The decreasing groundwater level that was observed by Wilcox et al. (2005) is consistent with the observed groundwater levels in monitoring wells used for the GPR surveys.

3.3 Geophysical results

3.3.1 *Ground penetrating radar*

3.3.1.1 Zero Offset Profiles (ZOP)

A zero offset profile (ZOP) survey was performed with 100 MHz antennae in water-filled boreholes (#2 and #3) in August of 2006 to determine the quality and preliminary effectiveness of the GPR equipment at the Savannah Valley subdivision. A step size 0.25 m was used for the ZOP survey based on recommendations by the manufacturer to obtain images with sufficient resolution. The 100 MHz antennae were used to obtain a compromise between resolution and signal strength.

The 100 MHz ZOP survey results presented in Figure 3-3(a) shows a large EM wave velocity contrast between 4 and 5 m below the surface corresponding well with the water level measurements of approximately 5 m below the surface in wells 1 and 4. The EM wave velocity shows a sharp drop from about 0.085 m/ns to 0.07 m/ns in the 100 MHz ZOP survey corresponding to the capillary fringe. Based on this change in the velocity, the volumetric water content θ is expected to increase approximately 10 % (Topp’s equation – Topp et al, 1980):

$$\theta = -0.053 + 0.029\kappa' - 5.5\times10^{-4}\kappa'^2 + 4.3\times10^{-6}\kappa'^3 \qquad (3\text{-}1)$$

The 100 MHz antennae yield excellent signal-to-noise ratio signals but have lower resolution than higher frequency antennae. To obtain higher resolution data to be used to generate tomographic images the 200 MHz antennae were also used. The 200 MHz ZOP profile shown in Figure 3-3(b) delineates the capillary fringe and large contrasts in velocity between the unsaturated and saturated zones. These results were consistent with the ZOP results obtained using the 100 MHz antennae.

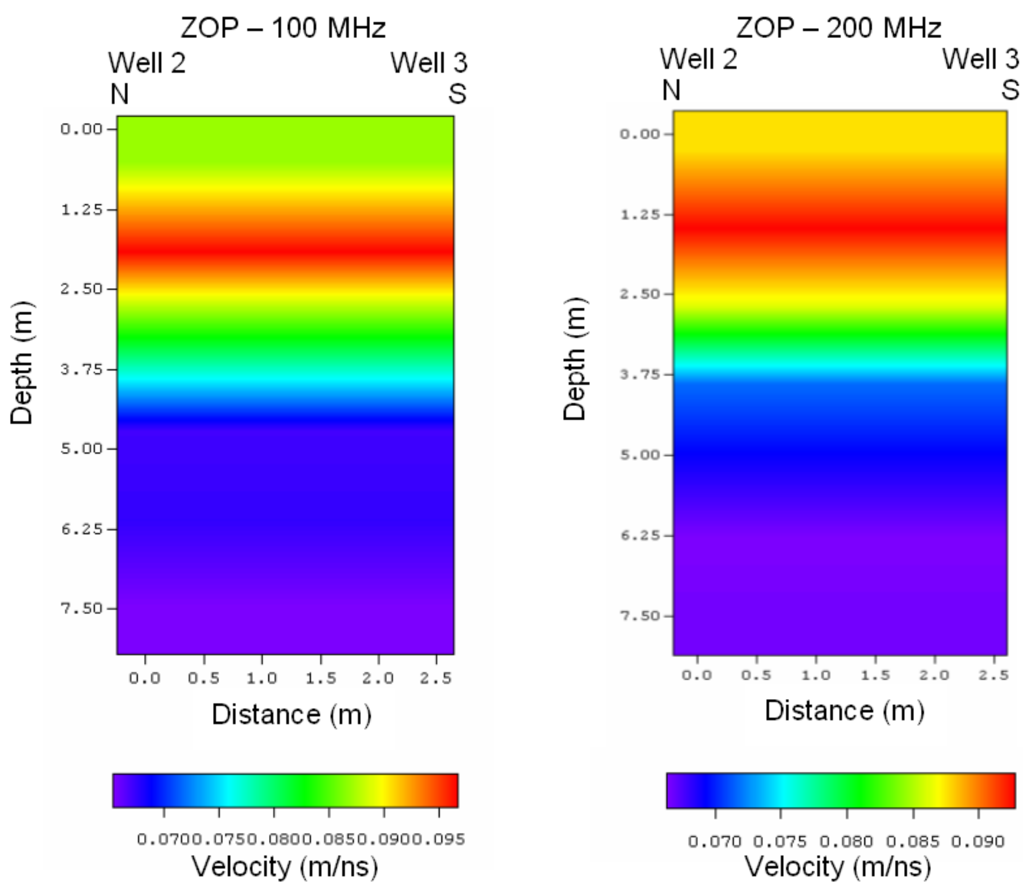


Figure 3-3: Zero-offset profiles between boreholes 2.42 m apart: a) 100 MHz antennae. b) 200 MHz antennae.

Electromagnetic wave velocity changes similar to those shown in Figure 3-3 can also be seen in Figure 3-4, which gives the EM wave velocity versus depth profiles for horizontal rays obtained using the 200 MHz antennae in 2006 and 2007. Figure 3-4 also shows the measured water levels in Borehole 4 during the surveys. Both the 2006 and 2007 surveys show significant variation in EM velocity between 2 and 4 meters depth, below which the wave velocity is approximately constant. The velocity changes correspond well with the observed water level of 3.7 m in Borehole 4 during the October 2007 survey and 5.3 m in August 2006. The 2007 data show that the constant EM wave velocity begins at a depth of approximately 3 m, meaning that the capillary fringe during this survey was 0.7 m thick, providing significantly greater than the 0.9 m of unsaturated soil between the bottom of the leach field and the saturated zone.

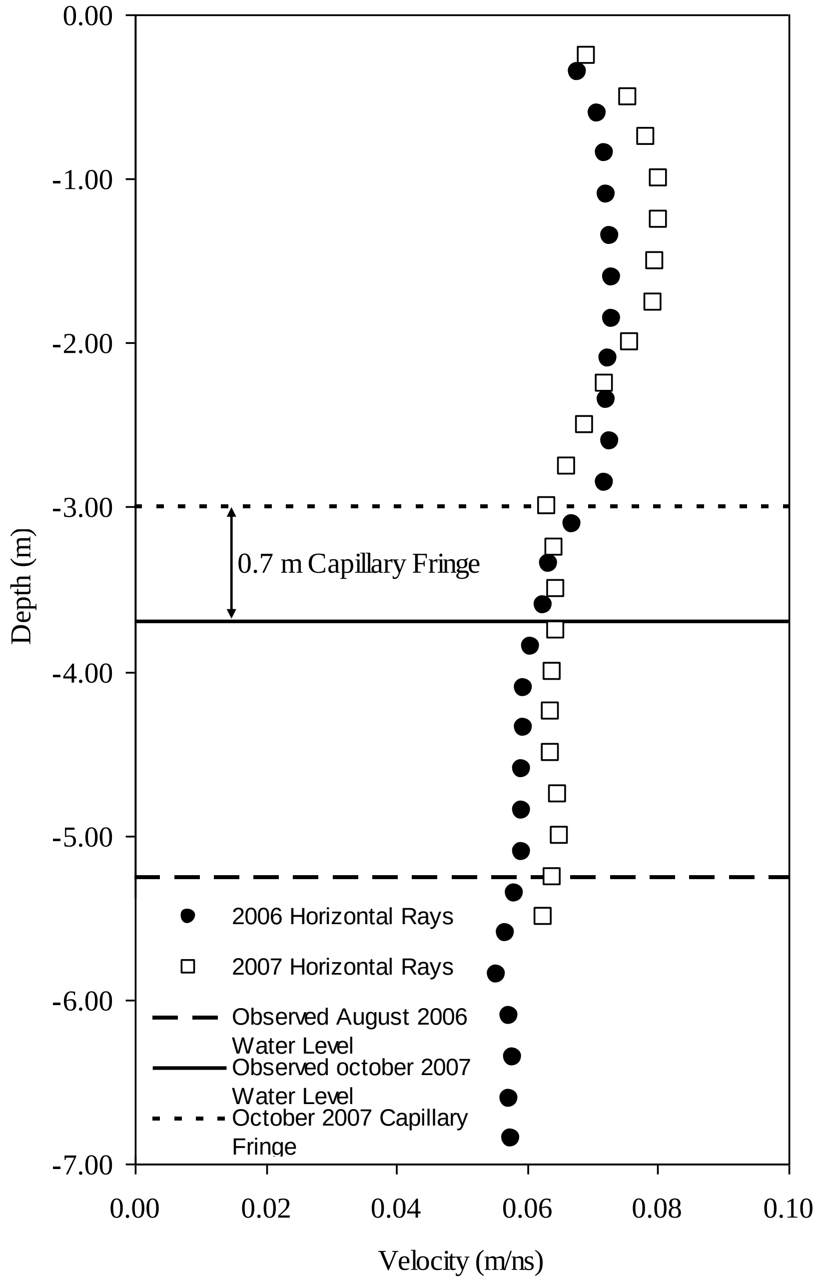


Figure 3-4: Velocity vs. Depth for horizontal rays in 200 MHz cross-borehole GPR survey with measured water levels from well #4.

A zone of high electromagnetic wave velocity is seen in both surveys at approximately 1 to 2 meters depth. This is likely the sand seam shown in the stratigraphic column in Figure 3-2. The 100 MHz and 200 MHZ ZOP profiles in Figure 3-3 show the same high EM wave velocity between 1.25 and 2 m that is seen in Figure 3-4.

3.3.1.2 Multiple Offset Gathers (MOG) Tomography

A multiple offset gather (MOG) was performed with the 100 MHz antennae in August of 2006. The travel-time data were interpreted using the PulseEKKO tomographic inversion software (Sensors & Software, Inc - Mississauga, Canada) and the results are presented in terms of electromagnetic wave velocity distribution in Figure 3-5. As was seen with the ZOP, the water table is at approximately 4.75 meters below ground surface in 2006. The lowest water contents (highest velocities) appear in a horizontal zone of soil at approximately 2 m depth between Wells 2 and 3 consistent with the ZOP surveys and representing the sand seam. The highest water contents (lowest velocities) are between 5 and 7 m depth where saturated soil is adjacent to bedrock. The increase in velocity at a depth of approximately 7 m is interpreted as the transition from soil to bedrock.

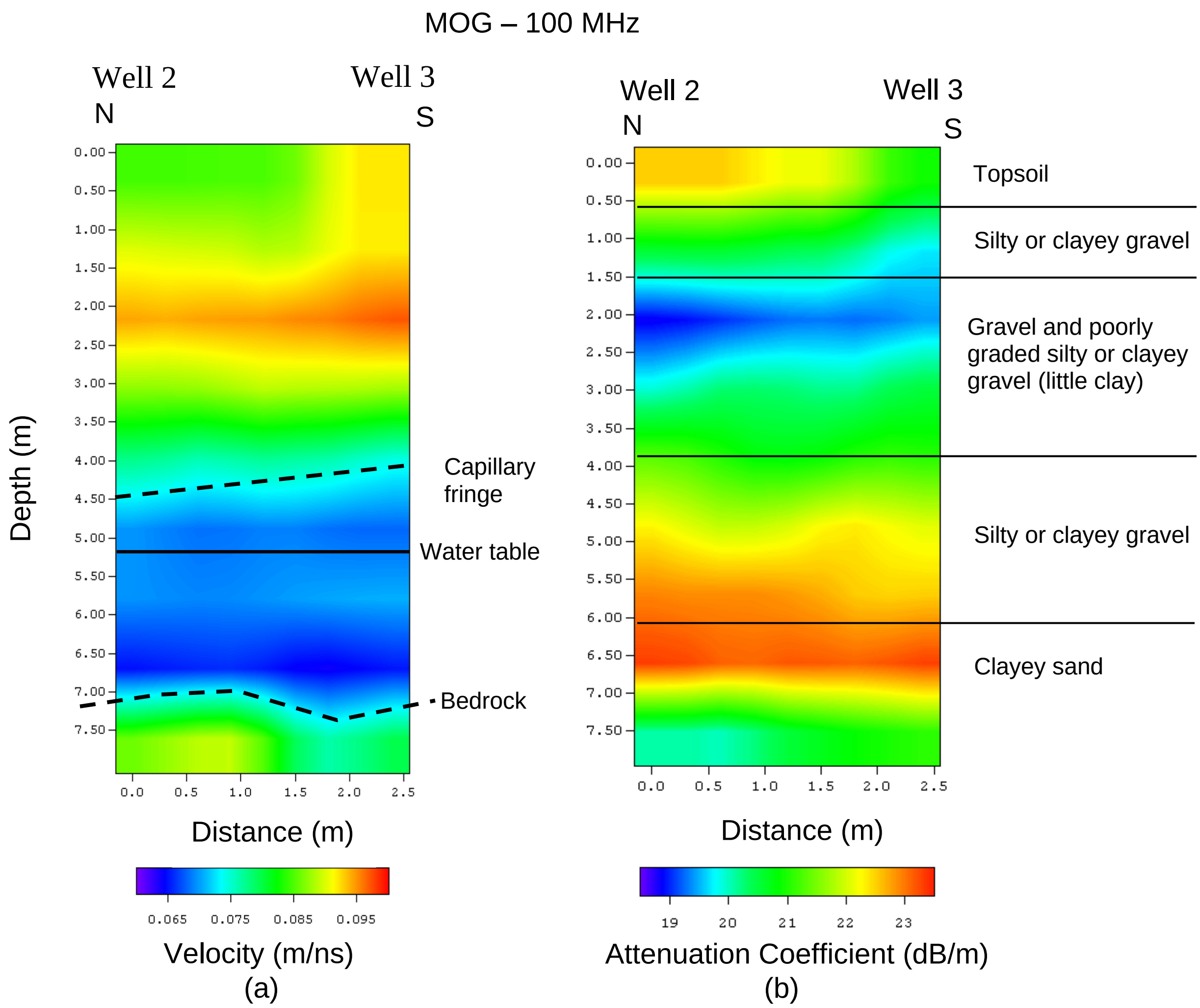


Figure 3-5: GPR tomographic images between boreholes 2 and 3 with 100 MHz antennae: a) electromagnetic wave velocity distribution. b) electromagnetic wave attenuation coefficient distribution. The soil types listed on the right come from soil samples taken while drilling.

The electromagnetic wave amplitude data were interpreted using the PulseEKKO tomographic inversion software and the results are presented in terms of electromagnetic wave attenuation coefficient distribution in Figure 3-5(b). The attenuation of the electromagnetic wave is proportional to the resistivity of subsurface soils and inversely proportional to the dielectric permittivity. The attenuation of a GPR signal is calculated using the attenuation equation shown in Equation 3-2, where ρ is the resistivity, μ is the magnetic permeability, ε is the dielectric permeability of the formation, and ω is the angular frequency (ω=2πf) of the GPR.

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\left(1+\frac{1}{\omega^2\rho^2\varepsilon^2}\right)^{\frac{1}{2}}-1\right]} \tag{3-2}$$

Based on the results of the other geophysical methods, the septic effluent plume does not reach the wells used in the borehole-to-borehole GPR surveys and the attenuation will therefore be controlled by the clay content and the degree of saturation of the soil.

Comparing the GPR data with the soil samples taken from Boreholes 2 and 3 during boring, the areas with lowest attenuation coefficients correspond to areas of increased gravel content and decreased clay content. Below the suspected water table, where soils are saturated, the attenuation coefficient is greater than above the water table. The wave amplitude for horizontal rays is plotted versus depth in Figure 3-6. In this figure, areas of low attenuation coefficient will have high wave amplitudes. Comparing the 2006 amplitude data in Figure 3-6 to the 2006 attenuation coefficient distribution in Figure 3-5(b), the zones of high wave amplitude agree with zones of low attenuation coefficients.

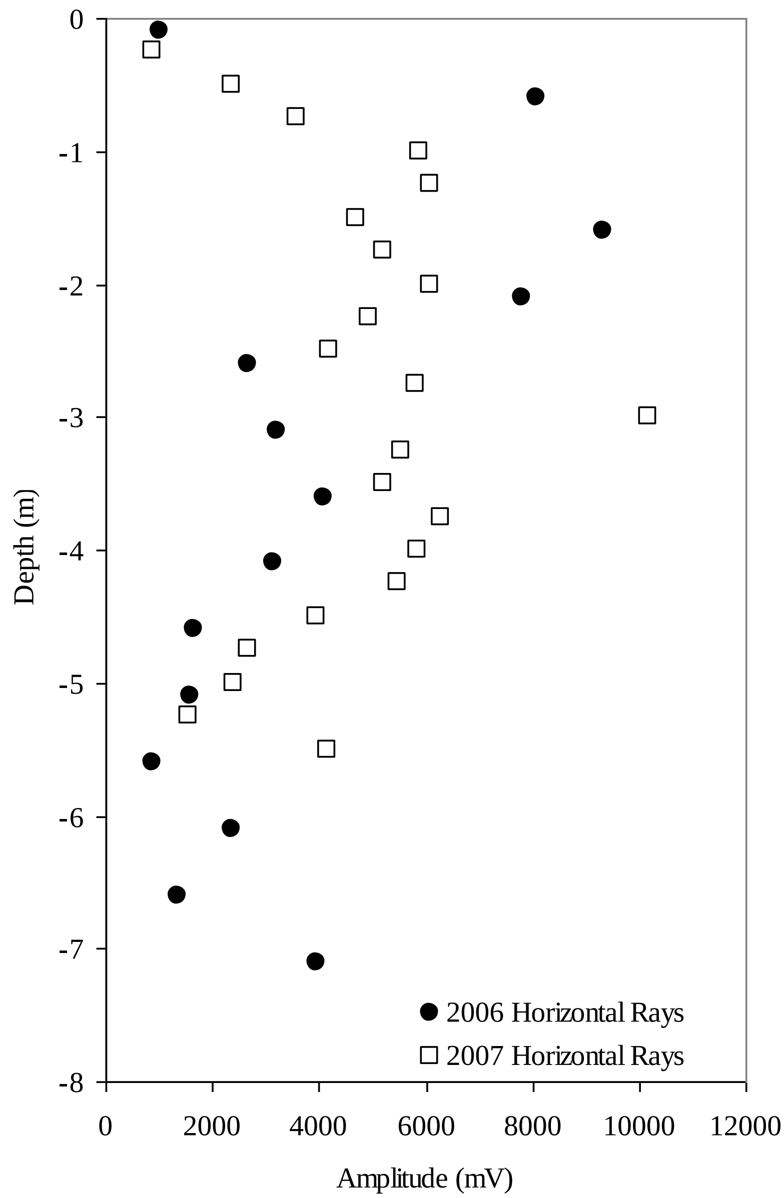


Figure 3-6: GPR ray amplitude plotted vs. depth for horizontal rays from 200 MHz MOG surveys.

In both the 2006 and 2007 surveys, the highest amplitudes (lowest attenuations) occur at approximately 1.75 m depth in Figure 3-6. A depth of 1.75 m corresponds to the zone of high velocity shown in Figure 3-3, Figure 3-4, and Figure 3-5(a) and is the sand seam identified in the geologic section (Figure 3-2). Furthermore, below approximately 4 m the amplitude is smallest and shows less variation. This is the saturated material below the water table. The amplitude increase occurs below 7 m depth in the 2006 survey and likely corresponds to bedrock (i.e., a sharp change in the obtained profiles).

Additional GPR surveys were performed using the 200 MHz antennae, including MOG surveys between Wells 2 and 3 and between Wells 3 and 4 in August of 2006 and between Wells 3 and 4 in October 2007. The MOG survey results from 2006 are presented in Figure 3-7. A velocity contrast occurs at the capillary fringe where the velocity decreases from about 0.10 to 0.08 m/ns. There appears to be some heterogeneity in soils in the vadose zone with velocities varying between 0.09 and 0.12 m/ns. An apparent rise in the capillary fringe near Well 3 is consistent with the 100 MHz MOG profile (Figure 3-5a). Below the water table, several relatively high velocity zones can be seen between Wells 3 and 4. Zones of higher velocity in the region around well 4 may be caused by decreases in the degree of saturation or clay content or by the presence of boulders commonly found in glacial tills.

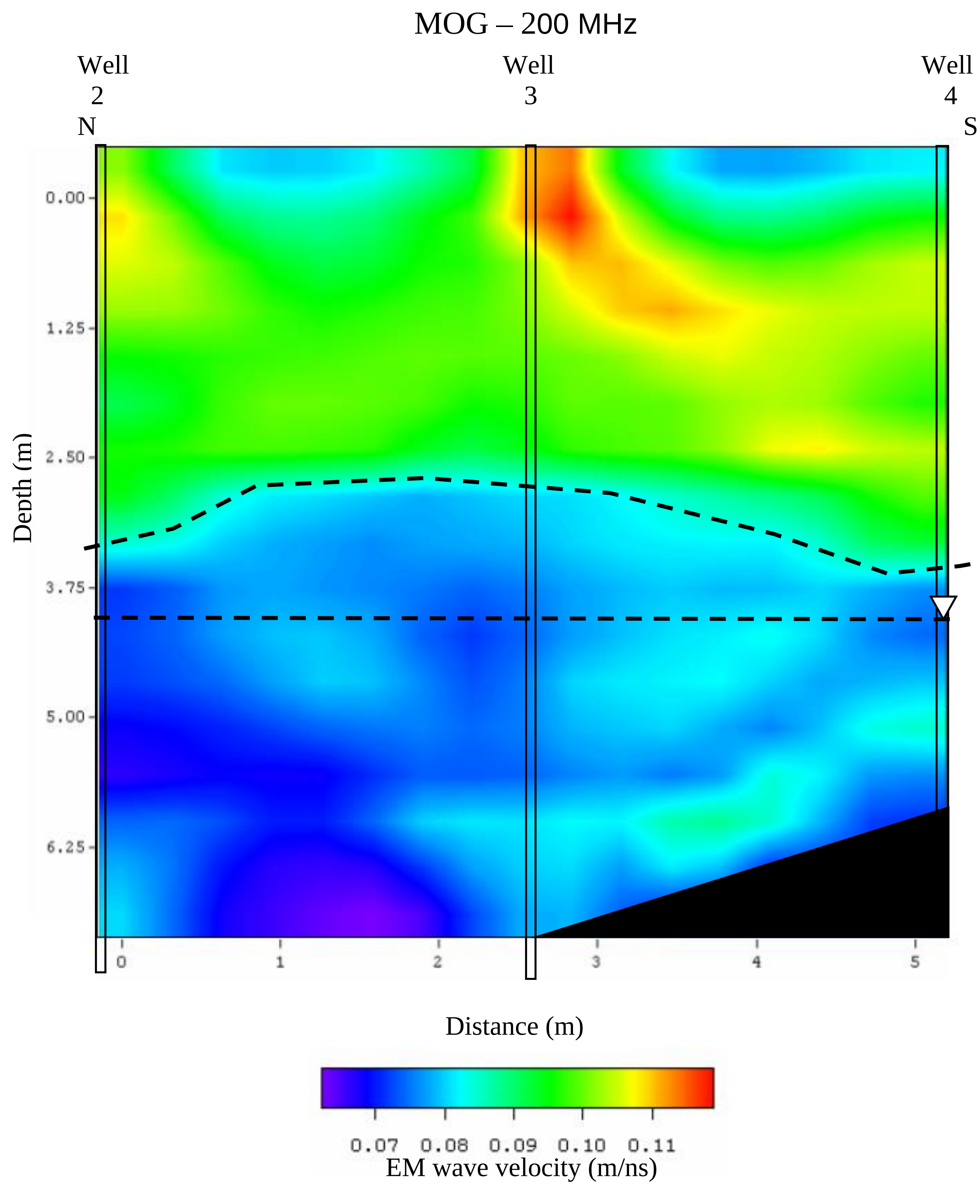


Figure 3-7: Tomographic image of velocity between boreholes 2, 3, and 4 with an antenna frequency of 200 MHz.

The results of the 2007 GPR survey are shown in Figure 3-8. This survey shows an area of high velocity near the top of Borehole 3, similar to that seen in the 2006 survey (Figure 3-7). There is also a region of higher velocity near Borehole 4 between 5 m and 6 m below the surface. This may be a boulder or an artifact caused by the bottom of the borehole and limited data at this point. The water table is between 3.5 and 3.75 m below the surface of

Borehole 4, consistent with the measured depth to water of 3.68 m, but significantly higher than the measured water level of 5.0 m in August 2006. As in the 2006 survey, the water table is slightly lower in Borehole 4 than near Borehole 3.

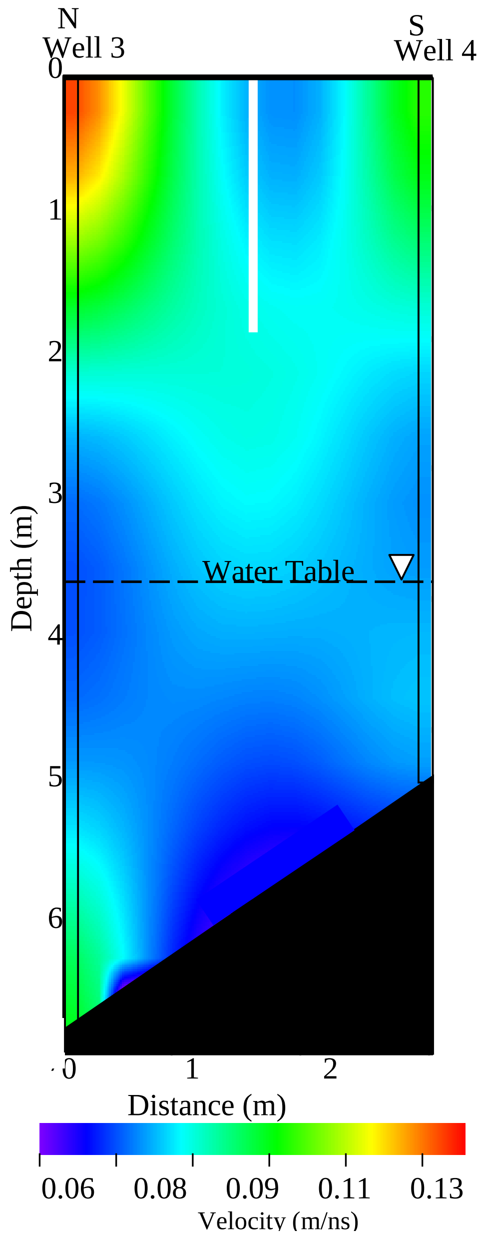


Figure 3-8: Tomographic image between wells #3 and 4 using 200 MHz multiple offset gathers from October 2007.

Water table measurements were compared between Wells 1 and 4 after the 200 MHz surveys were performed. The water level in Wells 1 and 4 at the end of December 2006 were 4.6 m and 5 m from the top of each well casing respectively. Considering the difference in elevation between the top of casing of Wells 1 and 4 of approximately 0.3 m, the water elevation in Well 4 is about 0.1 m lower than in Well 1. In 2007, the water table was measured at 3.3 m and 3.7 below the ground surface of Wells 1 and 4 respectively. This means that the groundwater level was 1.3 m higher in October 2007 than December 2006. Figure 3-9 shows that August 2007 was the wettest month at the site during the period of January 2001 to May 2009, receiving approximately 380 mm (15 inches) of precipitation.

Measured groundwater levels were compared to the precipitation records for the site. Since, no records exist for the exact site, precipitation was calculated using the U.S National Weather Service distance weighting approach using the four nearest weather stations; Arlington University Farms, Dane County Regional Airport (Madison, WI), Lake Mills, WI, and Watertown, WI (Linsley et al., 1958). Monthly precipitation totals were calculated for the Savannah Valley subdivision from January 2001 to December 2008 using the weighting factors calculated for the site by Wilcox (2003) shown in Table 3-1. Monthly and historical average precipitation data were obtained from the National Climatic Data Center for the period from 2006 to 2009.

Table 3-1: Weighting factors used to calculate monthly precipitation at the Savannah Valley subdivision using the U.S. National Weather Service distance-weighting method.

Station	Weight Factor
Arlington University Farms	0.233
Lake Mills, WI	0.268
Dane County Regional Airport-Madison, WI	0.396
Watertown, WI	0.103

Figure 3-9 shows that August 2007 was the wettest month at the site during the period of January 2001 to December 2008, receiving approximately 380 mm (15 inches) of precipitation.

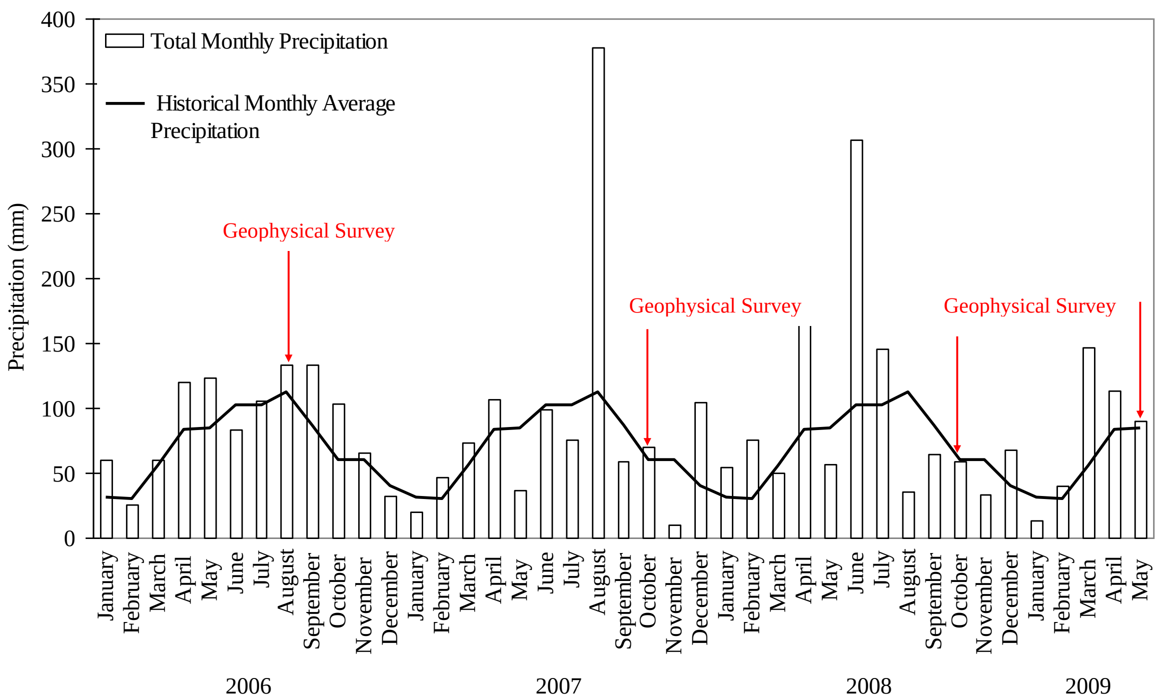


Figure 3-9: Monthly precipitation for Savannah Valley subdivision from January 2006 to December 2008 calculated using U.S. National Weather Service distance-weighting method of precipitation records for 4 nearest weather stations.

Wilcox et al. (2005) observed that the shallow aquifer at the Savannah Valley responds quickly to precipitation and that the water level typically drops as the year progresses. Between June 2002 and April 2003, Wilcox (2003) measured a groundwater level drop of approximately 0.9 m (3 ft) in a shallow well near the test area for this study. A single large precipitation event of 2.84 cm in early June 2002 also corresponded to a rise in the groundwater level of 24 cm in a well in the Savannah Valley subdivision (Wilcox, 2003). The combination of the 2007 survey being performed earlier in the summer and the unusually high rainfall prior to the 2007 GPR survey explain the higher water table seen in the water level measurements and GPR results from October 2007.

3.3.2 *Capacitive-coupled electrical resistivity*

3.3.2.1 OhmMapper survey descriptions and goals

Electrical resistivity surveys performed using the Geometrics OhmMapper provided additional electrochemical information about the shallow subsurface of the Savannah Valley subdivision near the septic mound. Surveys were performed in August of 2006, October of 2007, October 2008, and May 2009 by walking survey lines parallel to the mound in both directions for each dipole separation. The quality of the data was greatly improved by performing surveys in both directions along each survey line in the 2007, 2008 and 2009 surveys. The OhmMapper data were then inverted using the GeoTomo Res3Dinv inversion software to generate 3-dimensional profiles of electrical resistivity (GeoTomo, 2008). These profiles were used to map and monitor changes in the effluent plume from the septic mound.

The purpose of the electrical resistivity surveys was to map the effluent plume from the septic mound. At the depth of interest in this study, the formation resistivity is controlled by the resistivity of the pore fluid, porosity, and the surface conduction of clay minerals. It is expected that the septic effluent will have a higher ionic concentration than the natural groundwater, resulting in a decreased measured resistivity in the effluent plume.

3.3.2.2 3D inversion results

The inverted results of the electrical resistivity surveys using the OhmMapper are shown in Figure 3-10. The figures show horizontal slices of resistivity at different depths. The results of the August 2006 survey are shown in Figure 3-10(a). The main body of the plume, shown in blue, is located between 25 and 60 m along the survey line at the base of the mound. The plume is not evenly distributed along the length of the septic mound, with the majority of the effluent coming out of the southern half of the septic mound. Another conductive (less resistive) zone extends from the south end of the septic mound to the southeast. This zone is separated from the main plume by a higher resistivity zone approximately 5 m thick from 20 to 25 m. A smaller portion of the plume is located north of the mound at approximately 70 m along the survey line at the north end of the mound. The effluent plume is located in the upper 1 m of the subsurface. Below a depth of approximately 2 m, there is a high resistive zone that extends from about 30 to 70 m. This zone may be a clay layer, with high resistivity resulting from the decreased hydraulic conductivity, or other zone of low hydraulic conductivity and may be responsible for the split that is seen in the septic effluent plume from the mound.

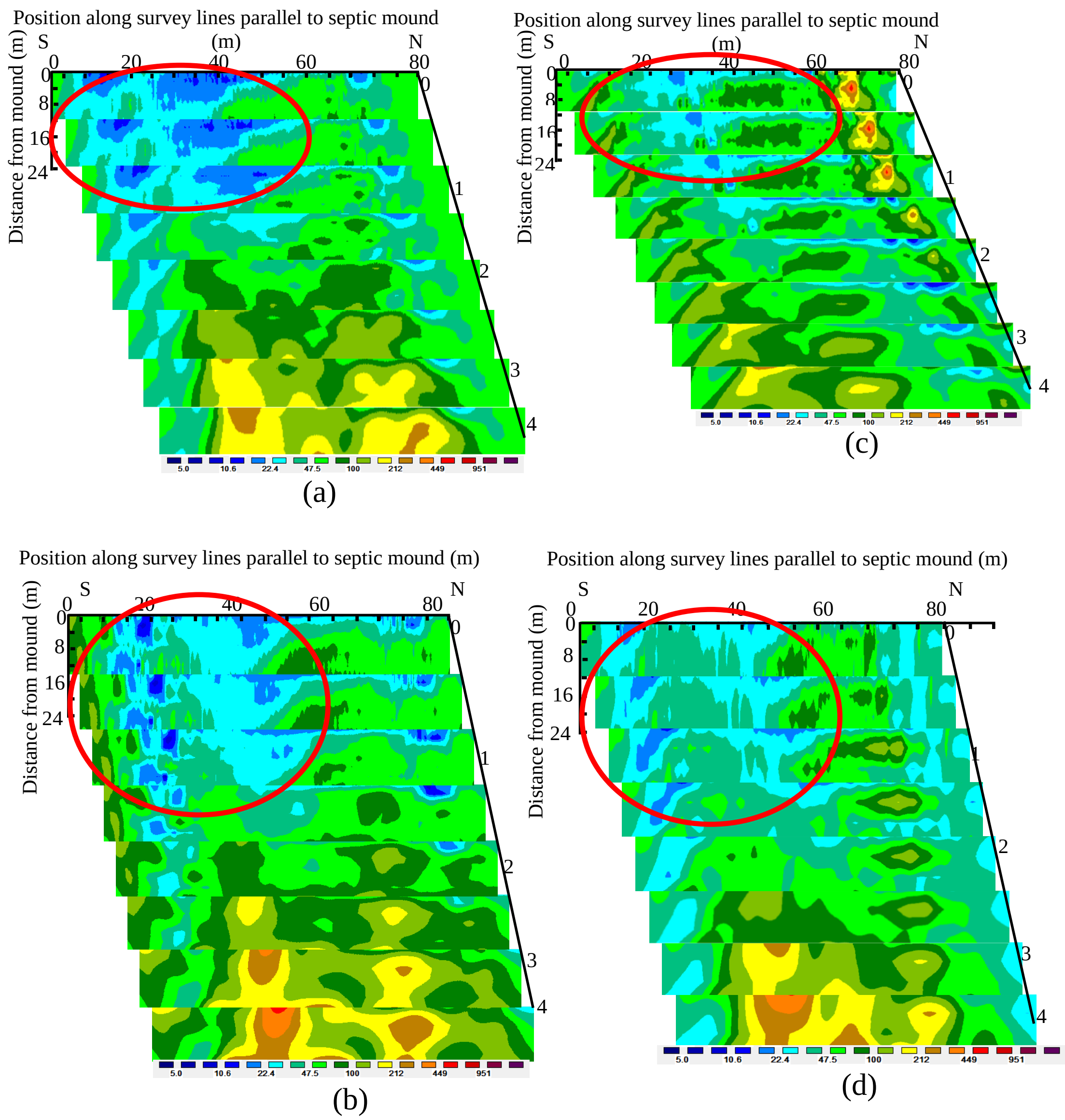


Figure 3-10: Inverted electrical resistivity depth slices at Sun Prairie field site from (a) August 2006 (b) October 2007 (c) October 2008 and (d) May 2009. Septic mound located between 20 and 80 m with base along horizontal axis in figure.

The surveys from October 2007, October 2008, and May 2009 shown in Figure 3-10 (b), (c), and (d) respectively show images of the septic effluent plume that is consistent with that from August 2006. The zones of low resistivity can still be seen at the two ends of the mound, especially the southern end. The high resistivity body located in the center of the survey area is present and has consistent measured resistivity values. These results suggest that the plume is still not evenly distributed along the mound with the majority of the effluent flowing from the southern half of the mound.

Prior to the construction of the Savannah Valley subdivision a number of groundwater samples were collected as part of the research by Wilcox et al. (2005). As part of the geochemical analysis, the conductivity of the samples was measured. Using these measurements of fluid resistivity and Archie's law (Archie, 1941) the background formation electrical resistivity that would be measured using capacitive-coupled electrical resistivity method was conservatively estimated to be approximately 30 Ωm. In all cases, what was interpreted as the septic effluent plume had measured resistivity well below this level, showing that the pore fluid is more conductive near the septic mound than it was prior to construction of the subdivision.

Comparing the different surveys shown in Figure 3-10, the general shape and location of the plume remains approximately constant, but there is some change in both the size and concentration of the effluent. At the Savannah Valley subdivision, 2006 and especially the months prior to the August survey, was drier than average. However, 2007 was significantly wetter than average and prior to the October survey there was especially high precipitation shown in Figure 3-9. This means that less freshwater was entering the shallow aquifer to dilute the plume in 2006, which is why the plume in 2006 is both larger and more concentrated than was observed in 2007. There was less precipitation prior to the 2008 survey than the 2007 survey, which can explains why the 2008 survey shows a larger plume than 2007. Finally, the May 2009 survey again shows a less concentrated plume, which shows that the septic system is working properly by releasing contaminants that slowly dissipate in the subsurface. The May 2009 survey was performed after two wetter than average months and not long after the aquifer received significant recharge due to snowmelt and ground thaw. The effect of this recharge would be to dilute the plume as is seen in the 2009 survey. However, in all of the OhmMapper surveys there is a zone of low attenuation south of the mound where high concentration effluent is moving rapidly away from the septic mound. This effluent is not being attenuated as much as the rest of the plume and poses a risk to down gradient groundwater and wells due to the distance it has travelled without significant attenuation.

3.3.3 *Self-Potential*

The self-potential results from October 2008 and May 2009 are shown in Figure 3-11. The septic effluent plume will have approximately the same potential as the septic mound because the ionic concentration of the two should be approximately equal. By placing the fixed electrode at the center of the mound, the plume will have measured self-potentials of approximately zero because the difference in potential between the two electrodes will be approximately zero.

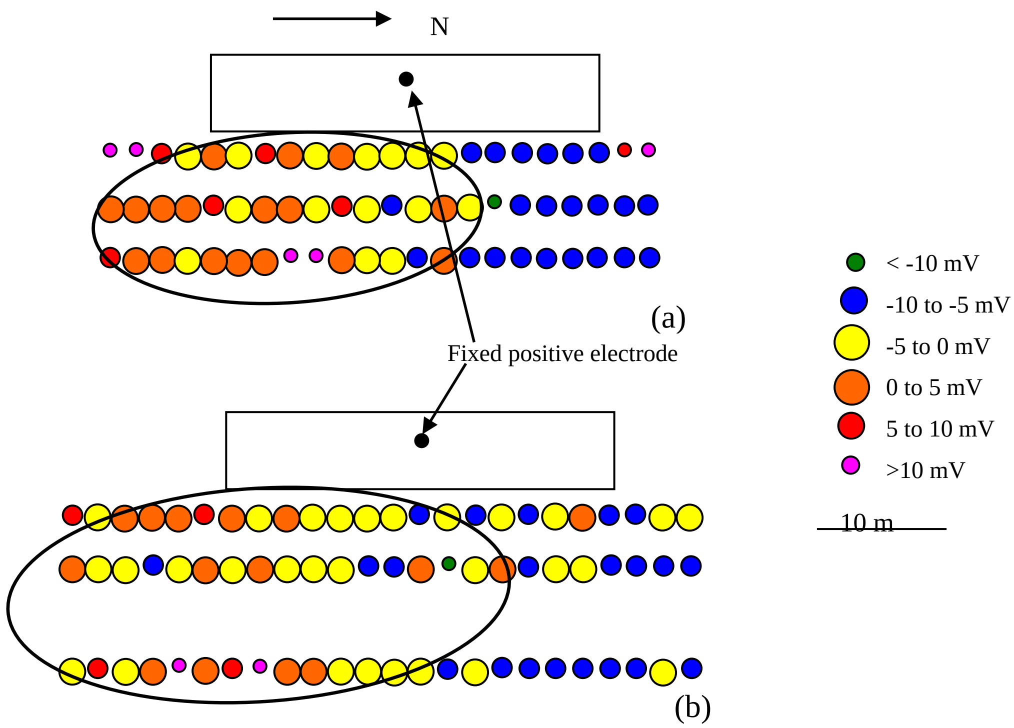


Figure 3-11: Self-potential measurements from Savannah Valley subdivision septic mound from (a) October 31, 2008 and (b) May 8, 2009.

SP surveys were performed along the same lines as the electrical resistivity surveys with measurements taken every two meters. Performing the survey in this manner allows the plume to be identified quickly; it does not, however, allow for high resolution near the edges of the plume. For this reason self-potential is a good method for identifying the effluent plume but not for defining its edges.

The October 2008 SP survey shown in Figure 3-11(a) shows that the effluent plume is located along the southern half of the septic mound. This location is consistent with all of the electrical resistivity results shown in Figure 3-10. The May 2009 survey in Figure 3-11(b) also shows that the plume is located at the southern half of the mound. The May survey appears to show a more even distribution of effluent at the base of the mound than in

October, but far from the mound the distribution is again located along the southern half of the septic mound.

3.4 Lessons Learned

Borehole to borehole GPR, 3D electrical resistivity tomography, and SP were used to image and monitor the effluent plume of a single-home septic system that receives continuous dosing. GPR was used in 4 wells at the site to image heterogeneities and water content distributions in the subsurface. Electrical resistivity and SP were used to identify and image the effluent plume near the septic mound. The combination of geophysical results was used to evaluate the performance of the septic system and the potential fate of contaminants within the effluent. The geophysical evaluation of the septic plume showed that:

- Effluent is being discharged from only about 50% of the mound area. The implication of this is that soil is receiving double the contaminant load than it was designed to.
- The concentration of the plume, especially in the near surface is heavily impacted by the precipitation and groundwater recharge at the site.
- High hydraulic conductivity heterogeneities are playing a dominant role in movement of effluent. The manifestation of this is the high concentration effluent “arm” on the south side of the mound.
- The high concentration effluent moving away from the plume quickly provides the potential for greater contamination down gradient than was designed for based on the average hydraulic conductivity of the site.

- The effluent plume is growing. Over the course of the study, the shape of the plume is very consistent. However, the plume was observed to extend farther down gradient and deeper as time progressed.

Chapter 4 Case Study: Collins Lake Park

4.1 Introduction

Using several geophysical methods and groundwater monitoring the performance of the septic mound at Collins Lake County Park was monitored over the course of the park's 2008 operating season (May 15-September 30) and prior to the park opening for the 2009 season. The park is adjacent to the 42-acre Collins Lake in Portage County, Wisconsin and concerns exist that a proposed increase in usage may negatively affect the small lake. At the site, all research was performed near the septic mound that services the park and campground. The septic mound is located approximately 45 m Collins Lake and there is concern nutrients from the system may reach the lake.

4.1.1 *Contaminants of concern*

Due to the close proximity of the SAS system to the lake, the principal constituents of concern for contamination are phosphate (PO_4^{3-}) and nitrate (NO_3^- - Harman et al., 1996). Nitrogen and phosphorus that discharge to surface waters, either directly or through groundwater flows, can cause algal blooms leading to eutrophication and low dissolved oxygen levels in lakes (USEPA, 2002). Of broader concern for all SAS effluent, repeated exposure to nitrate in groundwater has been linked to methemoglobinemia in infants ("blue baby syndrome" – Harman et al., 1996). Studies have also shown that near-by septic tanks are sources of phosphorus in lakes (Harman et al., 1996). Furthermore, common phosphorus concentrations of septic effluent (~5 to 20 mg/L) are significantly higher than those shown to promote algal growth (i.e. 0.03 mg/L - Robertson et al., 1998).

Phosphorus is a highly reactive constituent and is strongly adsorbed by most sediments (Robertson et al., 1998). Due to the potential for sorption, phosphorus is often attenuated over short distances (Harman et al., 1996). The study by Robertson et al. (1998) showed that a large percentage of the phosphorus mass (25 to 99%) will initially be removed in the first 1 to 2 m of flow from the septic system, typically within the unsaturated zone. However, the phosphorus not retained in this zone will be retarded by sorption but can remain mobile and has the potential to impact down-gradient water bodies (Robertson, 2008). Robertson and Harman (1999) showed that phosphorus plumes in decommissioned sites did not decrease in size or concentration, showing that removal of phosphorus is reversible and that almost all of the phosphorus mass is ultimately mobile in the subsurface. It was further determined by Robertson (2008) that the 20 m setback typical in most areas is insufficient for phosphorus attenuation alone to remove phosphorus in the groundwater.

4.1.2 *Site specific goals*

Using several geophysical methods, the effluent plume was monitored. The methods used were DC electrical resistivity, capacitive-coupled resistivity, self-potential, and electromagnetic induction. Ground penetrating radar was attempted but did not show a contrast between the septic effluent and surrounding area. All methods were used to observe changes in the bulk resistivity of the soil. A less resistive (more conductive) soil is associated with higher ionic concentrations below the water table and is indicative of the effluent plume of a septic system. In addition, self-potential was used to determine the groundwater flow direction at the site and to detect changes in groundwater chemistry.

Throughout the 2008 summer a total of 7 surveys were performed in which DC resistivity surveys were performed with at least one of the other methods. These surveys were typically performed before and after high usage weekends. The final survey of the season was performed in October 2008, after the park was closed using all of the geophysical methods. The October survey was supplemented by Geoprobe™ sampling in which soil and groundwater samples were collected and later tested in the lab for conductivity, nitrate concentration, chloride concentration, and total reactive phosphorus. These tests were used to determine the reliability and accuracy of the geophysical surveys.

In May 2009, prior to the park opening, another survey was performed using all of the geophysical methods. At this time, groundwater samples were collected and later tested in the laboratory for conductivity, nitrate-nitrogen, and dissolved reactive phosphorus. The objective of the 2009 testing was to evaluate the effect of non-use (October 2008 to May 2009) on the septic effluent plume and to monitor changes associated with groundwater recharge due to snow melt and spring recharge that occurred during this time.

4.2 Site description

The Collins Lake field site for this study is located at Collins Lake County Park in Portage County, Wisconsin near the town of Stevens Point. The location of the site is shown in Figure 4-1 and a base map of the site shown in Figure 4-2. This map is composed of data collected along side the geophysical surveys.

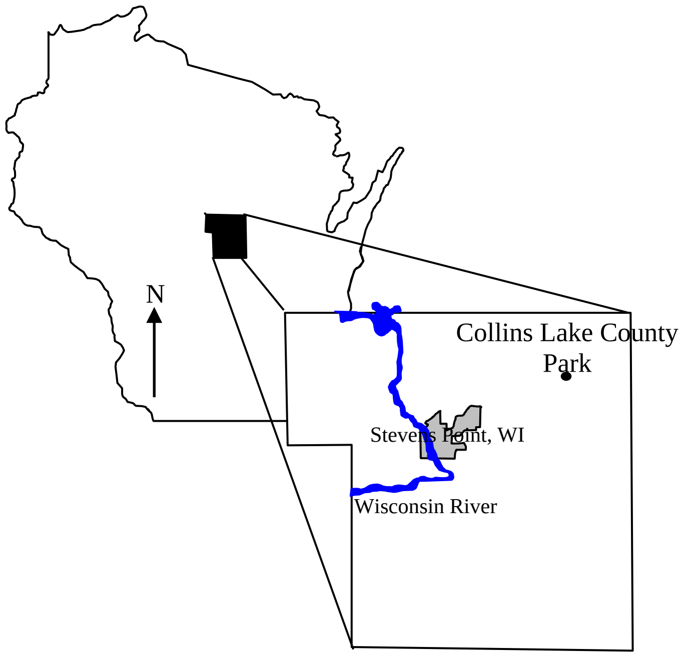


Figure 4-1: Location of Collins Lake County Park field site

Figure 4-2 shows the geophysical survey lines that were repeatedly used throughout the study. It can be seen that the investigation focused on the area immediately surrounding the septic mound. The principal survey line in the study was located 1 m from the base of the mound parallel to the long-axis and southeast of the mound. Additional survey lines parallel to the mound were located approximately 2 m north of the mound and 4 m south of the mound. Geoprobe™ samples were collected along these lines to allow direct comparison of results.

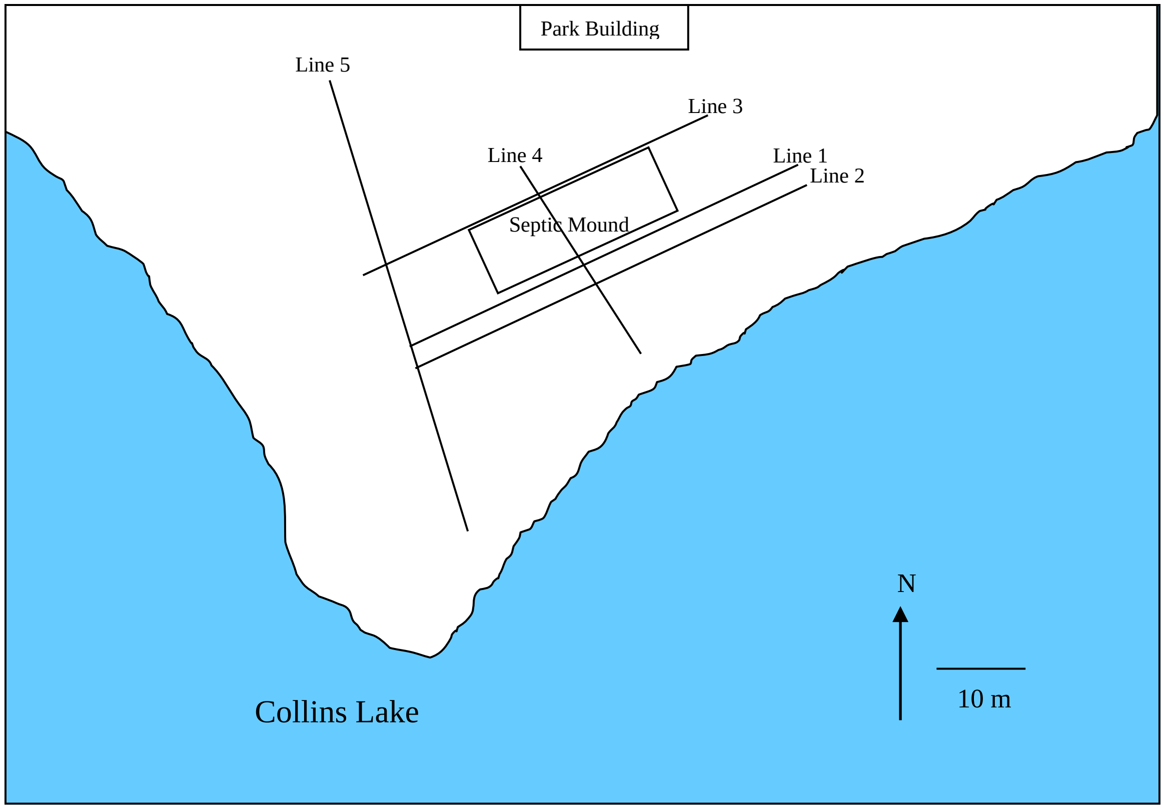


Figure 4-2: Collins Lake base map showing geophysical survey locations. DC resistivity surveys on Line 1. OhmMapper surveys on lines 1, 2, and 5. EM induction surveys on lines 1, 2, 3, and 5. SP surveys on lines 1, 2, 4, 5, and shoreline.

4.2.1 *Geology of the site*

The geology of this region in central Wisconsin is dominated by glacial till, stream, and lake sediment that were deposited by the Arnott and Wisconsin Glaciations during the Pleistocene (Clayton, 1986). Along the northern edge of Collins Lake, where the park is located, the near surface soils are "early-postglacial stream sediment" (Clayton, 1986). These deposits are composed of 10 to 20 m thick sands and slightly gravelly sands that were deposited by non-glacial streams shortly after the Wisconsin Glaciation (approximately 25,000 years ago). Soil samples were collected in 1.22 meter (6 ft) intervals during the

Geoprobe™ investigation in October 2008 southwest of the mound. A representative sample from each interval was tested according to ASTM D6913 to determine a profile of the grain-size distribution. The grain-size distributions for the four depth intervals are shown in Figure 4-3.

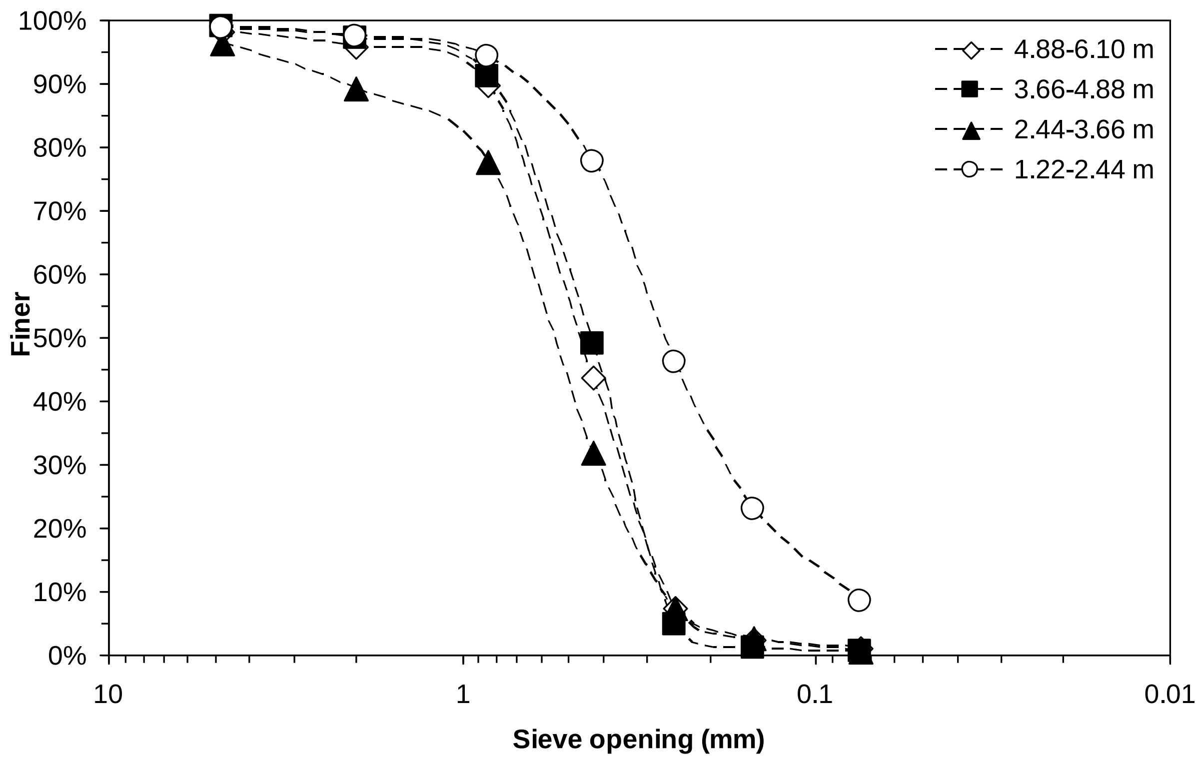


Figure 4-3: Grain size distributions for soil sample taken at Collins Lake County Park using GeoprobeTM 2.54 cm (1”) direct push sampler.

A very thin gravel layer, present at the water table at a depth of approximately 1.5 to 2 meters, is responsible for the higher gravel content in the 1.22 - 2.44 meter interval. The sediment from 2.44 – 3.66 meter is slightly finer grained and below 3.66 m, the soil is uniform coarse sand.

4.2.2 *Hydrogeologic conditions*

During the geophysical surveys a series of topographic points were taken to develop the topographic map shown in Figure 4-4. The 346.5 m contour represents the water level in October 2008 and the 346.75 m contour is the water level in May 2009. All measurements are in meters above sea level with a contour interval of 0.25 m. The septic mound is the high area near the center of the figure and rises roughly 1.5 meters above the surrounding flat area.

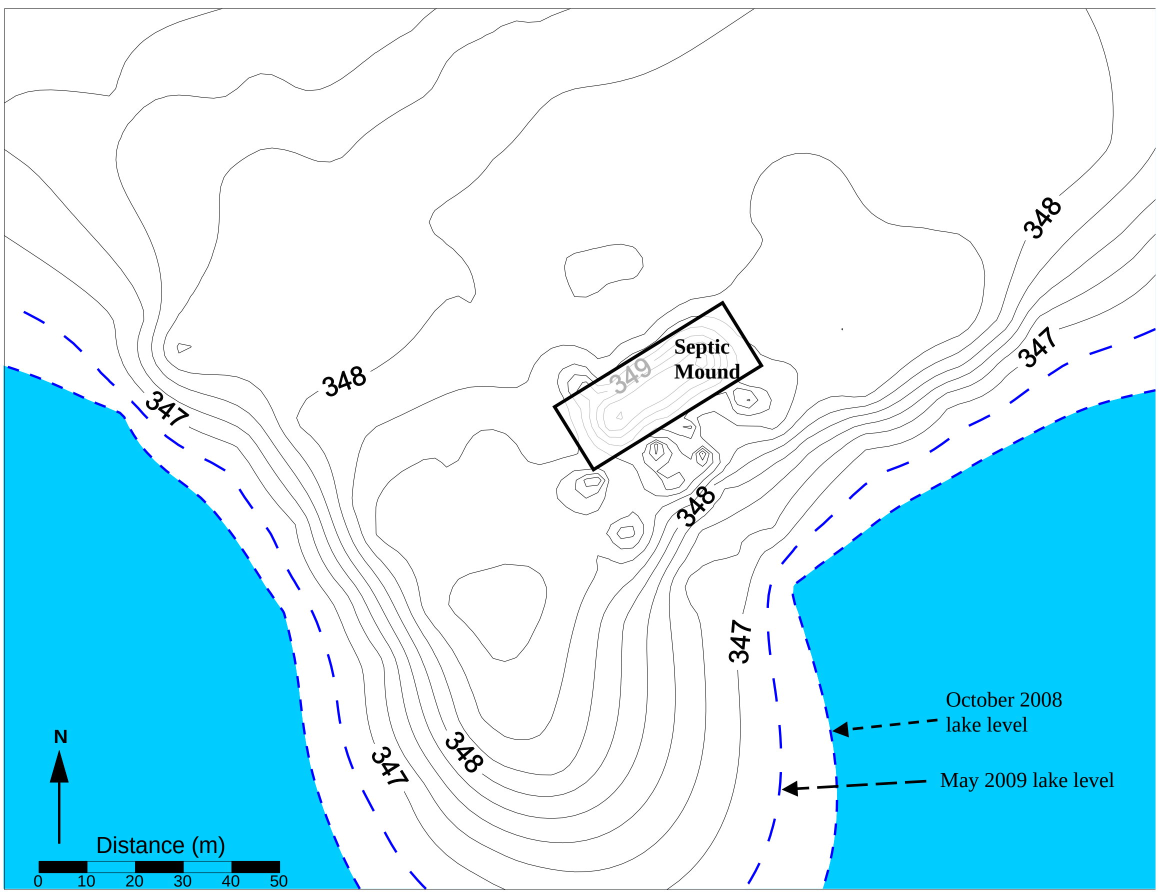


Figure 4-4: Topographic map of Collins Lake Park (All measurements are in meters above sea level with a contour interval of 0.25 m).

A series of slug tests and water level measurements were taken from wells installed into in the abandoned Geoprobe™ wells to better characterize the water table and hydraulic conductivity at the site. The slug tests were analyzed using the Hvorslev method and the results are summarized in Table 4-1. From the nine slug tests, the average hydraulic conductivity at the site is 1.93 x 10^{-4} cm/s. In order to determine the effectiveness of the septic system at Collins Lake County Park, changes in the plume size, location, and concentration were imaged over the duration of the study.

Table 4-1: Summary of slug test results analyzed using the Hvorslev method

Location	Hydraulic Conductivity, K (cm/s)
GPS 1	1.15E-04
GPS 2	1.90E-04
GPS 3	2.05E-04
GPS 4	2.11E-04
GPS 5	5.05E-05
GPS 6	4.70E-04
GPS 7	1.89E-04
GPS 9	1.12E-04
Average	**1.93E-04**

4.3 Geophysical results

The septic system at Collins Lake County Park was installed in 1996. The system has an average daily flow during the park's operating period of 1136 L (300 gal), corresponding to a loading rate of 32.6 L/m^2 per day. A study by Patterson (2003) found that the average electrical conductivity of septic effluent to be approximately 790 μS/cm. Measurements at the Collins Lake site outside of the influence of the septic system had conductivities measured in the lab about 200 to 300 μS/cm, significantly lower than the conductivity of septic effluent.

4.3.1 *DC Electrical resistivity results*

4.3.1.1 Identification of septic plume

The effluent plume from a septic tank is expected to contain higher ionic concentrations than native groundwater. This will be seen in electrical resistivity surveys as a zone of low resistivity (high conductivity). All of the DC electrical resistivity surveys show a similar size and location for the septic effluent plume, between approximately 1.5 to 3 meters depth located at about 24 to 38 meters along the survey line. This places the plume slightly to the southwest of the center of the septic mound, as shown in Figure 4-5 (a) through (g).

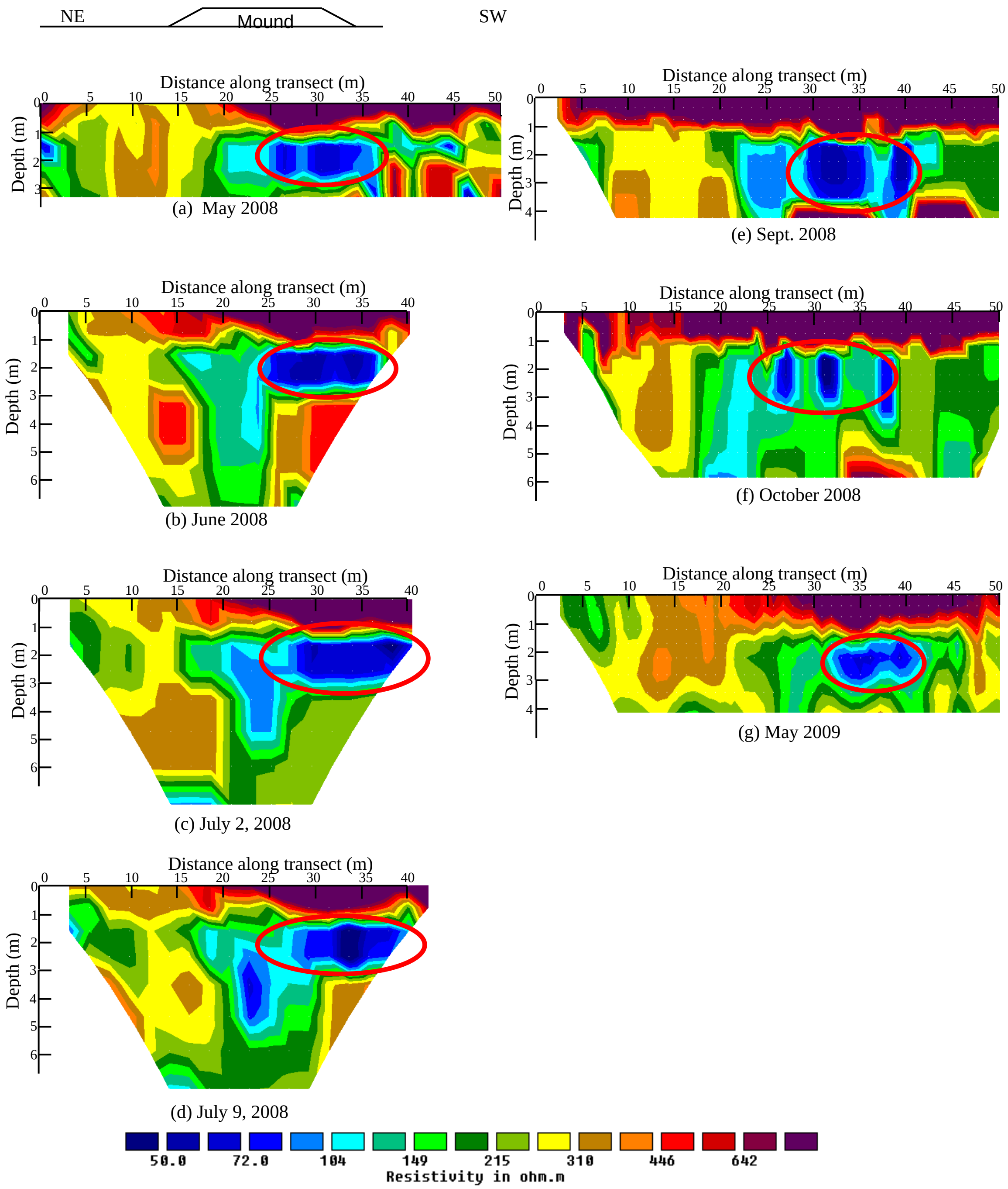


Figure 4-5: DC electrical resistivity inversion sections

4.3.1.2 Temporal changes of effluent plume

During the 2008 summer, the location of the effluent plume remained roughly constant at the southwestern half of the mound; however, its size increased slightly. Prior to testing, it was hypothesized that the plume would expand in the direction of groundwater flow, towards the lake, as more effluent was introduced. However, Figure 4-5 shows little to no change in the lateral size and location of the plume, but rather an increase in its vertical size (thickness). At the beginning of June 2008 the plume extended to a depth of approximately 3 m, by September 2008 this had increased to approximately 3.5 m. This suggests that the lateral groundwater flow is small and there is a slightly vertical flow component. If the lateral flow is negligible, the change in thickness of the plume can be explained by the dispersion of the effluent and vertical flow due to groundwater recharge. Self-potential and mini-piezometer data collected in October 2008 along the shoreline supported the negligible lateral flow assumption, showing either no flow or a slightly vertical flow out of the lake. The flow is believed to change from flow out of the lake to flow into the lake based on the level of the lake and the amount of precipitation that the park receives, a belief supported by water level measurements from May 2009 that showed a slight gradient towards the lake, a change in flow direction from October 2008. The change in the level of the lake can be seen in Figure 4-4.

The concentration of the septic effluent plume and the attenuation of contaminants appear to be dominated by groundwater recharge. The vertical flow of uncontaminated water due to groundwater recharge from snow melt and precipitation will lower the concentration of the effluent plume and develop the vertical flow system that the observations support. In

Wisconsin, there is significant recharge in the spring (just before the park opens) and much less during the summer months. This recharge pattern is the opposite of the loading pattern, meaning that when there is significant loading of the plume, there will be very little recharge but after the plume has stopped receiving effluent significant recharge will occur.

It was expected that there would be a decrease in the resistivity of the plume core as the park was used and the effluent in the plume became more concentrated. During the parks operating period (May through September), the core of the plume became larger and more conductive, showing that the effluent plume is becoming more concentrated as more low resistivity effluent is added. Between September 2008 and October 2008, the resistivity increased and the thickness of the plume increased. This corresponds to the closing of the park and thus the end of effluent introduction. The change in the effluent plume between these surveys is likely caused by the dilution of the plume due to groundwater recharge, resulting in a larger but less concentrated plume core.

Figure 4-5 (g) shows electrical resistivity results from May 2009. The plume has continued to decrease in size from October 2008 but has not disappeared completely. There has also been little change in the depths at which the plume is found. This suggests that during the winter and spring the plume will continue to shrink..

It was observed that the resistivity at the surface is high (>700 Ωm) and increased over the summer of 2008. At the depths of interest in this study (and in most engineering applications), electrical resistivity is predominantly controlled by porosity, fluid resistivity, and clay content (Auken et al., 2006; Zonge et al., 2005; Klein and Santamarina, 2003; Tabbagh et al., 2000). Collins Lake State Park is underlain almost exclusively by sand and at shallow depths there is little variation in porosity. Therefore, changes in bulk resistivity will be controlled by changes in the fluid resistivity. The very high resistivity values near the surface are likely due to unsaturated conditions; dry sandy soils have electrical resistivity that ranges from 80-1050 Ωm while saturated sandy soils have resistivity of approximately 50-100 Ωm (Reynolds, 1997). The increase in size of the unsaturated zone is consistent with the dry conditions in this part of Wisconsin during the summer of 2008.

4.3.2 *OhmMapper results*

4.3.2.1 OhmMapper results

The inverted electrical resistivity profiles from the October 2008 OhmMapper survey are shown in Figure 4-6.

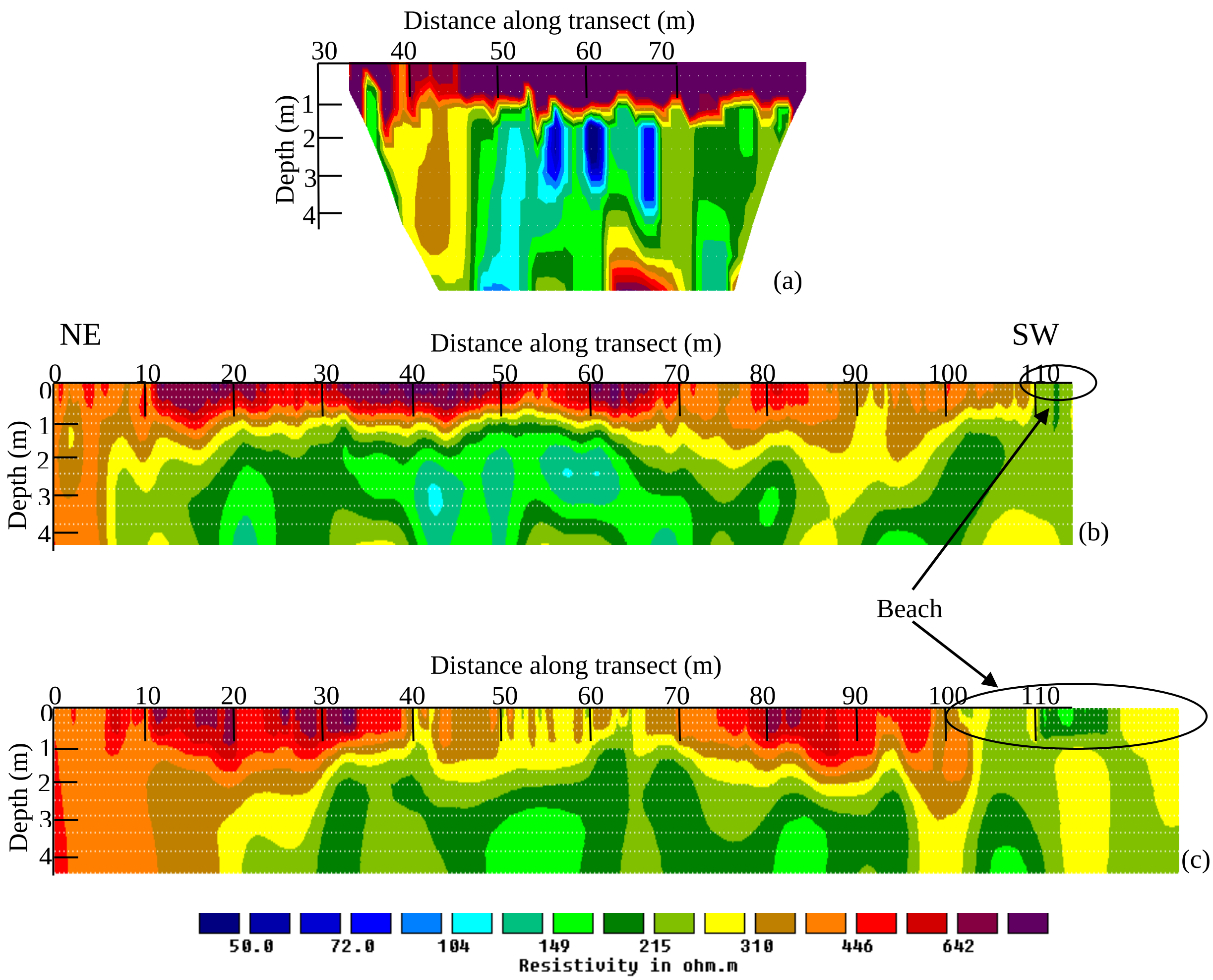


Figure 4-6: October 2008 OhmMapper inversions and comparison to DC resistivity results: (a) Line 4 inverted DC electrical resistivity data, (b) Line 4 inverted OhmMapper data, and (c) Line 6 inverted OhmMapper data

The near surface shows high resistivity caused by the unsaturated zone as was seen in Figure 4-5 for the DC resistivity method. The exception to this is at the southwest end of the survey lines where the lower resistivity zone extends to the surface. This represents the transitioning from the grass of the park to the beach and eventually to saturated sand at the ground surface near the lake. An effluent plume is visible again at approximately 1.5 m below the surface and extending downward to the bottom of the surveyed depth at the southwest half of the septic mound. The plume is not as clear as for the DC electrical resistivity measurements shown in Figure 4-5. The measured resistivity of the soil should not change between the DC method and capacitive-coupled method, the higher resistivity values seen for the capacitive-coupled system cannot yet be explained, and future experiments about the cause of the inconsistency are planned. The study by Allred et al. (2006) also showed higher resistivity using capacitive-coupled resistivity than DC resistivity along the same survey lines.

Figure 4-6 shows that the concentration of the effluent plume decreases with distance from the septic mound. This is shown by the higher inverted resistivity located between approximately 7.5 m and 79.5 m in Line 2 compared to Line 1. The decreased resistivity is due to a decrease in ionic concentration of the groundwater farther from the source. The size of the plume appears to be approximately constant and the change in concentration is likely due to dispersion of the effluent as it spreads away from the center of the plume.

The results of the May 2009 OhmMapper are shown in Figure 4-7. The plume is more identifiable in the 2009 survey than the 2008 survey as the low resistivity zone that is highlighted. As was seen in the 2008 survey, the plume decreases in size with increasing distance from the septic mound. Figure 4-7 shows that in addition to a size decrease, there is also an increase in the resistivity of the plume core, showing a decrease in ionic concentration. Finally, it can be seen that the resistivity near the surface in 2009 (Fig. 4-7) are significantly lower than in 2008 (Fig. 4-6). At the time of the survey in May 2009, conditions at the park were much less dry than in October 2008. This observation is supported by the levels of Collins Lake shown in Figure 4-4, which shows that the measured lake level was approximately 0.25 m higher in May 2009 than it was in October 2008.

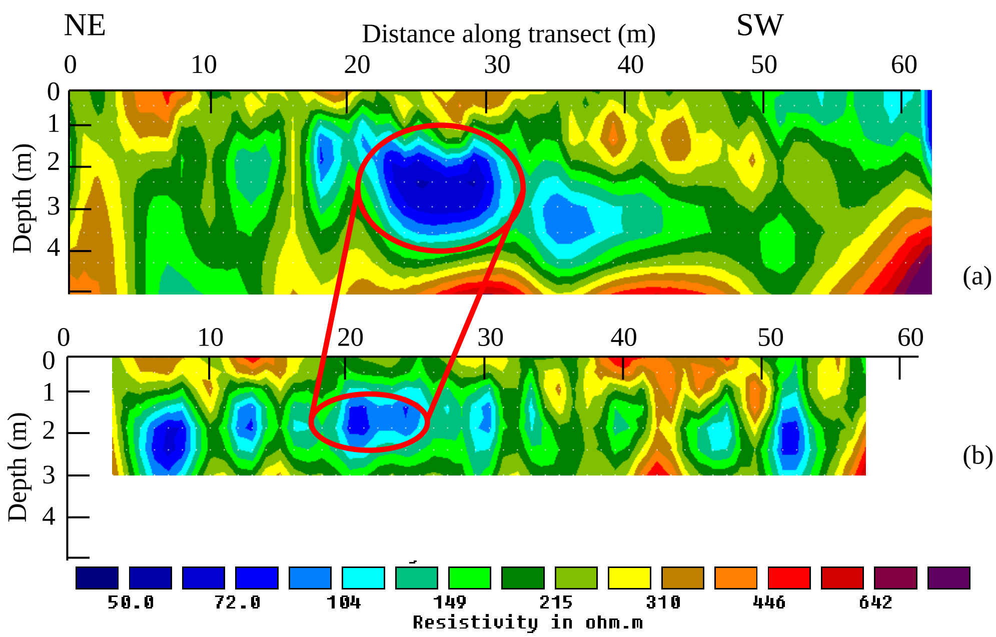


Figure 4-7: Inverted OhmMapper electrical resistivity results from May 2009 along (a) line 1 and (b) line 2

4.3.2.2 Comparison to DC resistivity

Both the DC and capacitive-coupled resistivity methods were used to both identify and track changes in the effluent plume. The capacitive-coupled resistivity (OhmMapper) gave higher magnitude resistivity, but showed the same plume pattern. The easiest method to analyze was the DC resistivity as the DC data were less noisy than the OhmMapper; however, the OhmMapper was significantly faster to use. These methods therefore work well when combined to track changes in a plume associated with septic effluent.

4.3.3 *Frequency Domain Electromagnetic Results*

4.3.3.1 Plume identification

FDEM surveys showed a consistent location and magnitude of the effluent plume as the electrical resistivity methods. A simple two-layer model was developed with the interface between layers assumed to be 1.5 m deep and corresponding to the water table. Figure 4-8 shows the results of this simple model from two survey lines performed in June 2008, one north of the mound (background side) and one south of the mound (plume side). All of the data in Figure 4-8 is for the layer below the water table, as this is where the effluent plume is assumed to exist. This assumption is supported by the results of the DC resistivity and OhmMapper surveys.

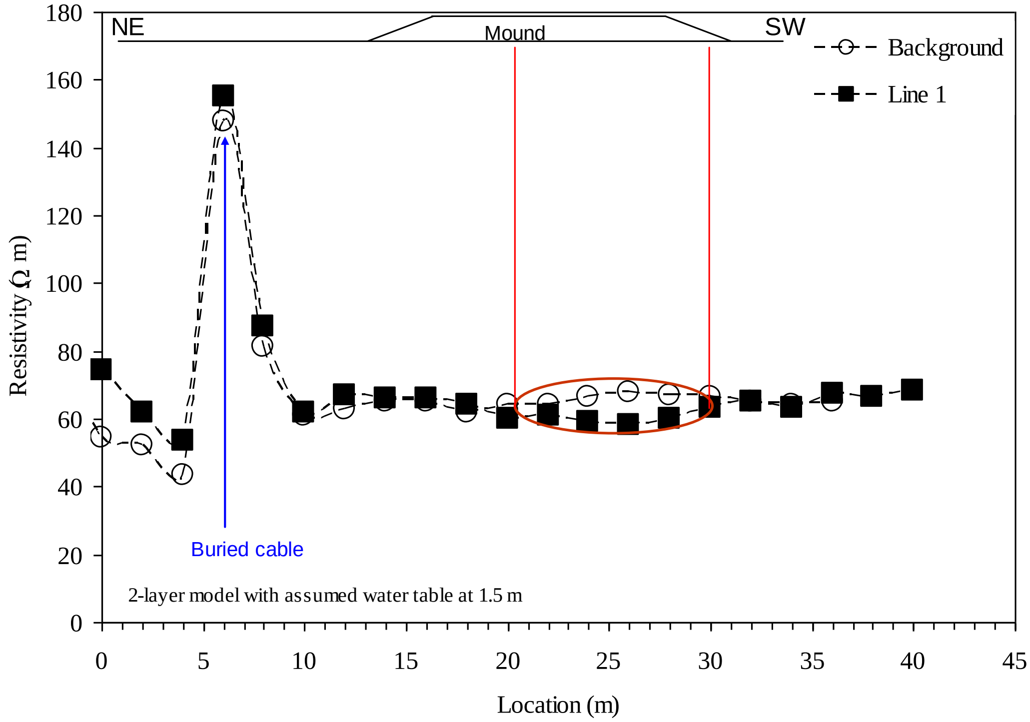


Figure 4-8: Comparison of effluent plume to background electrical resistivity for June 2008 survey using EM31 induction

The large peak at 6 m is an artifact caused by a buried cable that crosses both survey lines. This cable causes the apparent conductivity measurements to go out of range of the equipment; it is only included to show that the survey and background lines are parallel and highlight their agreement. The significance of Figure 4-8 is the extremely good agreement between the two surveys except for the circled region. Here, the line to the south of the septic mound shows a decrease in resistivity of 5 to 10 Ωm. This zone of decreased resistivity extending from approximately 18 m to 32 m represents the septic effluent plume. Again, the plume is located at the southwestern half of the mound as was seen for DC and capacitive-coupled resistivity.

The EM 31 survey was repeated in May 2009 using the same 2-layer model with the background levels measured on the north (up gradient) side of the septic mound. Background levels (Line 3) were compared to measurements taken along the two survey lines 1 and 2 shown in Figure 4-2. In order to compare the measurements taken during this survey better, all of the calculated resistivity values were normalized with respect to the calculated resistivity at 18 m. This location was selected because it was considered to be out of the influence of both the cable and the effluent plume. As was seen in the June 2008 survey, there is region where both lines south of the mound decrease in electrical resistivity, corresponding to the effluent plume. This analysis is shown in Figure 4-9

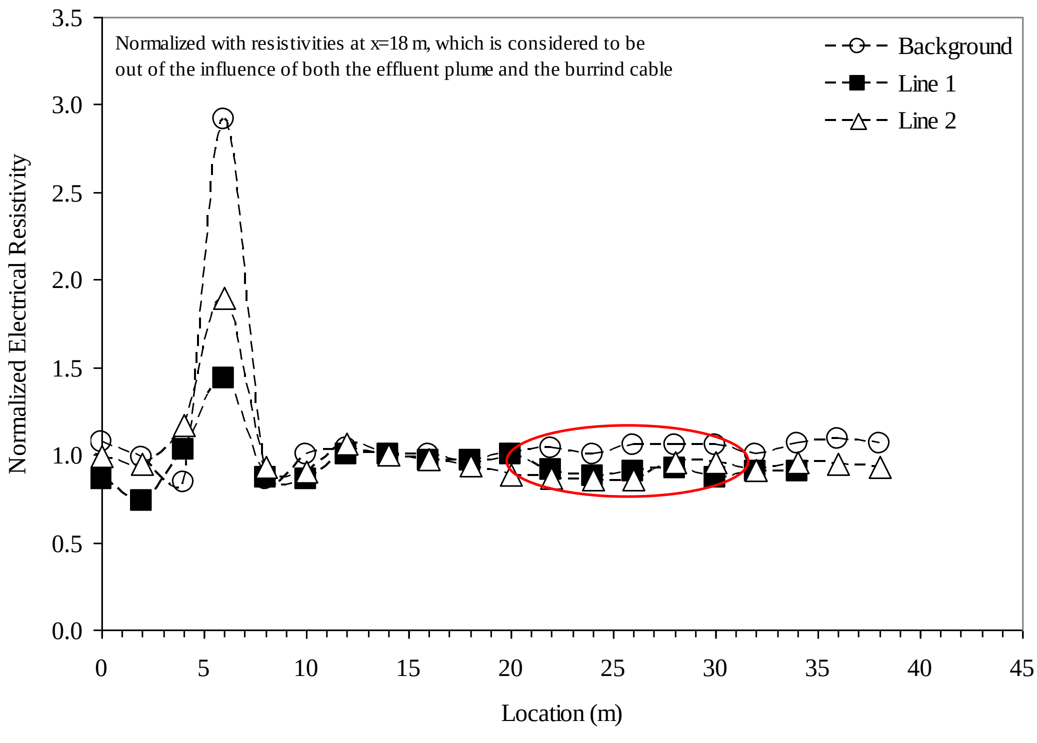


Figure 4-9: Calculated EM31 electrical resistivity from May 2009 parallel to mound compared to background values north of septic mound. Resistivity values are normalized with the resistivity at x=18 m because it is considered to be out of the influence of both the buried cable and the septic effluent plume.

The results of the electromagnetic induction results at 26 m along Line 1 (Figure 4-2) throughout the 2008 operating period and prior to the opening of the 2009 operating season are shown in Figure 4-10. All of the measurements in Figure 4-10 are taken at the same location within the core of the septic effluent plume. The figure shows a low resistivity plume after the major holidays with intermediate time showing higher resistivity effluent. After the park is closed, the plume concentration decreases and approaches a base level.

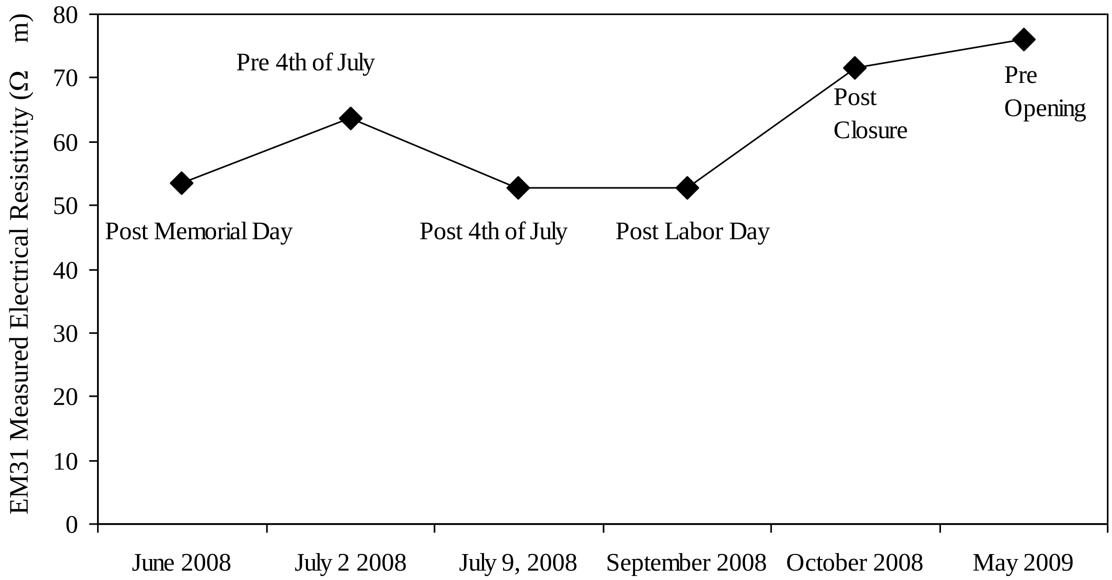


Figure 4-10: Electrical resistivity at 26 m along Line 1 for EM 31 surveys throughout the 2008 operating season and prior to the 2009 season.

4.3.3.2 Consistency with electrical resistivity

Comparing the different surveys, a pattern can be seen throughout the summer. The drop in resistivity for July 2008 is greater than that for June 2008, and the drop for September 2008 is greater than the drop in July. This shows that the plume is becoming more conductive throughout the summer. This same observation was seen in the DC resistivity data. Finally, the plume became more resistive after the park was closed as shown in the October 2008 survey. This is also consistent with the DC resistivity results as the plume begins to dissipate after the use of the system has stopped. In Figures 4- 8 through 4-10, the effluent plume has resistivity values of 50 to 65 Ω m, which is the same order of magnitude as the inverted DC resistivity results.

4.3.4 *SP results*

4.3.4.1 Near septic mound

The results of the SP surveys near the septic mound are shown in Figure 4-11. For these surveys, the positive electrode was fixed at the center of the mound. The survey was performed by placing the negative electrode in the ground at 2 m intervals along the survey lines shown. As can be seen in Figure 4-11 (a) through (c), there is an area of low potential to the south of the mound beginning approximately at the center and extending to the southwest. This area of low potential difference is interpreted as representing the effluent plume, again consistent with the location shown by the other methods. The surrounding areas have higher potential drops between the reading electrode and the mound, showing a difference in electrochemical potential between native groundwater and the septic effluent.

The three surveys show the same general trends for changes in the SP values. Some variation exists in the data; however, this is to be expected, as SP data will be influenced by changes in soil water content near the surface due to precipitation (Ernston and Scherer, 1986). The zone that is considered the plume extends farther to the west in the October survey than the September survey. However, noise in the data does not allow a definite boundary to be identified and therefore this method alone cannot determine if the plume is growing. While, definite boundaries of the plume could not be identified using the SP method, the presence of the low potentials identifies its general position.

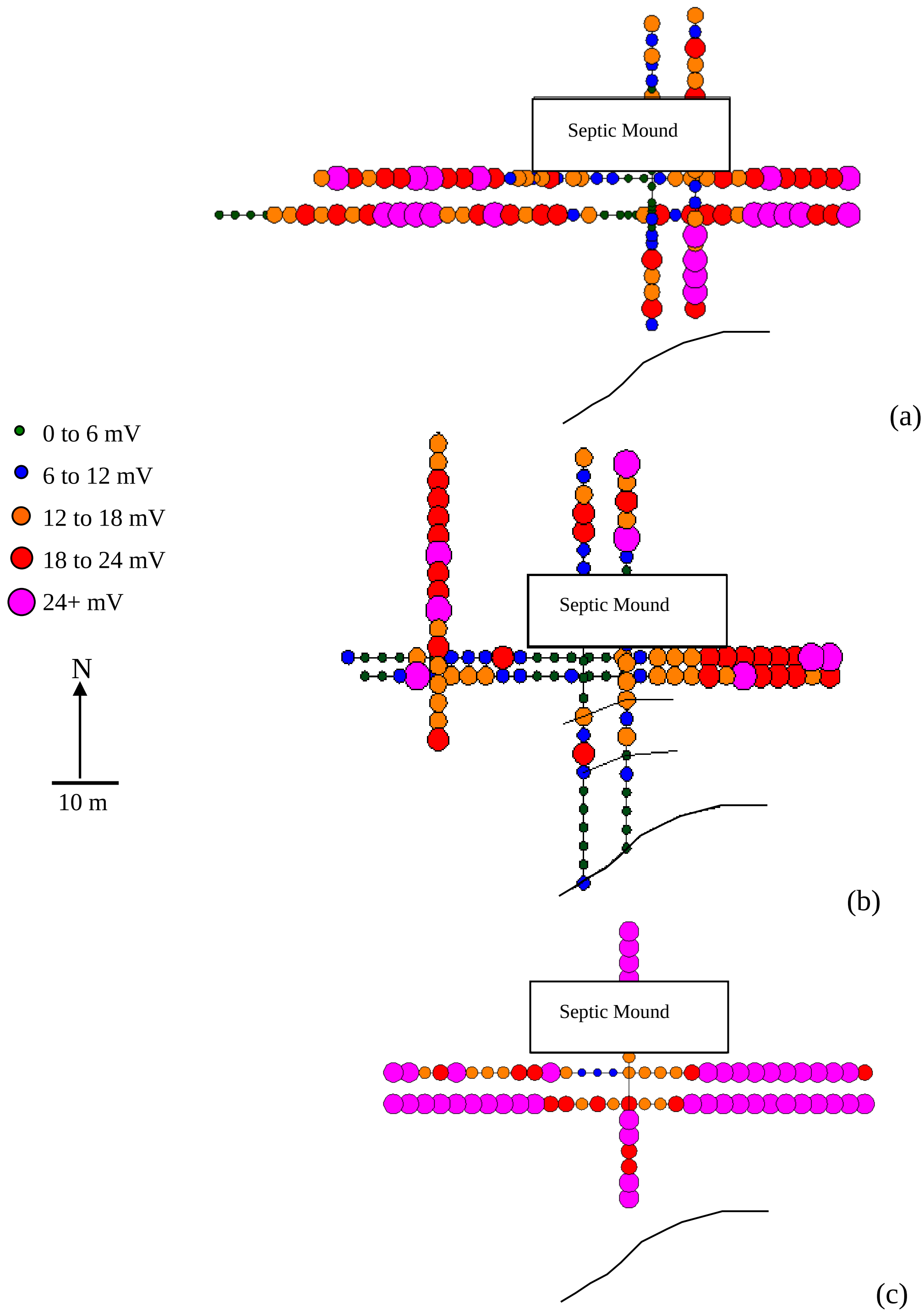


Figure 4-11: Self -potential surveys around septic mound at Collins Lake County Park (Stevens Point, WI) from (a) September 2008, (b) October 2008 and (c) May 2009.

4.3.4.2 Shoreline

A second phenomenon is seen along the western edges in both Figure 4-11 (a) and (b) as well as at the southern edge of survey lines in Figure 4-11 (b). Here the low self-potential values are not related to the changes in electrochemical potentials of the soil, but rather changes in water content due to the close proximity to the lake. The same phenomenon is also present in both surveys of Figure 4-12, where water content changes correspond to changes in soil type.

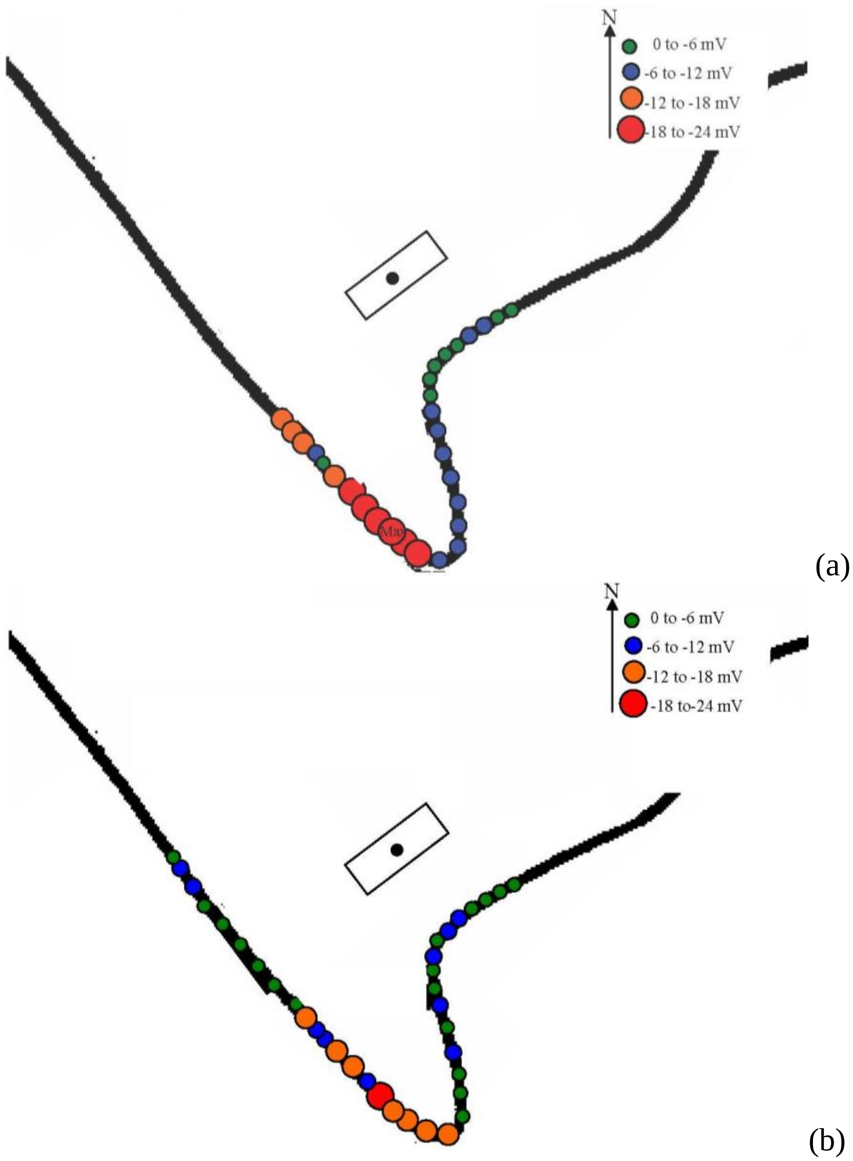


Figure 4-12: Self-Potential surveys of shoreline at Collins Lake County Park (Sevens Point, WI) from (a) September 2008 and (b) October 2008

As was seen in the surveys near the mound, the overall trend along the shoreline remains the same between both surveys, with small variations in magnitude. The SP values are slightly negative (0 to -6 mV) starting at the eastern edge of the shoreline until the southern tip of the point. Here, in both surveys, the values become increasingly negative before decreasing slightly moving northwest. The October 2008 survey was continued farther northwest and shows a sharp drop that represents a change from vegetative muddy soil to the sandy beach.

4.3.5 *Failure of reflection GPR*

The use of GPR at this site did not produce results that could be easily interpreted. It was expected that the water table would produce a strong reflector due to the large change in dielectric permittivity associated with dry and saturated soils and that the effluent plume would be seen as a region of high attenuation due to the lower electrical resistivity of the soil. In all GPR surveys, the water table was identified as a strong reflector, but the plume could not be identified. The absence of other layering made it difficult to see small changes in reflection magnitudes.

4.4 Geoprobe™ groundwater analysis

4.4.1 *Comparison to geophysical results*

The geophysical surveys were supplemented with groundwater testing performed on samples collected during the surveys in October 2008 and May 2009. The results of the lab conductivity measurements (reported as resistivity) from October 2008 and May 2009 are summarized in Table 4-1 along with the modeled formation resistivity calculated using Archie's Law (Archie, 1941). Archie's Law for saturated soils can be written as:

$$\rho_{formation} = an^{-m}\rho_{el} \tag{4-1}$$

In Equation 4-1 $\rho_{formation}$ is the bulk soil resistivity, ρ_{el} is the fluid resistivity, n is the porosity, and *a* and *m* are constants. The constant a ranges from 0 to 1 and is a curve fitting parameter. For the data in this study, *a* was set to 0.41. The parameter *m* is related to the cementation and ranges from 1.3 to approximately 2.4. In this study, m was found to be 1.4. The parameter m in clean sands has been found to be 1.3, which is consistent with the m used in these calculations (Archie, 1941).

Table 4-2: Comparison of 2008 and 2009 measured fluid resistivity in GeoprobeTM perforations with formation resistivity modeled using Archie's Law for the May 2009 fluid resistivity.

Site	Depth (m)	Fluid resistivity (Ω m)		Archie's law formation resistivity (Ω m)	
		October 2008	May 2009	n=0.15	n=0.25
GPS1	1.83 to 3.05	75.8	55.4	322.0	157.5
	3.05 to 4.27	48.3	36.5	212.1	103.7
	4.27 to 5.49	31.1	27.7	161.0	78.7
GPS2	1.83 to 3.05	25.1	17.5	101.6	49.7
	3.05 to 4.27	49.8	37.5	217.7	106.5
	4.27 to 5.49	-	34.6	201.1	98.4
GPS3	1.83 to 3.05	38.3	23.1	134.5	65.8
	3.05 to 4.27	48.3	36.6	212.9	104.1
	4.27 to 5.49	41.0	36.9	214.5	104.9
GPS4	1.83 to 3.05	-	34.0	197.7	96.7
	3.66 to 4.88	-	54.9	319.0	156.0
GPS5	1.83 to 3.05	-	28.8	167.5	81.9
	3.66 to 4.88	-	53.9	313.1	153.2
GPS6	1.83 to 3.05	-	42.4	246.3	120.4
	3.66 to 4.88	-	35.5	206.1	100.8
GPS7	1.83 to 3.05	25.2	37.2	216.0	105.7
	3.05 to 4.27	46.5	44.2	257.2	125.8
	4.27 to 5.49	35.7	41.3	240.2	117.5
GPS8	1.83 to 3.05	-	21.8	126.6	61.9
	3.66 to 4.88	-	38.9	226.1	110.6
GPS9	1.83 to 3.05	37.3	22.8	132.7	64.9
	3.66 to 4.88	10.1	34.7	201.8	98.7

The lab resistivity measurements are for the water collected in the Geoprobe™ boreholes at the given depths. The fluid resistivity values were converted to bulk soil resistivity using Archie's law with porosity values of 15 and 25% used as bounds. These bounds are shown as solid lines in Figure 4-13. It can be seen that the DC resistivity has good agreement with these bounds and that both the capacitive-coupled and DC resistivity measurements show a general trend of increasing formation resistivity with increasing fluid resistivity as would be expected.

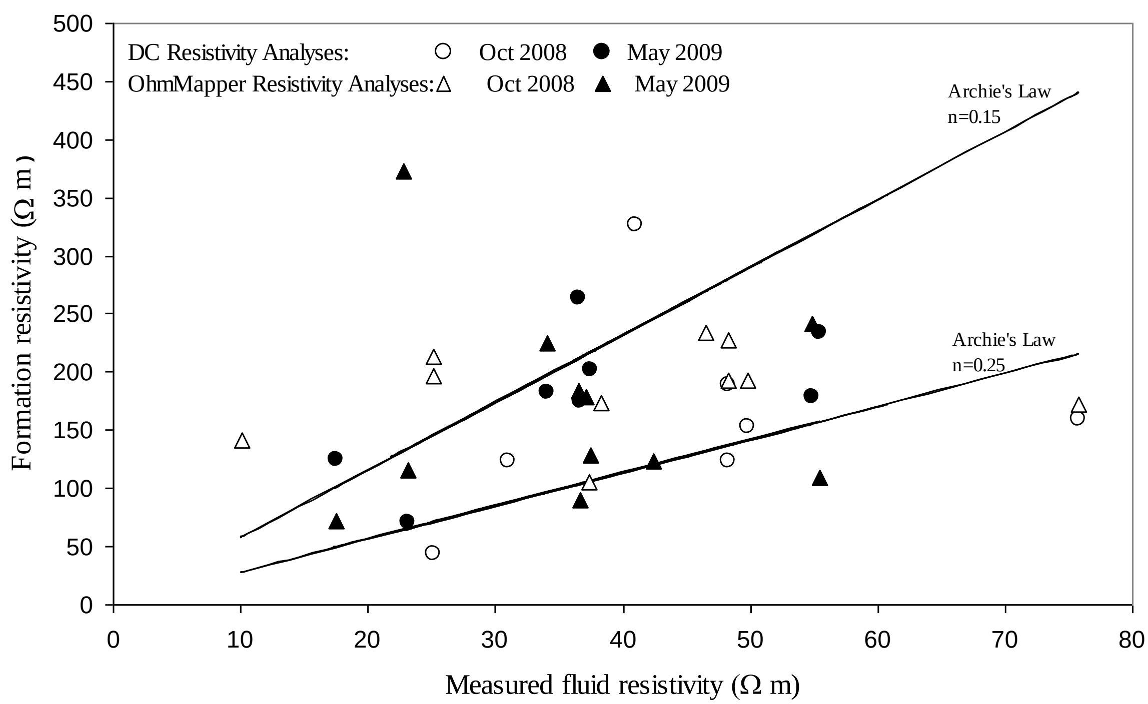
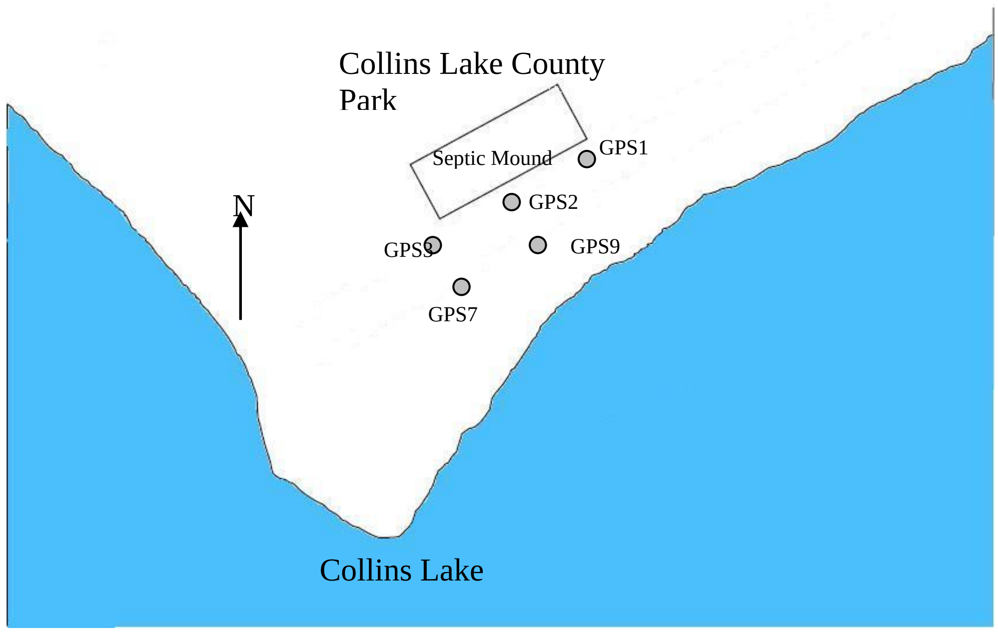
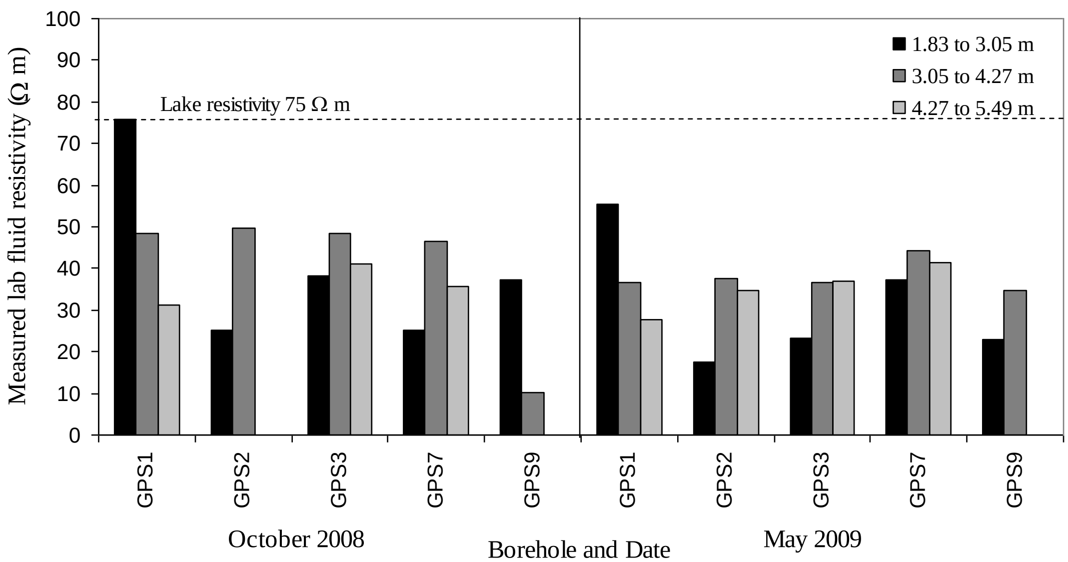


Figure 4-13: Comparison of the formation resistivity measured using DC electrical resistivity methods and OhmMapper capacitive-coupled resistivity methods to the measured fluid resistivity for October 2008 and May 2009.

A comparison of the measured fluid resistivity from samples collected at the same locations in October 2008 and May 2009 is shown in Figure 4-14. This figure shows that with the exception of at the water table in borehole GPS1 in October the resistivity of all the groundwater samples is less than that of the lake. Borehole GPS1 is outside the influence of the septic plume and therefore represents background resistivity levels. Boreholes GPS2, GPS3, GPS7, and GPS9 are all within the plume identified using geophysical methods. In GPS2, GPS3, and GPS 7 the measured resistivity of the groundwater is lowest at the water table and increases with depth. Below approximately 3 m, the measured resistivity values are approximately equal the background levels measured in GPS1, showing that at these locations the plume is focused at or near the water table. In the October 2008 analysis of borehole GPS9, the resistivity is greater near the surface and decreases with depth. This shows that as the effluent moves away from the mound it is also moving deeper. In May 2009, however the resistivity at depth increased as the plume shrank due to non-use.



(a)



(b)

Figure 4-14: (a) Location of GeoprobeTM perforations used in (b) comparison of measured lab fluid resistivity of samples collected in October 2008 and May 2009 from depth intervals of 1.83 to 3.05 m (6 to 10 ft), 3.05 to 4.27 m (10 to 14 ft) and 4.27 to 5.49 m (14 to 18 ft) below the ground surface in the vicinity of the septic mound at Collins Lake County Park.

4.4.2 *Location of plume based on groundwater analysis*

The geophysical methods used all detected changes in formation resistivity associated with the effluent plume. Figure 4-15 shows the concentration profiles with depth of total dissolved phosphorus for the October 2008 and May 2009 surveys compared to Collins Lake background levels. The October 2008 survey had consistently higher concentrations than the May 2009 survey. Similar plots of the total dissolved chloride concentrations for the October 2008 and May 2009 are shown in Figure 4-16. The chloride concentration profiles are consistent between the surveys with the October 2008 survey consistently having higher concentrations than May survey. Furthermore, the areas with high Cl^- concentrations are the same as those with high phosphorus concentrations showing that the areas with high nutrient concentrations correspond to the plume that was imaged using geophysical methods.

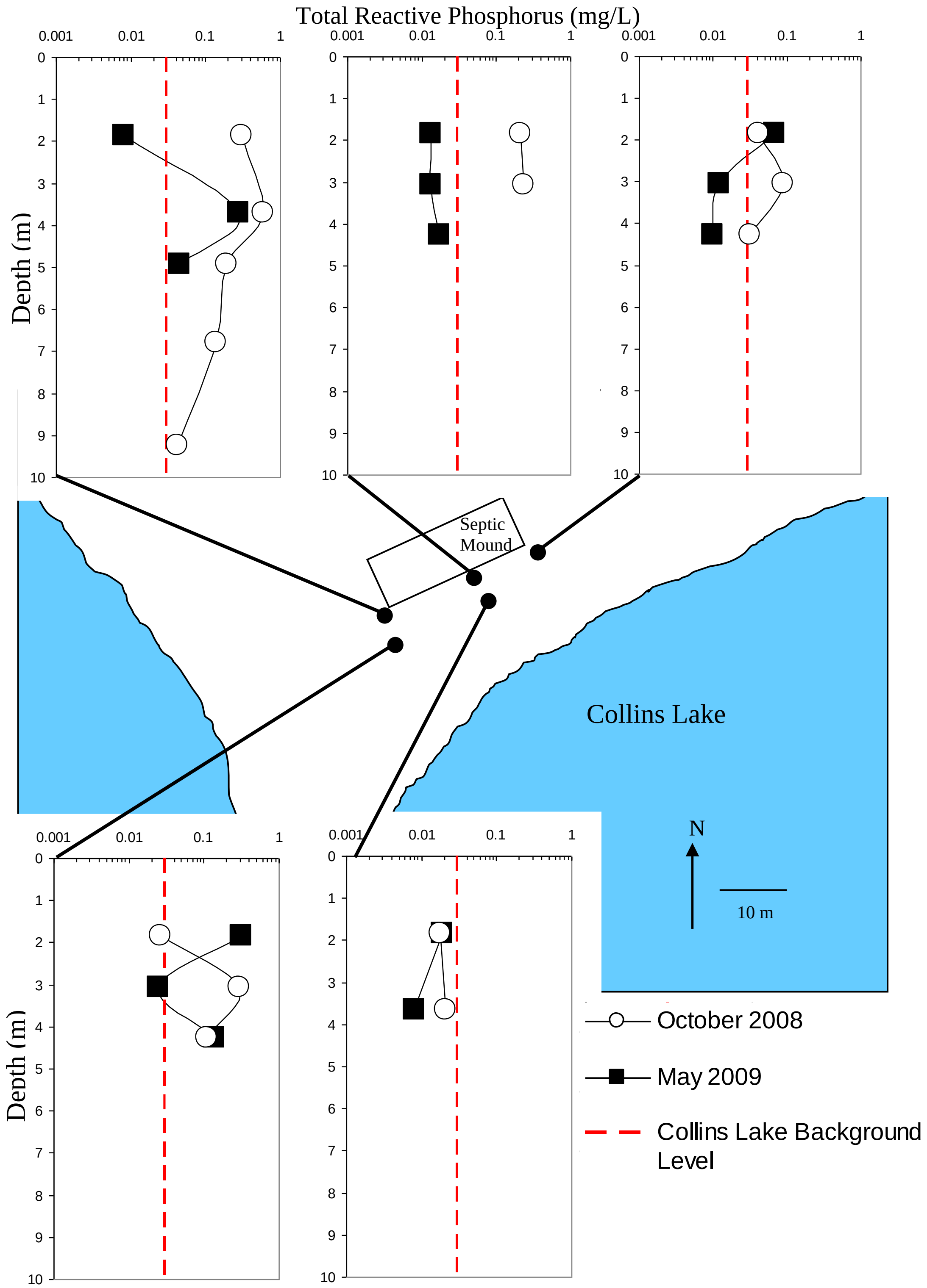


Figure 4-15: Measured concentrations of total reactive phosphorus from Geoprobe wells compared to Collins Lake background concentration

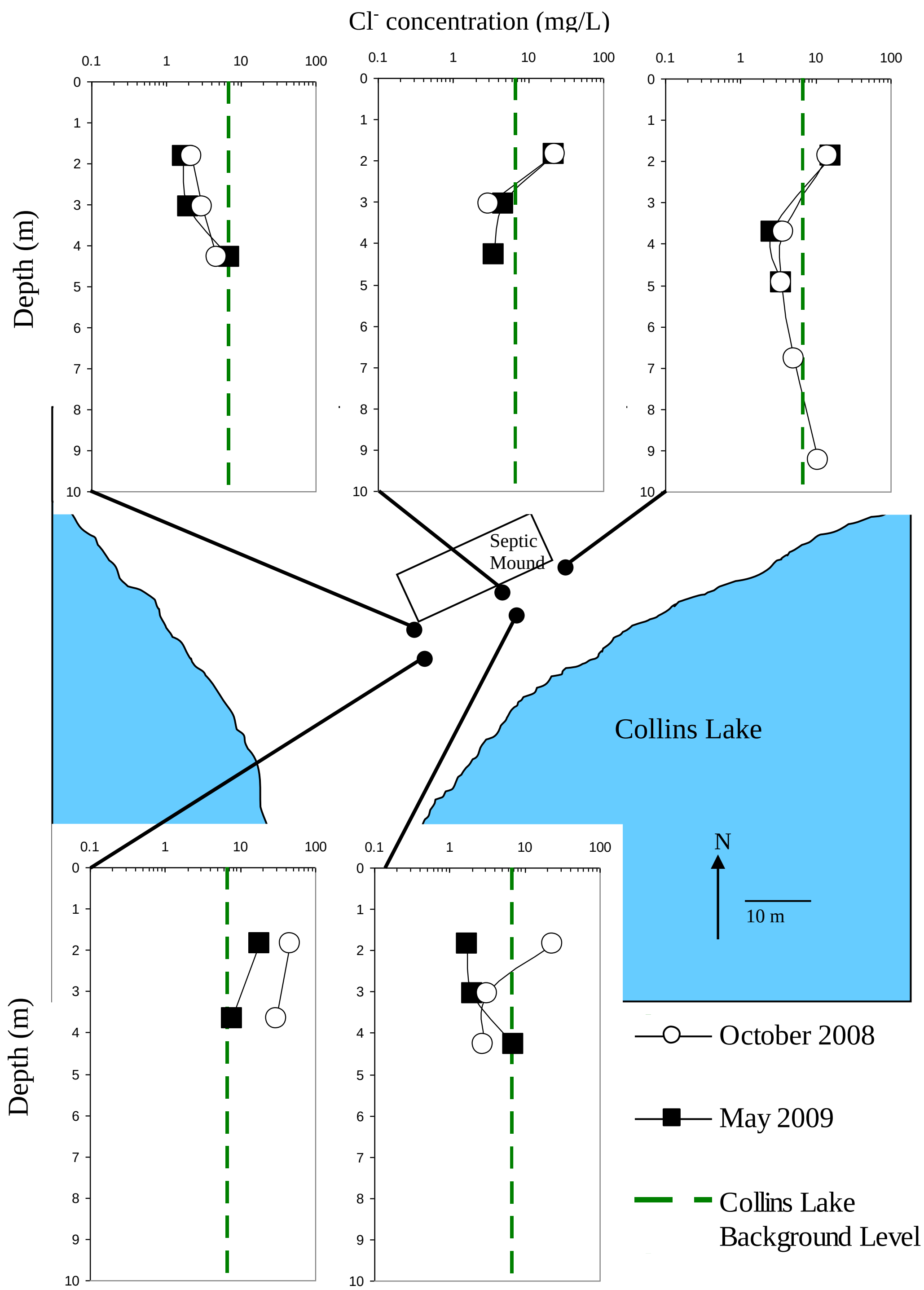


Figure 4-16: Measured concentrations of chloride from Geoprobe wells compared to Collins Lake background concentrations

4.5 Lessons Learned

A mounded septic SAS system was monitored using electrical and electromagnetic geophysical methods at a small county park near Stevens Point, WI. Direct current electrical resistivity, capacitive-coupled electrical resistivity, electromagnetic induction, and self-potential were all used successfully to image and monitor the septic plume at Collins Lake County Park. Geophysical methods were complemented by Geoprobe™ groundwater sampling to groundtruth and quantitatively compare the geophysically measured effluent to the lab measured groundwater concentrations. The monitoring of the Collins Lake County Park septic mound showed that:

- Although the mound was designed to be 150% of the required size, only approximately 50% of the mound is discharging effluent, resulting in a mound that is effectively only 75% of the required size.
- The septic mound receives sporadic loading over the park's operating season (May to September) with 3 large events occurring over holiday weekends (Memorial Day, 4th of July, and Labor Day).
- The effluent plume size and location is controlled predominantly by the groundwater flow, which is largely dependant on the precipitation and lake level.
- The plume increases its concentration immediately after each holiday weekend. The effluent level then slowly dissipates until the next major loading, at which point the concentration increases again. This is repeated throughout the operating season and is then followed by a long period of dissipation during the offseason where the plume concentration returns to approximately the same base level.

- Currently the plume is stable. The concentration increases over the summer before returning to a base level prior to the next season's opening. If the park capacity were increased as proposed, the increase from each loading may be greater than the soil is capable of dissipating. If this were the case, the impact would be for the plume to receive more effluent every year than it could dissipate, causing an increase in both size and concentration from year to year, eventually leading to possible contamination of Collins Lake.

Chapter 5 Summary and Conclusions

5.1 Summary of Research

The in-practice function of mounded soil absorptions systems was investigated at two sites using geophysical methods. The septic mounds served a (1) single-family home that received continuous effluent dosing and (2) and small county park that received sporadic dosing associated with summer holidays (Memorial Day, 4th of July, and Labor Day). Direct current electrical resistivity, capacitive-coupled electrical resistivity, electromagnetic induction, GPR, and self-potential were used to monitor the changes in the septic plumes over the study periods. At the beginning of the research, it was expected that:

- All of the geophysical methods would detect the low electrical resistivity of the septic effluent plume compared to the surrounding groundwater.
- The geophysically measured electrical resistivity could be related to the fluid resistivity to estimate the concentration of the effluent plume.
- The septic and SAS would dissipate contaminants downward and away from the mound at a rate at or greater than the dosing rate preventing the plume from growing over time.

5.2 Effectiveness of methods in monitoring septic effluent plumes

All of the geophysical methods that were used are sensitive to changes in the electrical resistivity of the subsurface. At Sun Prairie capacitive-coupled electrical resistivity, SP, and borehole-to-borehole GPR were used. At Collins Lake DC electrical resistivity, capacitive-coupled resistivity, EM induction, SP, and reflection GPR were used.

With the exception of GPR, the septic effluent plumes were imaged successfully with all of the geophysical methods.

- DC electrical resistivity tomography was used to successfully produce both 2D (Collins Lake) and 3D (Sun Prairie) profiles that were used to identify and monitor the septic effluent plume.
- The measured bulk resistivity from the DC surveys compared very well with the modeled bulk resistivity using Archie's law and the Geoprobe™ collected groundwater samples.
- Capacitive-coupled resistivity was successful in imaging the effluent plume at both sites.
- Using capacitive-coupled resistivity significantly more data can be collected than using DC resistivity allowing for larger and more detailed surveys.
- EM induction was used successfully to image the plume, but could only be interpreted when compared to a "background" profile parallel but outside of the plume.
- SP can identify the resistivity anomaly associated with the septic effluent plume.
- SP data is very noisy due to the small voltage potentials on the small-scale of the surveys in this study.
- EM induction and SP do not provide the necessary resolution to delineate the boundaries of the plume, but can identify its location quickly.
- DC resistivity and EM induction quantitatively agree, while capacitive-coupled resistivity results in higher measured resistivity.

- Borehole to borehole GPR was used successfully to image heterogeneities and water contents of the subsurface at Sun Prairie. The water table and capillary fringe was identified in both the MOG and ZOP surveys and agreed well with measured water levels.
- No plume was identified in Sun Prairie GPR surveys because the plume has not reached the GPR wells.
- Reflection GPR did not produce the attenuation anomaly that was expected due to the low resistivity effluent plume at Collins Lake. The absence of the anomaly may be due to the very homogeneous conditions and the absence of reflectors below the water table.

5.3 Performance of mounded SAS systems

The performance of mounded soil absorption systems was evaluated using two systems under very different loading conditions.

- Both SAS only dissipated effluent from approximately 50% of the mound area. This means that the soil that is receiving effluent receives double the dosing and that it was designed to.
- The concentration of the effluent plume, especially in the shallow subsurface, was heavily influenced by the precipitation at the site.
- Soil heterogeneity is a controlling factor in the extent and shape of the effluent plume. Low hydraulic conductivity zones can develop high concentration portions of the

plume that move down gradient quickly, potentially contaminating nearby surface or groundwater.

- At Collins Lake County Park, the plume increased in concentration over the summer before dissipating to a base level over the off-season. However, if the usage of the park is increased the soil may not be capable of dissipating the additional effluent and the plume may begin to grow over time as was observed at the Sun Prairie subdivision. If this occurs, the plume may soon contaminate nearby Collins Lake.

5.4 Future research

Based on the research presented in this study, there are a couple of unanswered questions that merit further research. It has been observed that both mounded septic systems in this research used only approximately 50% of the available soil absorption area. Further research to determine if this is typical behavior of mounded septic systems should be conducted as well as investigation into the cause and potential remedy for this behavior. It was also observed that many of the geophysical methods, especially DC and capacitive-coupled resistivity had the same qualitative results but were not quantitatively the same. These systems measure the same physical phenomenon and should produce identical results. Further research should be conducted to determine why the systems did not produce quantitatively similar results.

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