Use of the ASTM D6391-11 Borehole Infiltration Methodology for Measuring In-Situ Hydraulic Conductivity of Compacted Clay Liners

By

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Abstract

This thesis focuses on the use of the ASTM D6391-11 (the ASTM) Borehole Infiltration Methodology for Measuring Hydraulic Conductivity in the field. The study's primary objective is to establish a procedure for using the ASTM to test the validity of site-specific hydraulic conductivity measurements and liner discharge estimations in the field relative to the current Shelby tube collection and laboratory testing method. The study is conducted through experiments testing hydraulic conductivity values in the laboratory and field, resulting data is analyzed and compared to previous studies, and a numerical model is developed to describe the liner discharge from the system.

The findings of this study suggest that when applied to compacted clay liners that (1) the ASTM methodology produced reliable estimates of hydraulic conductivity, and that (2) borehole infiltration can be an effective and economical alternative to traditional laboratory testing for assessing hydraulic conductivity and estimating liner discharge.

The study notes the low number of tests completed and the need for future research to investigate the environmental factors which may impact in-situ and laboratory testing. There is opportunity for further study to correlate in-situ and laboratory testing, examine the effect of borehole diameter, varying testing parameters, and subsurface soil conditions on the analysis. The engineering practice should consider using borehole infiltration as a tool for commissioning earthen manure and wastewater storage facilities and to calibrate liner discharge models to better understand and describe the performance of the liner systems and design innovative solutions to remediate deficient liners.

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1.0 INTRODUCTION

1.1 Background

Clay lined cells are commonly used in industrial and agricultural settings to store toxic or deleterious materials which may be threatening to the surrounding environment. These facilities must meet specific containment standards in order to be commissioned for use. In Manitoba, the following specifications must be followed (Manitoba Conservation, 2007):

1. The liner shall be made of clay;
2. The liner shall be at least one meter in thickness;
3. The liner shall have a hydraulic conductivity of $1x10^{-9}$ m/s or less at all locations; and
4. The liner shall be constructed to the top of the dikes above the floor elevation or base of each cell.

The hydraulic conductivity, or the measured ability of a soil or material to transmit water, is one of the key factors in the design and functioning of clay-lined earthen manure storage (EMS) or other lagoon storage and treatment facilities. The permeability of a soil is influenced by several factors, including the deposition history, composition of the clay, compaction method and density of the clay (Daniel, 1984), and the presence of cracks or other defects (Benson & Daniel, 1990) such as rootlets or inclusions in the clay lining. Permeability is an intrinsic property of the soil and may influence the hydraulic conductivity under different testing conditions.

In-situ testing is a commonly used method for determining the hydraulic conductivity of clay and other soils for a variety of applications, such as predicting groundwater flow and estimating infiltration rates. The accepted practice in Manitoba to commission a clay lined wastewater pond requires the collection of relatively undisturbed samples via thin-walled Shelby tubes, transportation to a geotechnical laboratory, preparation and saturation of the soil cores, and pressurized testing of the material to estimate the hydraulic conductivity of the liner.

The hydraulic conductivity of the soil is only one parameter for the flow rate of contaminated water (liner discharge) from the EMS to the surrounding environment, however, is typically used as the sole parameter for commissioning an EMS.

There is potential for significant variability between laboratory-tested samples and the actual conditions on-site and as a result there is a need to evaluate alternative methods for assessing the commissioning eligibility of clay-lined EMS. Several alternative methods have been developed to determine the hydraulic conductivity of low-permeability materials.

1.2 Purpose

The purpose of this study was to compare the means and methods of in-situ and laboratory hydraulic conductivity testing for the purpose of commissioning EMS facilities. The intent of the study is to consider the procedure, data quality, encapsulation of site conditions, and compare the in-situ hydraulic conductivity testing of clay lined EMS against traditional laboratory testing of relatively undisturbed specimens.

The study also intends to examine the input parameters and design criteria for commissioning EMS facilities in a more comprehensive and consistent manner, and leverage the in-situ data collected to calibrate a numerical model to estimate liner discharge. If successful, the study would establish a procedure in Manitoba to evaluate an alternative method of assessing the EMS for commissioning.

1.3 Objective

The objectives of the study were to:

- Develop and implement a methodology for conducting in-situ hydraulic conductivity testing of clay-lined EMS per ASTM D6391-11 Method A (the ASTM Method A) in Manitoba.
- Collect and analyze data on the hydraulic conductivity of the EMS.
- Compare the results of in-situ testing with traditional Shelby tube collection and laboratory testing methods.
- Evaluate the feasibility of using in-situ testing as a supplementary or alternative method for assessing the commissioning eligibility of clay-lined EMS.
- Evaluate the function of hydraulic conductivity in the transfer arrival time of contaminates and liner discharge from the system.
- Establish design aids for common liner systems encountered in Manitoba.

Despite the importance of hydraulic conductivity in the design and functioning of clay-lined EMS, there is limited research in Manitoba on in-situ testing methods for assessing the commissioning eligibility of these EMS. The results of this study will provide information for the design and management of clay-lined EMS, as well as contribute to the existing knowledge on the hydraulic conductivity of clay materials and the feasibility of using in-situ testing as an alternative method for assessing commissioning eligibility.

2.0 LITERATURE REVIEW

2.1 Darcy's Law and Hydraulic Conductivity

Darcy's law is a fundamental principle in hydrogeology that describes the relationship between the flow of water through a porous medium and the hydraulic gradient, which is the difference in fluid pressure between two points in the medium. Darcy's law is often used to understand the hydraulic conductivity of soils, rocks, and other materials.

Hydraulic conductivity is a measure of how easily water can flow through a porous medium. It is represented by the symbol k and has units of length per time, typically measured as meters per second (m/s). Hydraulic conductivity depends on the properties of the porous medium, such as its grain size distribution, porosity, and tortuosity, as well as the fluid properties, such as viscosity and density. The quantitative flow of water through a material is represented by the symbol Q and has the units of volume per time. Though influenced by hydraulic conductivity, the flow through a material is equally as dependent on the hydraulic gradient or pressure differential over a given length and may be influenced by site or seasonal dependent factors.

Darcy's law can be expressed mathematically as:

Equation 1 - Darcy's Law

$$Q = -kA\left(\frac{dh}{dl}\right)$$

Where:

> Q *is the flow rate of water through the porous medium*
>
> k *is the hydraulic conductivity*
>
> A *is the cross-sectional area through which water is flowing*
>
> $\frac{dh}{dl}$ *is the hydraulic gradient, which is the change in hydraulic head (fluid pressure) over a given distance*

The negative sign indicates that water flows from areas of high pressure to areas of low pressure. For a large surface area such as an EMS the flow per unit width, q, is used and the cross sectional area parameter is removed. This simplified model assumes free drainage is allowed on the top and bottom of the material, and the pressure differential is consistent across the material.

Darcy's law provides a simple but powerful way to estimate the hydraulic conductivity of a porous medium, given measurements of the flow rate and hydraulic gradient. It is commonly used in hydrogeology, geotechnical engineering, and environmental science to model the movement of fluids through the subsurface and to design and evaluate groundwater remediation systems, landfills, and other engineering structures.

2.2 Methods for Measuring Hydraulic Conductivity in Low Permeable Soils

There are several methods for testing hydraulic conductivity, which can be broadly categorized as laboratory methods and in-situ methods.

Laboratory methods typically involve inducing a high gradient across a prepared, saturated sample to measure the flow of water and calculate the hydraulic conductivity.

The common laboratory methods include:

- Flexible wall permeameter
- Rigid wall permeameter

Laboratory methods are generally more controlled, and results are easier to replicate on the same specimen. Laboratory testing is the primary testing method currently used to evaluate the permeability of engineered clay liners in Manitoba.

In-situ methods involve installing an apparatus at the site of interest and measuring the flow through the subsurface. The flow is typically measured with a closed system falling head test where the drop in water level is measured against time, or an open system constant head test where the water level is maintained and the necessary flow is measured. For soils with a low permeability, the flow rate may be too low to be accurately measured and the constant head test may not be feasible.

The common in-situ methods include:

- Pumping test
- Ring infiltration
- Borehole infiltration
- Slug testing

Some advantages of in-situ testing may include:

- In-situ testing may provide a more accurate representation of the actual conditions in the EMS facilities (Sari & Tarhan, 2007). This is important because the hydraulic conductivity of the liner may be governed by the preferred seepage paths through small cracks and gaps, or other imperfections that may not be present in laboratory samples. By testing the liner in location, in-situ testing may better account for these factors and provides a more accurate measurement of the flow through the liner.

- In-situ testing provides real-time data, which allows for immediate adjustments to be made if necessary. This is particularly important for EMS facilities that are still being constructed or have not been in operation for very long. Real-time data can help identify potential issues while construction equipment is still on site and prior to problems worsening.
- In-situ testing may be more cost effective to laboratory testing when a large number of tests are required, and may be run concurrently while the qualified technician is on site for additional tasks.
- In-situ testing typically provides a larger sample size than laboratory testing (Boutwell & Trautwein, 1994), which can improve the accuracy of the results and scale the effects of roots, inclusions, or soil variability.

Some disadvantages of in-situ testing may include:

- The uncertainty of weather conditions may impact the planning and execution of the test. Extended rainy conditions may soften the running surface and prevent access for construction equipment from installing the testing equipment. Negative ambient temperatures may be mitigated by using fluids with lower freezing points, however this must be identified in advance and additional uncertainty is introduced for temperature corrections.

- In-situ testing can be more technical to set up compared to a traditional field program as it requires the proper installation of test equipment and the preparation of the test site. An experienced technician is necessary to install and operate the in-situ testing equipment.
- In-situ testing can be more challenging to control and verify consistent testing conditions when compared to laboratory testing (Benson & Daniel, In Situ Hydraulic Conductivity Tests for Compacted Clay Liners, 1994), as the testing conditions are influenced by factors such as ground water levels, weather, and the natural variability of the site. The repeatability of results for in-situ testing may be less consistent than laboratory testing.
- To achieve flow through the liner, the hydraulic gradient across the material must be high enough to overcome the suction pressure of the material; however, the embedment depth must be large enough to prevent hydraulic jacking (ASTM, 2020). For this reason, the upper region of the liner may not be tested using the borehole infiltration method.

It is important to note that each testing method has its own advantages and limitations and the appropriate method will depend on the specific goals and constraints of the application.

2.3 Previous Studies on the Borehole Infiltration Method

A series of papers and articles have been published that discuss the challenges of field assessment of hydraulic conductivity in fine-grained soils and the various test methods that have been developed to address this issue. The studies compared the hydraulic conductivity values obtained from different field and laboratory testing methods and identified the factors that can cause discrepancies in test results, including the type of apparatus, its geometry, specimen preparation, soil behaviour, and test-analysis methods.

An important distinction to be made is the specific property that is being tested by an in-situ test versus a laboratory test. Although hydraulic conductivity is being measured in both methods, a key distinction is made between micro permeability and macro permeability, with laboratory tests focusing on micro permeability and field tests measuring macro permeability (Olson & Daniel, 1981). The authors presented a demonstration of the effect of effective stress level on hydraulic conductivity, and the governing mechanism of macro permeability controlled flow changes to micro permeability controlled flow when the stress level reaches 55 to 95 kPa (8 to 12 psi) (Olson & Daniel, 1981). Throughout the lifecycle of an EMS facility, the flow of water and associated contaminates, or liner discharge, will occur via macro permeability. In one study, dye and tracer tests confirmed significantly higher flows through a network of "preferential flow pathways" (Rogowski, 1990), which indicated that only a small fraction of the total pore space is involved in active transport. Based on preferential flow pathways, hydraulic conductivity distribution of laboratory testing may underestimate site conditions by a factor of five and individual values at the same location could differ by several orders of magnitude (Rogowski, 1990).

One of the main challenges in the assessment of hydraulic conductivity of fine-grained soils is the potential for large variability in test results, which can be caused by several factors. These factors include the type of apparatus used, its diameter and geometry, and specimen preparation, as well as soil behaviour and test-analysis methods (Cazaux & Didier, 2002). To overcome these challenges, various test methods have been developed including open, sealed, single and double infiltrometers, and borehole methods, as well as laboratory-testing methods such as oedometer cells or rigid and flexible-wall permeameters.

A testing program was carried out to evaluate these methods using a hydraulic field infiltrometer method (sealed single-ring infiltrometer) and a laboratory rigid-wall permeameter method that reproduces surface field test conditions (Cazaux, 2002). The laboratory tests were continued until saturated hydraulic conductivity was obtained so that this value could be compared against the hydraulic conductivity estimated from early-time analysis on the same specimen. The obtained results show the influence of several factors, including the initial moisture content, the sorptivity and hydraulic head on the early-time infiltration rate, and the final estimated hydraulic conductivity.

In-situ tests are becoming increasingly important to augment laboratory tests to verify hydraulic conductivity. Many different in-situ tests have been proposed, and of these, the Sealed, Double-Ring Infiltrometer and the Two-Stage Borehole test have received the widest acceptance and use (Boutwell & Trautwein, 1994). Both ring and borehole infiltration are examined in detail, including theoretical basis, field procedures, and data reduction. A schematic of the Double-Ring Infiltrometer is shown on Figure 1.

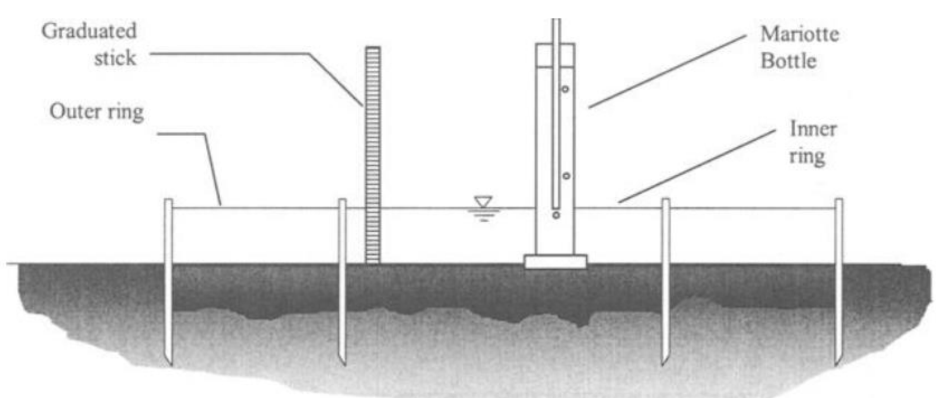

Figure 1 - Double-Ring Infiltrometer Schematic (Sara & Everett, 2002)

The Sealed Double-Ring Infiltrometer measures one-dimensional infiltration from which vertical hydraulic conductivity is determined. Testing times are comparatively long, but a larger volume of soil is tested,1000 to 3000 times more than what is typically tested in the laboratory (Boutwell & Trautwein, 1994). It is the better of the two methods for testing thin liners (<50 cm). The Two-Stage Borehole method involves three-dimensional infiltration, from which both vertical and horizontal conductivities are determined. A typical study involves multiple tests, with the total volume of soil affected by a 5-test group being 250 to 1000 times that typically tested in the laboratory (Boutwell & Trautwein, 1994). Testing times are comparatively short, and the method is the better of the two for evaluating variability in hydraulic conductivity with depth, on slopes, and where horizontal conductivity is needed.

In one study, comparative results from 15 projects are presented and the sealed double-ring infiltrometer and two-stage borehole infiltration methods were found to yield comparable values (Boutwell & Trautwein, 1994). Both tests have been successful in verifying well-built barriers and identifying those with defects. It is evident from the study that further enhancements in test techniques are imperative to ensure that results obtained from field and laboratory tests are dependable and precise.

The review highlights the critical role of ongoing research in hydraulic conductivity testing, emphasizing the potential for innovation to meet regulatory requirements for EMS facilities. It identifies significant challenges in field assessments of hydraulic conductivity in fine-grained soils, particularly in the construction of EMS facilities. Various test methods have been developed to address these challenges, which are essential for mitigating the disadvantages associated with in-situ testing. The comparison of hydraulic conductivity values from different field and laboratory methods reveals several factors that can cause discrepancies, including apparatus type, geometry, specimen preparation, soil behavior, and test-analysis methods. This underscores the need for continuous improvements in testing techniques to ensure the construction of high-quality EMS facilities that adhere to regulatory standards.

The review concludes that field testing, due to the larger sample sizes and scale effects, offers a more representative understanding of permeability mechanisms and soil liner behavior. This highlights the increasing necessity of in-situ tests in many jurisdictions for verifying hydraulic conductivity and estimating liner discharge. While several in-situ tests have been proposed, the Sealed Double-Ring Infiltrometer and the Two-Stage Borehole test are the most widely used and accepted. The review also emphasizes the dynamic nature of the field, where ongoing research and development are essential to enhance the accuracy, reliability, and repeatability of hydraulic conductivity measurements, both in the laboratory and in the field. In-situ borehole infiltration testing is recognized as a viable method for determining the hydraulic conductivity of engineered clay liners and is commonly used in many regions.

2.4 ASTM D6391-11 Borehole Infiltration

The methodology for the ASTM Method A borehole infiltration test is intended to leverage the benefits of in-situ testing to better represent site specific conditions in a streamlined process. This method is effective because it is capable of removing or accounting for typical uncertainties associated with field testing, such as evaporation, temperature variances, and surface infiltration, while maintaining site specific boundary conditions. ASTM D6391-11 has three variations: Method A, Method B, and Method C depending on the critical parameter being investigated and the level of effort available for testing.

One of the benefits of using borehole infiltration is the ability to dramatically increase the soil volume being tested compared to the Shelby tube method. The increased soil volume is beneficial as the test becomes less sensitive to variations in particle size distributions, presence of rootlets or other intrusions, and preferential hydraulic pathways.

A benefit of ASTM Method A over Method B and Method C is the ability to delineate the vertical and horizontal flow in the system by separating the test into two stages, and extending the borehole for the second stage. The intent of stage 2 of the method is to evaluate the horizontal flow from the borehole infiltration, which is useful in calibrating numerical models.

By testing the soil within its engineered system, the borehole infiltration test provides a more representative picture of the transport arrival time and liner discharge.

For the borehole infiltration method to be successful, there are a number of considerations which need to be made (ASTM, 2020):

2.4.1 Practical Implementation

There are many factors impacting the practical implementation of borehole infiltration testing, including environmental hazards such as weather, flooding, drought, and internal factors such as the availability of resources and concurrent operations at the site. Many of the difficulties affecting the practical implementation of in-situ testing may also impact the traditional method of sample collection.

The practical implications unique to in-situ testing include the fabrication and quality control of the testing apparatus, and mitigation of sub-zero temperatures during testing.

2.4.2 Resource Requirements

To practically implement the ASTM Method A of borehole infiltration, adequate resources should be allocated to the program that is appropriate for its size. Very small programs with only one or two tests may be installed and read manually; however, programs with multiple apparatuses running concurrent tests should require the use of equipment and instrumentation. The level of effort and cost of a full-scale in-situ program would likely be comparable to that of the same-sized laboratory program. The following table summarizes the resources likely required for a full-scale test. It is likely that the consultant performing the borehole infiltration testing would procure, own, and maintain their own apparatus as they are reusable and may be customized based on the Engineer's requirements.

Table 1 - Resource Requirements

Resource	***In-Situ Borehole Infiltration***	***Laboratory Flexible Wall Permeation***
Heavy Equipment	Drill rig or mini excavator for one day Water tote (delivered by on site equipment)	Drill rig for one day
Sample Collection	6+ borehole apparatus 6+ vibrating wire piezometers and data loggers 16+ bentonite bags Reamer	6+ Shelby tubes 3+ bentonite bags
Technician Time Commitment	4 days on site	1 day on site 7 days in the laboratory

2.4.3 Fabrication

The ASTM Method A does not prescribe the dimensions of the chamber and standpipe as the apparatus should be designed for the soil which it will be testing. The apparatus should be leak tested during the quality assurance step of the fabrication prior to going to the field. The removable top cap of the apparatus should be secured with a toggle latch or thread and should not rely on friction. Friction-based lids may not perform as intended in the field when in contact with clay and water. The apparatuses are reusable when properly installed and removed from the site. The installed apparatus is shown in Appendix A Photo 4. This implication was highlighted during the testing for this project as the leaking of the device installed on the floor was observed and had to be mitigated with sealant and adhesives.

2.4.4 Time of Year

The nature of EMS construction will typically follow the design in the winter or spring, construction during the summer, and the commissioning stage happening in the fall. The placement of clay must occur in non-freezing temperatures to reach specified compaction and moisture content. The borehole infiltration may be started immediately after the liner is installed, preferably while the construction equipment is still on site (e.g., water truck, skid steer). With uncertain construction schedules, there may be a tight window between construction completion and freezing temperatures when conducting the borehole infiltration test.

2.4.5 Protecting the Apparatus

While the test is in progress, the apparatus may be very sensitive to any movement or disturbance. If other parts of the EMS are under active construction, each apparatus should be clearly marked with delineator posts and fluorescent tape. At least two thirds of the chamber should also be seated into the ground to prevent disruption due to wind. If two thirds are not possible the chamber should be trimmed, or sandbags should be piled around the apparatus for the length of the chamber.

2.4.6 Site Conditions

The site should be accessible to a drill rig and/or construction equipment for the transport, installation, operation, and removal of the infiltration test. The nature of clay liners is typically soft when wet and should be considered when planning the program if recent rainfall has occurred.

2.4.7 Installation

The hole for the apparatus should be done with a 355 mm or 406 mm cast-in-place piling rig, or a geotechnical rig equipped with a sufficiently sized auger. The hole may be excavated by hand or with a mini-excavator however extra attention should be paid to reaming base of the hole flat prior to placing the apparatus in the hole. The mini excavator or hand methods may also require substantially more bentonite chips to fill the annulus. The chips should then be completely saturated with water for a minimum of 24 hours.

2.4.8 Testing on Slopes

When conducting the borehole infiltration testing on-site slopes, the apparatus should always remain vertical to prevent the risk of overturning. Because the hydrostatic pressure will always remain perpendicular to the surface against it, the horizontal and vertical hydraulic conductivity calculations will remain the same. If the drill rig can reach the location on the slope or corner, the borehole infiltration method and sample collection may be used without an additional level of effort. If the location is not accessible by a drill rig, the borehole may be to be excavated by hand, which would add effort but still be feasible.

2.4.9 Advancing Stage 2

The annulus should be drained prior to advancing the borehole to prevent creating a clay slurry at the base and to use the reaming tool effectively. A sump pump or wet vac may be needed on site to pump out the water.

2.4.10 Instrumentation

A variety of instruments may be used to collect data. The basic instrumentation is the scale adhered to the standpipe, which may be used to conduct the test or as a confirmatory redundancy for an automated sensor. A vibrating wire piezometer (VWP) shown in Figure 2 may be secured at or near the base of the apparatus. If pressure-based automated instrumentation is used to measure the height of water, a second instrument should be installed outside of the apparatus to account for changes in barometric pressure. If the standpipe is being measured manually, the temperature of the water should also be measured to account for changes in water viscosity.

Figure 2 - Vibrating Wire Piezometer (RST Instruments, 2023)

2.4.11 Data Collection

The data may be collected manually by readings of the standpipe or through an automated water level reading system. The data should be collected over a period long enough for the readings to equalize, which may range from hours to days depending on the type of soil and current saturation level. The ASTM Method A should be consulted when determining the time period. The total test length is indicated by the expected hydraulic conductivity and should be considered when sourcing the apparatuses and data collection devices if running concurrently. For this study, an RST standard VWP and DT2011B Single Channel Data logger were used.

2.4.12 Liners At Depth

A limitation of ASTM is for the application of liners at greater depths, such as a cutoff or keyway. The limitations of the method in this application would be:

- A custom-fabricated chamber or chamber extension
- Ability to inspect the proper placement of bentonite chips
- Ability to inspect a clean surface at the base of the chamber
- It may be difficult to remove an extended chamber

The depth of water within the chamber should not exceed 5.5 m (18 ft) as induced pressures above 55 kPa (8 psi) may instead measure the micro porosity of the soil skew the flow results.

Slug testing or borehole infiltration packer testing may be a more suitable alternative for testing liners at depth however, these tests may be cost-prohibitive and are not referred to in the ASTM Method A.

2.5 Opportunities for Research

There are several opportunities for research identified though the literature review in the field of soil and hydraulic conductivity, including:

- Developing and improving field-testing methods for measuring hydraulic conductivity in fine-grained soils, particularly for unsaturated soils.
- Investigating the sources of variability in hydraulic conductivity measurements, including the scale effect, soil behaviour, and test-analysis methods.
- Developing better methods for measuring the liner discharge from an EMS facility.

- Investigating the long-term performance of soil liners and caps in EMS facilities, including the factors that affect their stability and hydraulic conductivity over time.

Overall, there are many opportunities for research in this field, and addressing these could help to improve our understanding of Darcy’s Law and how it relates to liner discharge from clay liners for EMS facilities.

3.0 METHODOLOGY

3.1 Experimental Design

The intent of the experimental design is to assess if the ASTM Method A is a viable alternative for determining the commissioning eligibility of engineered clay liners in Manitoba. A thorough review and understanding of the ASTM Method A is necessary to successfully complete an in-situ borehole infiltration field program and is important for understanding this study. The viability of the method will be evaluated against the quality of the data tested and the practical implications of the method.

3.2 Variable Control

The nature of in-situ testing introduces additional variables to be controlled through the experimental design. Each variable was considered and mitigated to achieve consistent and repeatable results. These variables are presented in Table 1 (ASTM, 2020).

Table 2 - Variable Control

Variable	***Mitigation Technique***
Evaporation	Placing a cover over the standpipe to prevent vapour from exiting. The cover should have a small hole for pressure equalization.
Rainfall	The standpipe should have a 90-degree bend at the top to prevent rain from entering. A tarp or polypropylene plastic should be placed around the base of the apparatus to prevent infiltration from rain fall to impact the results.
Temperature	The temperature of the water in the apparatus should be monitored at each reading to capture any viscosity changes and ensure no freezing occurred. If sub-zero temperatures are anticipated, another fluid should be selected for the test and any change in viscosity must be accounted for.
Leakage	The design of the apparatus should consider leakage potential in the field after clay has been introduced to the joints. The removable lid connection should not rely on friction but should rather be a toggle latch or threaded system.

	A leak test should be completed on the apparatus in the fabrication shop prior to shipping.
Atmospheric Pressure	If a vibrating wire piezometer or pressure transducer is being used to measure the standpipe water level the atmospheric pressure outside the apparatus must also be tracked.

3.3 Materials and Equipment

The apparatus used is made from a 300 mm diameter Schedule 40 PVC pipe and a 100 mm standpipe. The chamber is fabricated at 1 m tall however the length may be reduced in the field to fit any site-specific needs. Fabrication details and shop drawings were produced by Prairie Agricultural Machinery Institute (PAMI) and the components of the apparatus are shown on Figure 3.

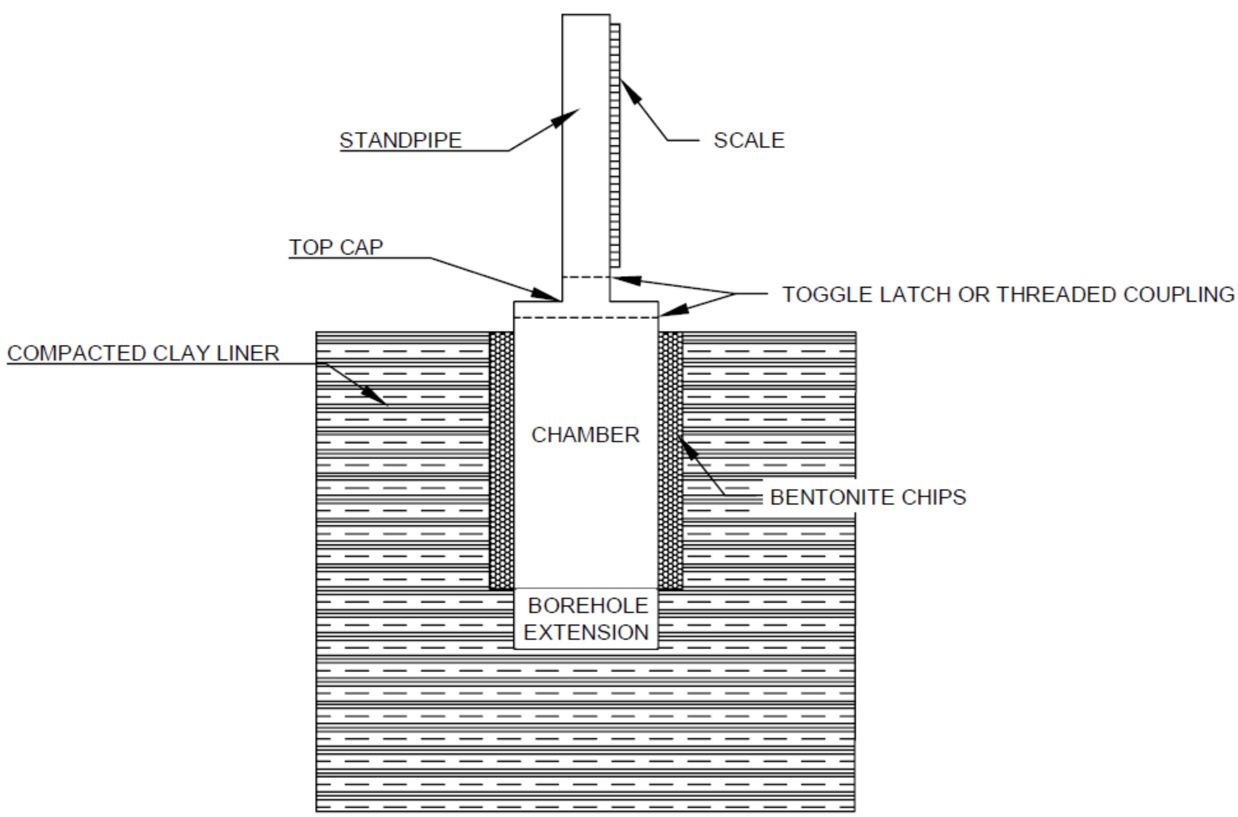

Figure 3 - Components of the Apparatus

The in-situ apparatus is sized to better characterize the field hydraulic conductivity of the system and reduce noise in the data. The standpipe has a smaller diameter, which is designed to obtain more sensitive readings. The cap and standpipe are removable from the rest of the cylinder to allow the borehole extension between stage 1 and stage 2 without removing the whole apparatus.

To make the method replicable, the ASTM Method A prescribes the procedure to carry out the test (ASTM, 2020). Every facility, location, and soil conditions are different and should be considered when designing an in-situ testing program. This study is not intended to replicate the prescriptive nature of the ASTM Method A; however, the following list summarizes the steps for this program to provide context for how the testing was conducted. Pictures of the installation process are included in Appendix A.

1. Drill borehole or dig hole with a minimum radius of 350 mm and depth of 600 mm (Photo 3);
2. Ream (the act of cutting a hole to accurate size) base of the hole and check for a clean surface (Photo 5);
3. Insert apparatus by placing into the hole without “driving” into the material;
4. Measure the distance from the floor to the cap;
5. Pour bentonite chips into annulus (gap between apparatus and hole walls) (Photo 12);
6. Saturate chips with approximately 10 L of water and let hydrate for 24 hours;
7. Place removeable geotextile sock filled with granular material at the base of the chamber;
8. Secure the vibrating wire piezometer to the top of the geotextile sock so it will not move;
9. Fill chamber and standpipe with approximately 100 L of water and check for leaks at all joints;

10. Initialize pressure readings/take standpipe reading;
11. Initialize pressure transducer outside the chamber to record atmospheric pressure (if unavailable from a nearby reliable source);
12. When flow stabilizes, drain water from chamber and remove cap. The ASTM Method A specifies when flow has stabilized;
13. Using the reaming tool, remove material directly below the chamber of the apparatus an additional 100 mm.
14. Inspect the floor is a clean surface and remeasure the distance from the floor to the cap; and
15. Refill apparatus and take readings until flow restabilizes.

The ASTM Method A goes into further detail for each step to prescribe steps and help reduce errors. Depending on the size of the program, site access and conditions, scheduling requirements and available budget, additional equipment may be used to help streamline the process. Optional equipment includes:

- Drill rig/piling auger to reduce manual labour for excavating the borehole
- Water truck/tote to have a constant supply of water for testing
- Sump pump to remove the water when advancing the borehole to stage 2
- Vibrating wire piezometer/pressure transducer to automate the standpipe readings and reduce time on-site

4.0 STUDY AREA

The study area was provided by a dairy farm in Southern Manitoba with a recently constructed EMS facility. The farm agreed to allow in-situ testing of their facility as third party research.

4.1 Surficial Geology

The site where the study was held is located near Landmark, Manitoba, approximately 20 km southeast of Winnipeg. A review of the surficial geology maps (SG-62H) produced by the Province of Manitoba indicates the soil conditions in the area consist of "*offshore glaciolacustrine sediments: clay, silt, minor sand; 1-20 m thick, very low relief massive and laminated deposits; deposited from suspension in offshore, deep water of glacial Lake Agassiz; commonly scoured and homogenized by icebergs"* (Matile & Keller, 2004). The study area is presented on an excerpt of the surficial geology map shown in Figure 4.

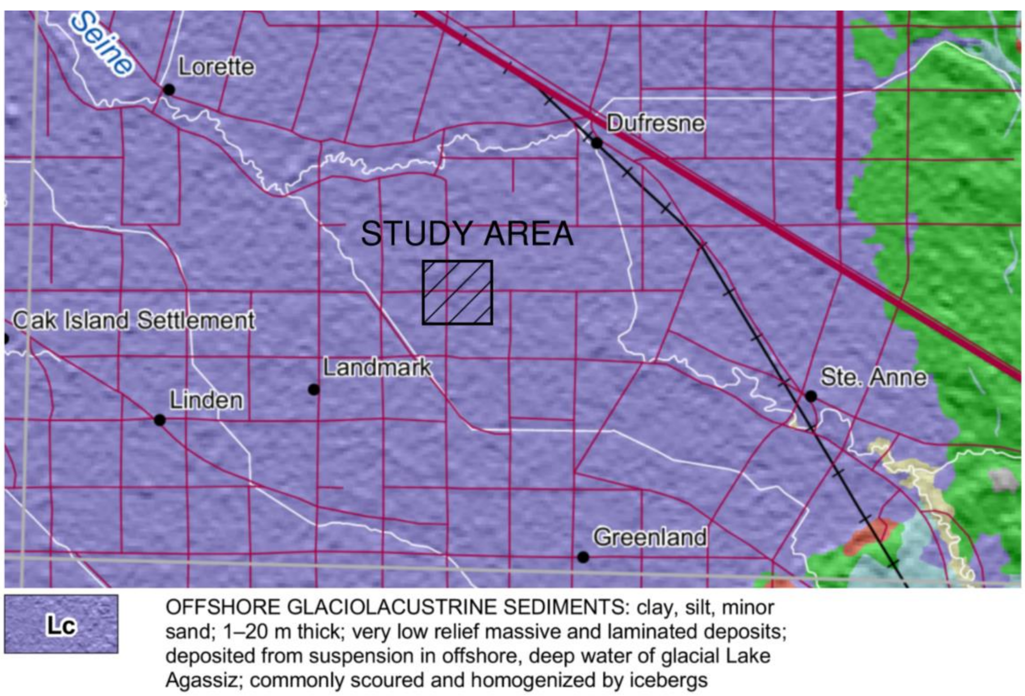

Figure 4 - Surficial Geology Map Excerpt (Matile & Keller, 2004)

A site investigation was conducted by BGC Engineering in which three test pits were excavated to depths of 3.4 m to 3.7 m below surface grade. A layer of clay was encountered in all test pits from 0.3 m to the depth explored. The layer was typically clay (CH), some silt, trace sand, trace gravel, damp to moist, high plastic, and stiff to firm. No water was encountered in any of the test pits throughout the site investigation.

4.2 EMS Facility

The EMS on-site was constructed in the summer of 2022 and is approximately 40 m wide and 330 m long. The crest of the embankments is 2.5 m above the original grade and has a height differential of 4.85 m from floor to crest. The floor is approximately 2.3 m below the original grade. Photos of the EMS are shown in Figure 5.

Figure 5 - Photos of EMS Floor (left) and Berm (right)

Additional site photos are available in Appendix A.

The compacted clay liner is 1 m in thickness and extends from the crest through the manure storage floor. In the fall of 2022, the EMS was in the commissioning stages for a manure storage permit, but it had not yet been approved. The embankments were constructed with existing on-site materials, placed in 0.15 m lifts, and compacted to 95% of maximum dry density (MDD) at moisture contents between 0.9% and 1.2% of the optimum moisture content (OMC). The liner was constructed with high plastic clay suitable for earthen liners.

5.0 FIELD PROGRAM

On October 25, 2022, Maple Leaf Drilling was on site to install the borehole infiltration apparatus and collect relatively undisturbed soil samples with Shelby tubes. The track mounted Geoprobe 7822DT drill rig was equipped with a 14" piling auger and a 275 gallon water tote.

5.1 Installation

On October 25, 2022, Maple Leaf Drilling was on site to install the borehole infiltration apparatus and collect relatively undisturbed soil samples using Shelby tubes. The track-mounted Geoprobe 7822DT drill rig, equipped with a 14-inch piling auger and a 275-gallon water tote, was used for the installation.

The field testing program involved two borehole locations at a single EMS site. The first test was conducted on the berm of the EMS, while the second test was conducted on the floor of the EMS. The berm test apparatus was installed on October 25, 2022, using the drill rig. Due to wet conditions the drill rig could not access the floor of the EMS, so the floor test apparatus was installed manually on October 26, 2022.

The installation procedure included drilling a 350 mm wide, 0.55 m deep hole, reaming the base to 0.60 m to produce a clean surface, and placing the chamber in the hole. Figure 6 shows the drilling of the borehole with the geotechnical drill rig.

Figure 6 - Drilling of Borehole Infiltration Chamber

The apparatus was placed in the borehole and bentonite pellets were placed in the annulus around the chamber and hydrated with water for 24 hours. A vibrating wire piezometer was then positioned at the bottom of the chamber and covered with pea gravel wrapped in a non-woven geotextile. The apparatus was filled with water to begin the testing process. Figure 7 shows the borehole infiltration apparatus immediately after installation, prior to the hydration of the bentonite pellets.

Figure 7 - Installation of Apparatus

After completing stage 1, the reaming tool was used to advance the borehole an additional 4 inches, and the apparatus was reset for stage 2 testing.

5.2 Infiltration Test

The infiltration tests were conducted in two stages. Stage 1 of the berm test began on October 26, 2022, and stage 2 commenced on October 30, 2022. The berm test concluded on November 1, 2022. For the floor test, stage 1 started on November 1, 2022, and stage 2 began on November 3, 2022, with the test concluding on November 5, 2022.

During the tests, the chamber was refilled with water daily, and time measurements were recorded in field notes. The water levels were also truthed against the standpipe scale to verify accuracy.

The data was collected using a single-channel DT2011B data logger manufactured by RST Instruments, which recorded the water level data within the apparatus every two minutes. The collected data was then downloaded in a CSV format and correlated with field notes based on time signatures.

5.3 Sample Collection

Sample collection was conducted with Shelby tubes pushed in the embankment berm, and with a hammer and wooden block in the floor when rig access or a manual tube pusher was not available. The block and hammer method is not in accordance with ASTM D1587 and therefore this sample would not be eligible to be used for commissioning purposes, however, may still provide data for a qualitative correlation. Samples obtained were brought back to the University of Manitoba geotechnical laboratory for testing.

6.0 THEORY

6.1 Working Equations

The ASTM Method A supplies guidelines for the data analysis of the in-situ borehole infiltration (ASTM, 2020) and the constant head hydraulic conductivity laboratory test (ASTM, 1997).

The general equation for the vertical hydraulic conductivity is:

Equation 2 - In-Situ Vertical Hydraulic Conductivity

$$k_1 = \frac{R_T G_1}{(t_2 - t_1)} \ln\left(\frac{Z_1}{Z_2}\right)$$

Where:

k_1 *is the vertical hydraulic conductivity, m/s*

R_T *is the temperature coefficient for the viscosity of water*

G_1 *is the geometric coefficient relating the diameter of the standpipe and borehole casing, m*

t *is the elapsed time, s*

Z *is the height of the water in the standpipe, m*

The general equation for the horizontal hydraulic conductivity is:

Equation 3 – In-Situ Horizontal Hydraulic Conductivity

$$k_2 = \frac{R_T G_2}{(t_2 - t_1)} \ln\left(\frac{Z_1}{Z_2}\right)$$

Where:

k_2 is the horizontal hydraulic conductivity, m/s

R_T is the temperature coefficient for the viscosity of water

G_2 is the geometric coefficient relating the diameter of the standpipe and dimensions of the borehole extension, m

t is the elapsed time, s

Z is the height of the water in the standpipe

The differentiator between the vertical and horizontal conductivity is based on G, which in Equation 2 describes the relationship between the diameter of the standpipe and the dimensions of the borehole extension. The geometric and temperature coefficients are described in the ASTM Method A.

The constant head test for the laboratory hydraulic conductivity testing described in ASTM D5084 uses a differential pressure to induce flow across a specimen under a confining pressure.

The general equation for vertical hydraulic conductivity from the constant head test is:

Equation 4 - Laboratory Vertical Hydraulic Conductivity

$$k = \frac{QL}{Ath}$$

Where:

k is the vertical hydraulic conductivity, m/s

Q is the quantity of flow through the specimen, m^3

L is the length of the specimen, m

A *is the cross-sectional area of the specimen,* m^2

t *is the time interval over which the flow Q occurs, s*

h *is differential pressure across the specimen measured in meters of hydraulic head, m*

6.2 Baseline Numerical Model

The numerical model uses the finite element software Seep/W by GeoStudio to map the flow from the borehole into the clay liner on the berm. The model specifies a fixed number of parameters that describe the underlying relationship between the variables in the model. A baseline model was produced using the basic assumptions of a clay liner overlying free-draining sand as eligible for commissioning in Manitoba. These assumptions include:

- A liner hydraulic conductivity of $1x10^{-9}$ m/s
- Underlying sand hydraulic conductivity of $1x10^{-2}$ m/s
- A hydraulic gradient of 1 m/m across the liner
- The liner is homogeneous
- Free-flowing lateral and lower boundary conditions
- Hydraulic head at the ground surface
- Undefined groundwater surface

Figure 8 shows the output of a modelled liner with adequately low permeability. Detailed outputs of the Seep/w including soil parameters and pressure contours may be found in Appendix B.

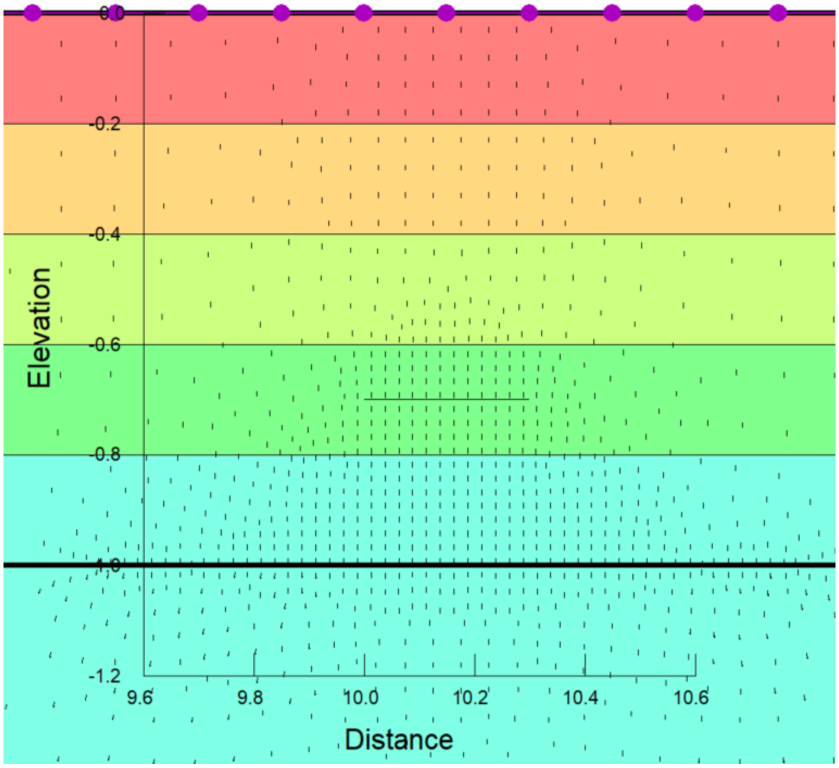

Figure 8 - Baseline Model

Figure 9 shows the estimate flux along the interface of the liner and the underlying sand soil, representing release to the environment and denoted as liner discharge.

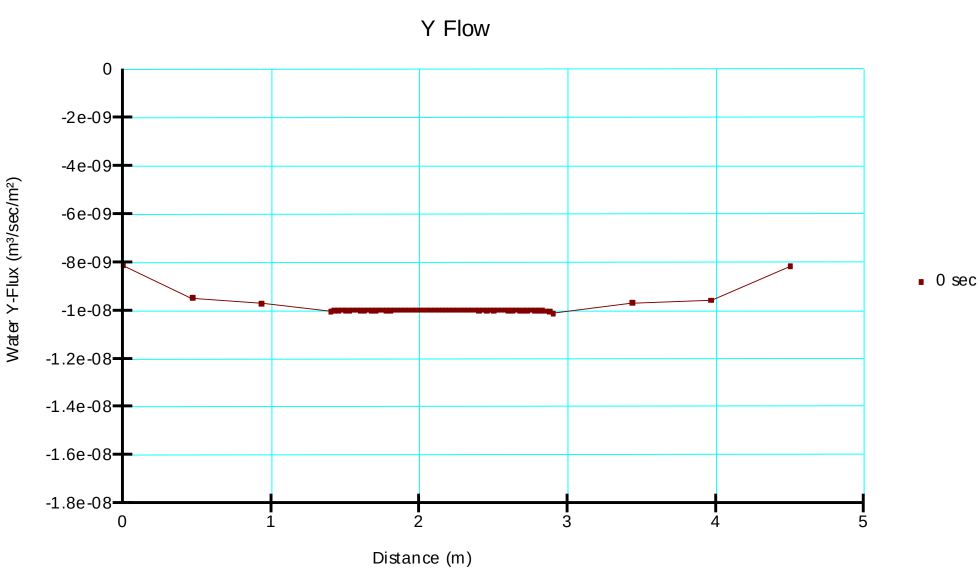

Figure 9 - Baseline Model Flux Output

For this idealized test condition flux at the lower liner interface is estimated to be 1.0e-8 $m^3/s/m^2$, or approximately 40 $mL/hr/m^2$

To represent the testing conditions of an idealized scenario, a 0.7 m deep and 0.3 m wide void is modelled into the liner with the hydraulic head modelled at ground surface. Figure 10 shows the output of a modelled 2-stage borehole infiltration test with an adequately impermeable liner.

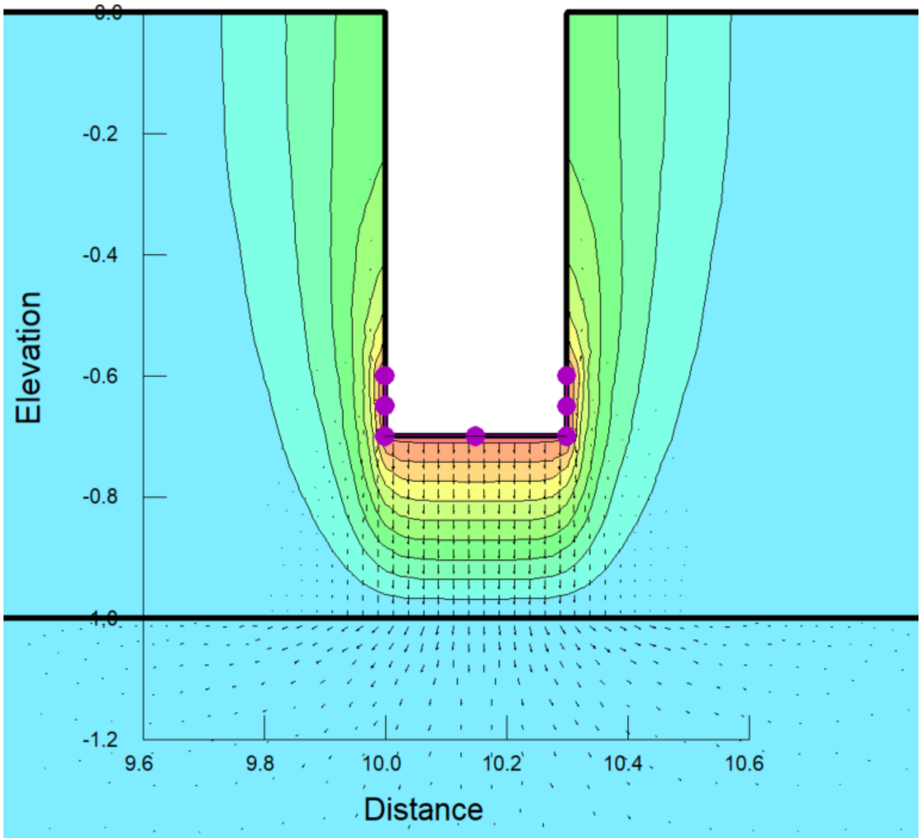

Figure 10 - Baseline Model Borehole Infiltration

A detailed output of the seepage model including soil parameters and pressure contours is included in Appendix B. Figure 11 shows the estimate flux along the interface of the liner and the underlying sand soil, representing release to the environment and denoted as liner discharge.

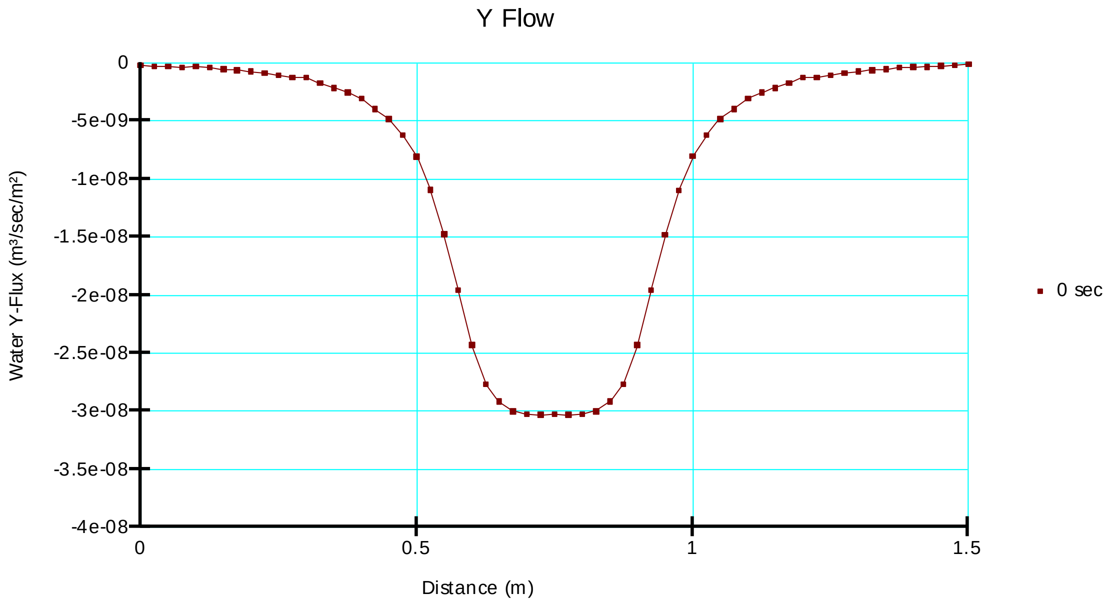

Figure 11 - Baseline Model Borehole Infiltration Flux Output

For this idealized test condition flux at the lower liner interface is estimated to be 3.0e-8 $m^3/s/m^2$, or approximately 110 $mL/hr/m^2$.

7.0 RESULTS AND ANALYSIS

7.1 In-Situ Testing

Two locations at the EMS were investigated with the borehole infiltration method. The tests were conducted at the crest of the berm and on the floor of the EMS and are referred to as the berm test and floor test respectively.

7.1.1 Berm Falling Head Test

Figure 12 illustrates the water height recorded during the progression of the berm test.

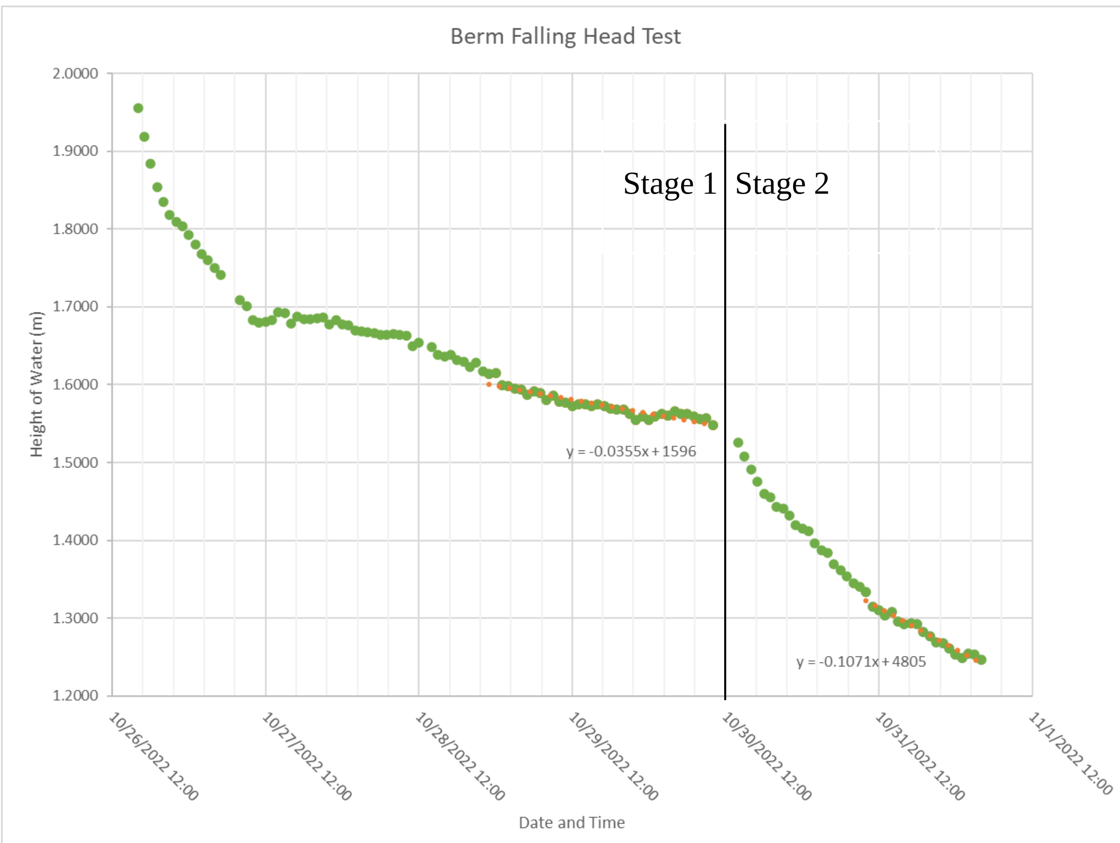

Figure 12 - Berm Falling Head Test Results

Table 3 summarizes the calculation of the hydraulic conductivity of the berm material for stage 1 and stage 2 of the borehole infiltration test using equations 2 and 3. The points that best indicated linear behaviour were collected from Figure 12 and used for the calculation.

Table 3 - Analysis of Berm Falling Head Test

Time	***Reading***	***Temp***	***Δt, (t2 - t1)***	***H_1***	***H_2***	***Rt***	***K***
	cm	*deg C*	*s*	*cm*	*cm*	*[-]*	*cm/s*
10/27/2022 8:00	170.9	5.57	0		405.9		
10/28/2022 14:00	164.8	6.72	108000	405.9	399.8	1.488	2.0E-07
10/28/2022 23:00	161.4	7.18	32400	399.8	396.4	1.460	3.7E-07
10/30/2022 9:00	155.7	5.77	122400	396.4	390.7	1.550	1.7E-07
10/30/2022 15:00	150.8	8.38	0		385.8	1.396	
10/31/2022 10:00	133.4	8.74	68400	385.8	368.4	1.378	1.6E-08
11/1/2022 3:00	125.4	8.73	61200	368.4	360.4	1.378	8.3E-09

The vertical and horizontal hydraulic conductivity is $k_y = 2x10^{-9}$ m/s and $k_x = 8x10^{-11}$ m/s respectively and the k_y/k_x ratio is approximately 20.

The vertical flux at the end of stage 1 is 186 mL/hr/m^2.

7.1.2 Floor Falling Head Test

Figure 13 illustrates the water height recorded during the progression of the floor test.

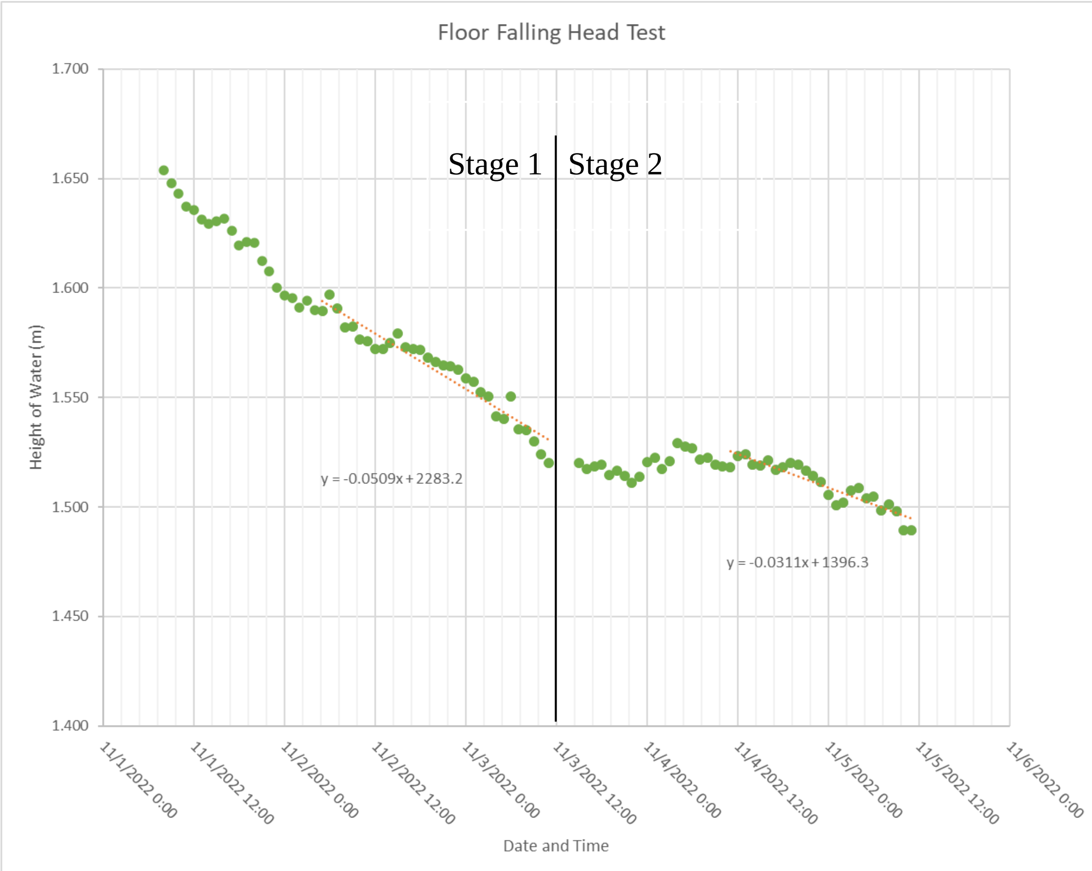

Figure 13 - Floor Falling Head Test Results

Table 4 summarizes the calculation of the hydraulic conductivity of the floor material for stage 1 and stage 2 of the borehole infiltration test using equations 2 and 3. The points that best indicated linear behaviour were collected from Figure 5 and used for the calculation.

Table 4 - Analysis of Floor Falling Head Test

Time	***Reading***	***Temp***	***Δt, (t2 - t1)***	***H_1***	***H_2***	***R_t***	***K***
	cm	*deg C*	*s*	*cm*	*cm*	*[-]*	*cm/s*
11/1/2022 8:00	165.4	5.8	108000		400.4		
11/3/2022 10:00	155.7	6.6	180000	400.4	390.7	1.495	1.75E-06
11/3/2022 15:00	152	6.08		235	387	1.529	
11/4/2022 17:00	151.7	5.54	93600	387	386.7	1.567	7.17E-08
11/5/2022 11:00	148.9	5.44	64800	386.7	383.9	1.574	9.75E-07

The vertical and horizontal hydraulic conductivity is $k_y = 2x10^{-8}$ m/s and $k_x = 1x10^{-10}$ m/s respectively and the k_y/k_x ratio is approximately 200.

7.2 Laboratory Constant Head Testing

The Shelby tube samples that were collected at the same time and corresponding location of the berm and floor borehole method tests were analyzed using laboratory methods at the University of Manitoba.

7.2.1 Berm Constant Head Test

Table 5 summarizes the results for the flexible walled permeability test on the berm material and calculations for vertical hydraulic conductivity using Equation 4.

Table 5 - Analysis of Berm Constant Head Test

Time	***Δt***	***Bot Burette***	***Top Burette***	***Delta h***	***Velocity, m/s***	***Flow, Q***	***k***
	s	*m*	*m*	*m*	*m/s*	*m^3*	*m/s*
2/22/2023 17:42		0.11	0.292				
2/22/2023 20:00	8280	0.112	0.291	0.0015	1.8E-07	4.7E-07	4.7E-10
2/23/2023 13:35	63300	0.115	0.289	0.0025	3.9E-08	7.9E-07	1.0E-10
2/26/2023 9:57	246120	0.121	0.283	0.006	2.4E-08	1.9E-06	6.3E-11
3/1/2023 10:55	262680	0.127	0.276	0.0065	2.5E-08	2.0E-06	6.4E-11
3/2/2023 11:10	87300	0.128	0.276	0.0005	5.7E-09	1.6E-07	1.5E-11

At the final time step, the measured hydraulic conductivity to one significant figure is $k = 2x10^{-11}$ m/s.

7.2.2 Floor Constant Head Test

Table 6 summarizes the results for the flexible walled permeability test on the floor material and calculations for vertical hydraulic conductivity using Equation 4.

Table 6 - Analysis of Floor Constant Head Test

Time	***Δt***	***Bot Burette***	***Top Burette***	***Delta h***	***Velocity, m/s***	***Flow, Q***	***k***
	s	*m*	*m*	*m*	*m/s*	m^3	*m/s*
2/22/2023 17:42		0.071	0.32				
2/22/2023 17:46	240	0.081	0.325	0.0025	1.0E-05	7.9E-07	2.7E-08
2/22/2023 17:52	360	0.085	0.315	0.007	1.9E-05	2.2E-06	5.0E-08
2/22/2023 18:30	2280	0.098	0.301	0.0135	5.9E-06	4.2E-06	1.5E-08
2/22/2023 20:00	5400	0.144	0.254	0.0465	8.6E-06	1.5E-05	2.2E-08

At the final time step, the measured hydraulic conductivity to one significant figure is k = $2x10^{-8}$ m/s.

It should be noted rootlets were observed in the specimen after testing and the hydraulic conductivity value will be skewed from this. The typical Shelby tube method would have discarded this sample on site however for the purpose of the study the data is used as a qualitative observation.

7.3 Summary Table

Table 7 summarizes the comparison of the ASTM Method A borehole infiltration method to the constant head laboratory method which is most commonly used in industry for current EMS applications.

Table 7 - Summary of Hydraulic Conductivity Values

Location	***Borehole Infiltration Hydraulic Conductivity***		***Constant Head Hydraulic Conductivity***
	Ky [m/s]	*Kx [m/s]*	*K [m/s]*
Berm	$2x10^{-9}$	$8x10^{-11}$	$2x10^{-11}$
Floor	$2x10^{-8}$	$1x10^{-10}$	$2x10^{-8}$*

*Rootlet observed in sample

By the commissioning requirements of a maximum vertical hydraulic conductivity of $1x10^{-9}$, as measured by the flexible walled permeability test the berm element would pass, and the floor element would fail. The same conclusion is reached by the borehole infiltration method for the berm test, and inconclusive for the floor test.

7.4 Numerical Model Calibration

In this model, the horizontal and vertical hydraulic conductivity was specified based on the results of the in-situ testing. Other specified parameters include the depth of the groundwater table, the hydraulic head in the borehole, the geometry of the system, and the properties of the underlying material.

The numerical model replicated the berm borehole infiltration for the duration of the test and extrapolates the time frame to a steady state condition. The properties of the surrounding environment is an important factor to understand the implications of the water flow through the clay liner and for the development of the model. As the underlying soil is not considered in the Province of Manitoba’s specifications, a material with a low hydraulic conductivity may be selected based on the geotechnical investigation conducted on the site. The underlying soil was modeled as clay with a saturated vertical hydraulic conductivity of $1x10^{-7}$ m/s and a hydraulic anisotropic ratio of 1 (Budhu, 2006).

The clay liner is modelled as saturated to represent the conditions likely during the operation of the EMS. The flow of water through the liner is depicted in Figure 14 and quantified in Figure 15.

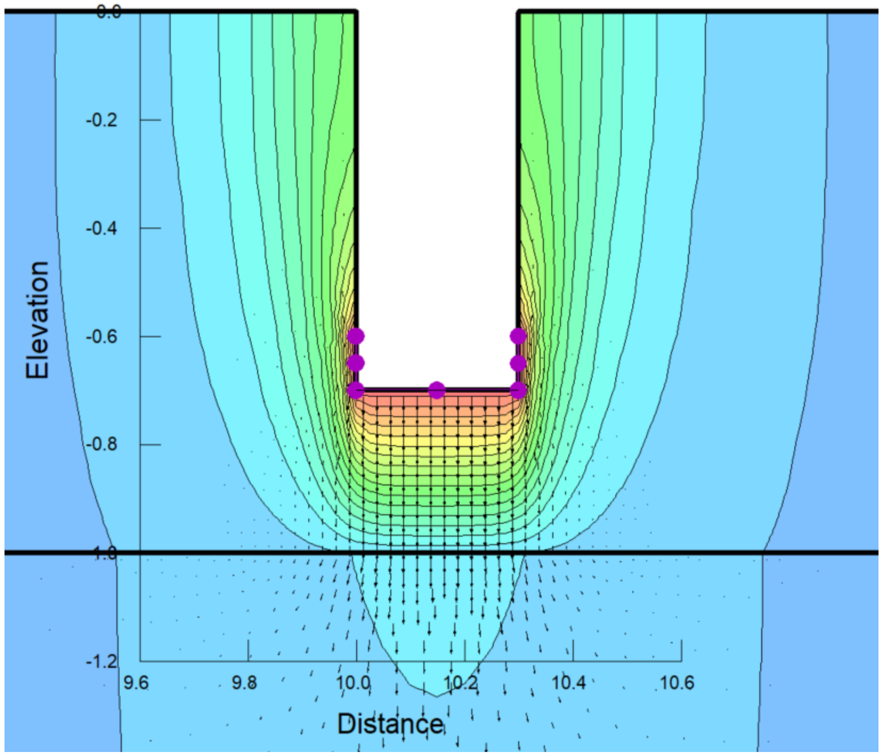

Figure 14 - Seep/W Output for Stage 2 Testing

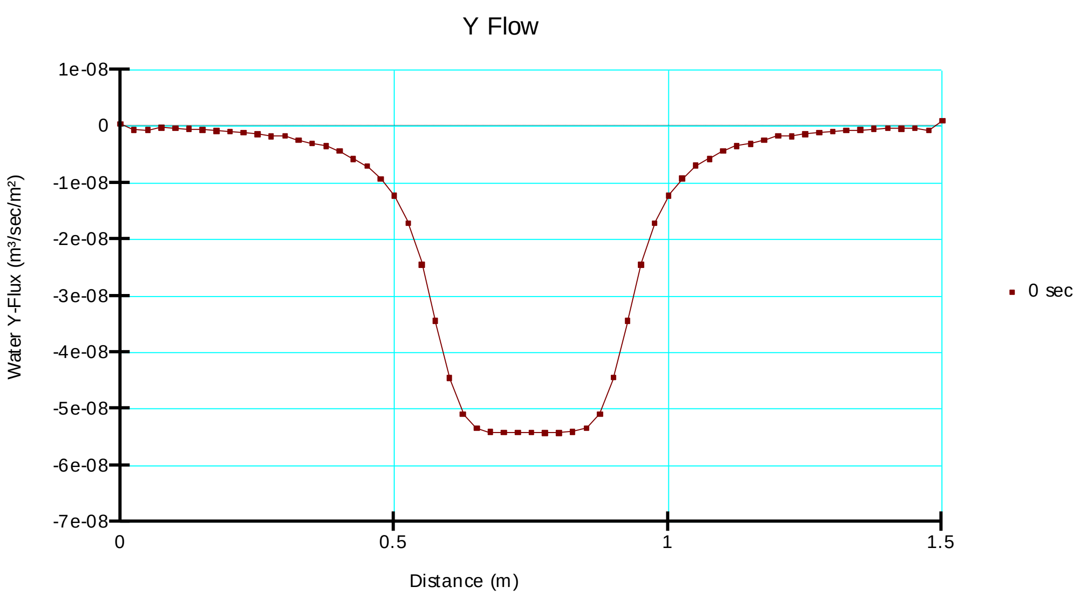

Figure 15 - Seep/W Calculation of Vertical Flux

A detailed output of the seepage model including soil parameters and pressure contours is included in Appendix B.

The flux at the base of the chamber is plotted in Figure 12 and calculated as $5.4x10^{-8}$ $m^3/sec/m^2$, which is equivalent to approximately 200 mL/hr/m^2. When this value is compared to the baseline numerical model, the estimated flux below the base of the chamber is approximately two times greater than the baseline value of 110 mL/hr/m^2 for this geometry. When the full depth of the liner is calibrated within numerical model the numerical model, the estimated liner discharge is 61 mL/hr/m^2, which is approximately 1.5 times greater than the baseline value of 40 mL/hr/m^2 determined in Section 6.2 The conclusion of the borehole infiltration method is consistent with the traditional method and indicates the liner would not be eligible for commissioning.

The implication of a calibrated numerical model may allow engineers to consider hydraulic conductivity as an input parameter for designing liners instead of a performance criterion.

8.0 FINITE ELEMENT LINER DISCHARGE MODEL

As discussed in previous sections, hydraulic conductivity is the primary metric used for commissioning waste lagoons in Manitoba. Hydraulic conductivity measures the ability of water to flow through a defined volume of soil but is only one variable that characterizes the system. A better metric for characterizing the entire system is by measuring the liner discharge, which is measured by the total flow through the liner and may be modelled as flux with the units $m^3/s/m^2$ or $mL/hr/m^2$. The criteria for commissioning an EMS in Manitoba specifies a 1 m thick clay liner must have a minimum hydraulic conductivity of $1x10^{-9}$ m/s, which corresponds to a maximum flux of 40 $mL/hr/m^2$.

There are numerous parameters which may be adjusted within an liner discharge model to achieve an equivalent baseline flux.

8.1 Liner Thickness

Considering the same liner properties as measured in the berm test where the hydraulic conductivity was $2x10^{-9}$ m/s, the thickness of the liner was varied to determine an equivalent flux to the baseline model. Table 8 summarizes the liner thickness with a corresponding flux under the same hydraulic head, and is graphically presented in Figure 16 - Flux Based on Variation in Liner Thickness.

Table 8 - Flux Based on Variation in Liner Thickness

Thickness (m)	***Flux***	
	m3/s/m2	*mL/hr/m2*
1	1.70E-08	61
1.5	1.25E-08	45
2	1.00E-08	36

2.5	8.60E-09	31
3	7.50E-09	27
3.5	6.80E-09	24
4	6.20E-09	22

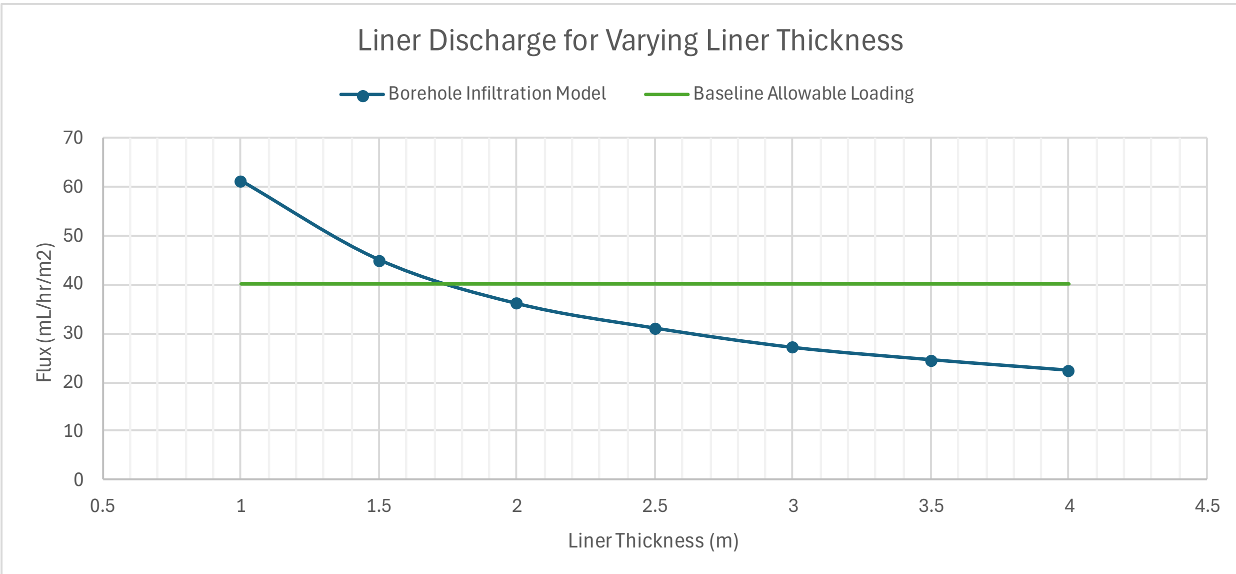

Figure 16 - Flux Based on Variation in Liner Thickness

Figure 16 shows that if the liner was approximately 1.8 m thick, the liner discharge would be equivalent to the baseline model. Furthermore, as the thickness of the liner is increased, the effectiveness of the incremental change is diminished.

8.2 Underlying Soil

The conditions of the underlying soil contribute heavily to the magnitude of flux of the liner system. In this model the parameters of the underlying soil observed in the geotechnical investigation are assumed however more advanced models may be calibrated with in-situ or laboratory testing. The underlying high plastic clay is assumed to have a saturated vertical hydraulic conductivity of $1x10^{-7}$ m/s and a hydraulic anisotropic ratio of 10 (Budhu, 2006).

Table 9 summarizes the scenario of the results of the berm liner which has been modelled with varying underlying soil conditions and is graphically presented in Figure 17.

Table 9 - Flux Based on Variation in Hydraulic Conductivity of Underlying Soil

Ky of Underlying Soil (m/s)	***Flux***	
	m3/s/m2	*mL/hr/m2*
1.00E-07	1.70E-08	61.2
9.00E-08	1.67E-08	60.12
5.00E-08	1.47E-08	52.92
3.00E-08	1.25E-08	45
2.00E-08	1.00E-08	36
1.00E-08	7.10E-09	25.56
5.00E-09	4.30E-09	15.48

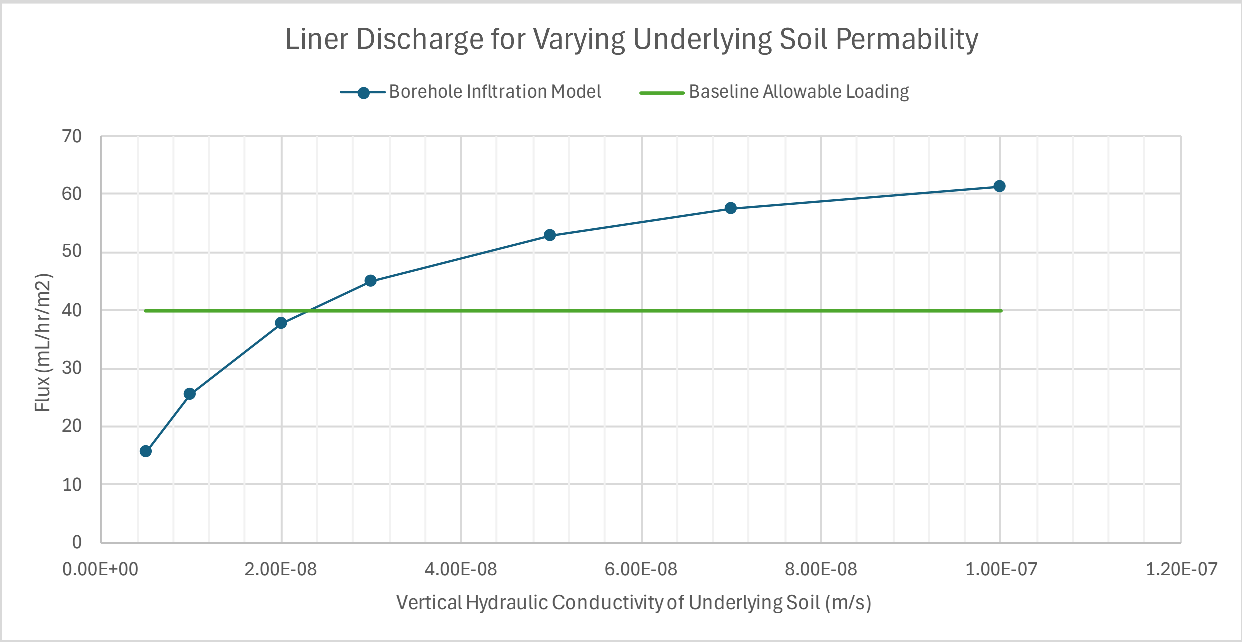

Figure 17 - Flux Based on Variation in Hydraulic Conductivity of Underlying Soil

Figure 17 shows that if the underlying soil had a vertical hydraulic conductivity of approximately 2.4×10^{-8} m/s, the liner discharge would be equivalent to the baseline model.

A sensitivity analysis was conducted for varying hydraulic anisotropic ratios of the underlying soil and found the model is not sensitive to this parameter.

8.3 Other Factors

The liner discharge model may be influenced by other parameters such as a differing hydraulic conductivity anisotropy ratio (Ky'/Kx') of the liner, groundwater levels and flow direction, variable soil conditions, operational pond levels, sloping infrastructure, atypical boundary conditions, and other physical elements. Depending on the severity of the influence and complexity of the liner discharge model, each factor may be account for through a measured or assumed parameter to enhance the accuracy of the model.

8.4 Model Advancement Opportunities

This model was developed based on one borehole infiltration test to analyze the results and determine liner discharge. More advanced models should consider a series of tests at a site to determine the model parameters.

9.0 LINER DISCHARGE CURVES

Based on the expected range of test results and site conditions typical for clay-lined facilities in Manitoba, a series of Liner Discharge Curves (LDC) have been developed through a series of 180 numerical models to aid in the estimation of discharge from a liner system. The LDC compares the liner discharge to the hydraulic conductivity of the liner and were developed from the numerical modeling output. They are useful to estimate the hydraulic loading based on the system the liner is acting in.

9.1 Underlying Soil Condition Model

Figure 18 plots a series of LDCs representing the measured hydraulic conductivity of a 1 m thick clay liner and shows the associated liner discharge when varying the underlying soil conditions. Full scale curves may be found in Appendix C.

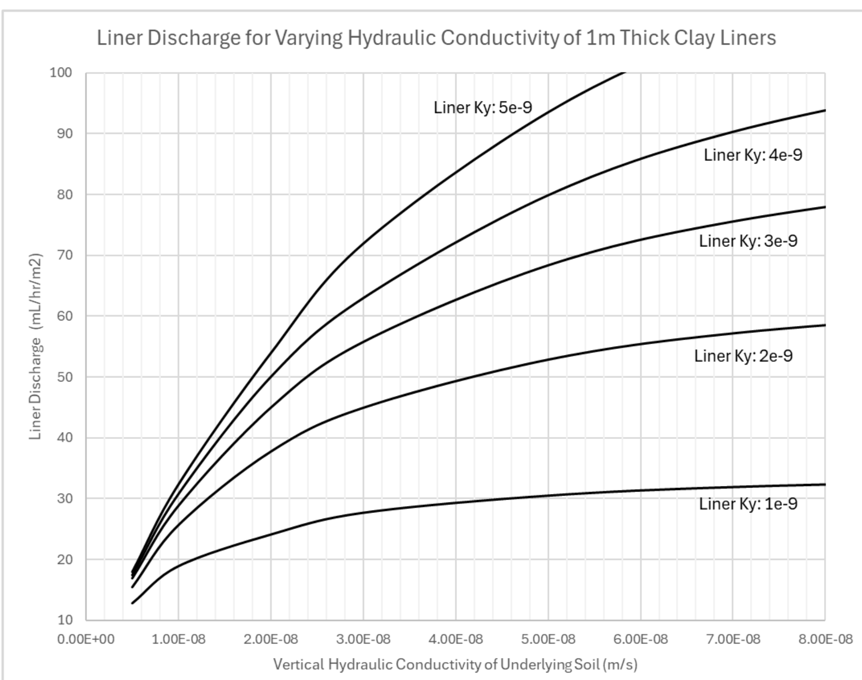

Figure 18 - Liner Discharge Curves for a 1 m Thick Clay Liner

9.2 Liner Thickness Sensitivity

The thickness of the liner is another variable influencing the liner discharge of the system. Increasing the thickness of the liner reduces the hydraulic gradient across the material and therefore reduces flow. Figure 19 shows a series of LDC envelops based on varying the thickness of the liner from 1 m to 2 m.

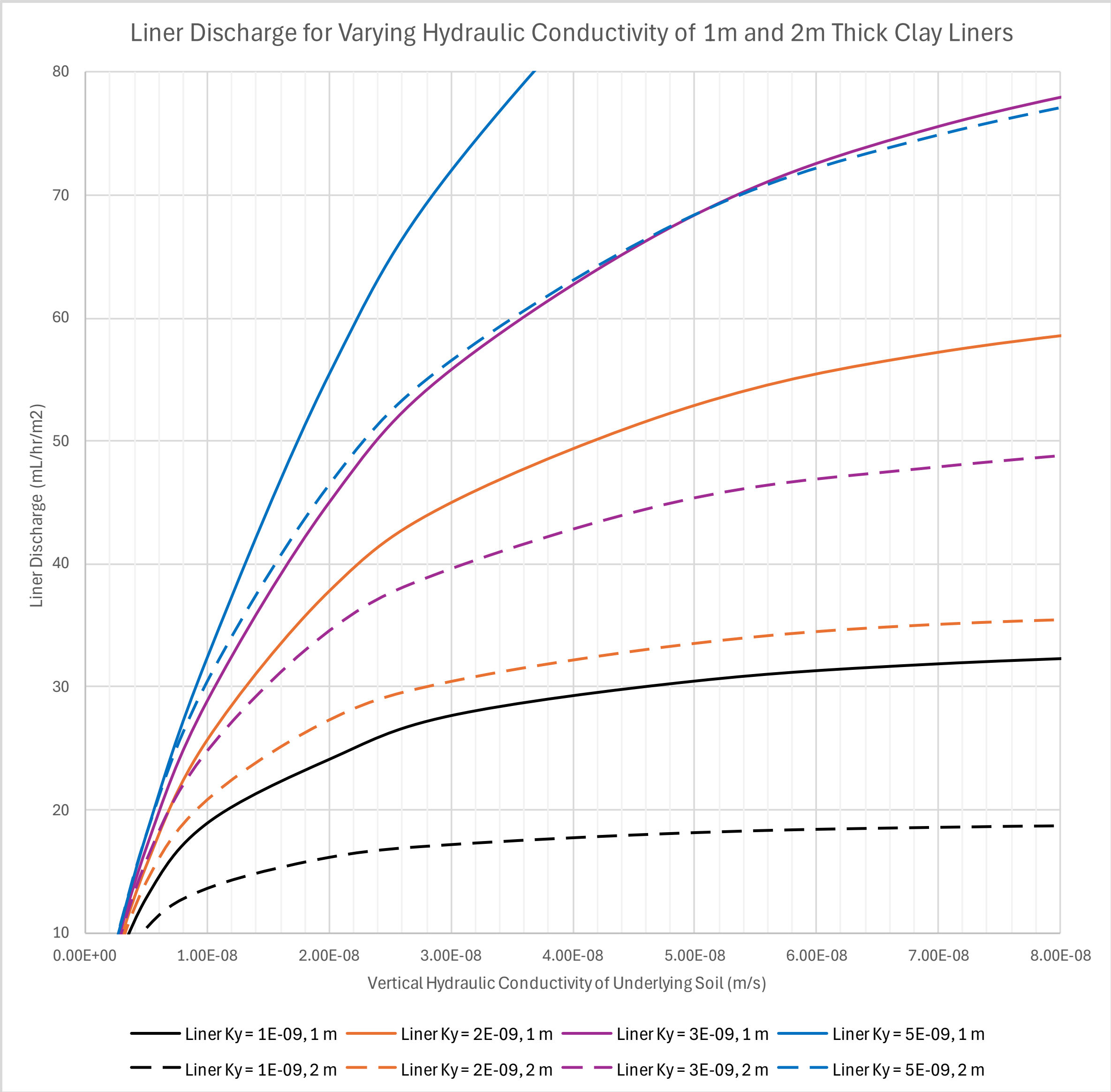

Figure 19 - Liner Discharge Curve Envelopes for 1 m and 2 m Thick Liners

Figure 20 shows the liner discharge sensitivity due to varying the liner thickness.

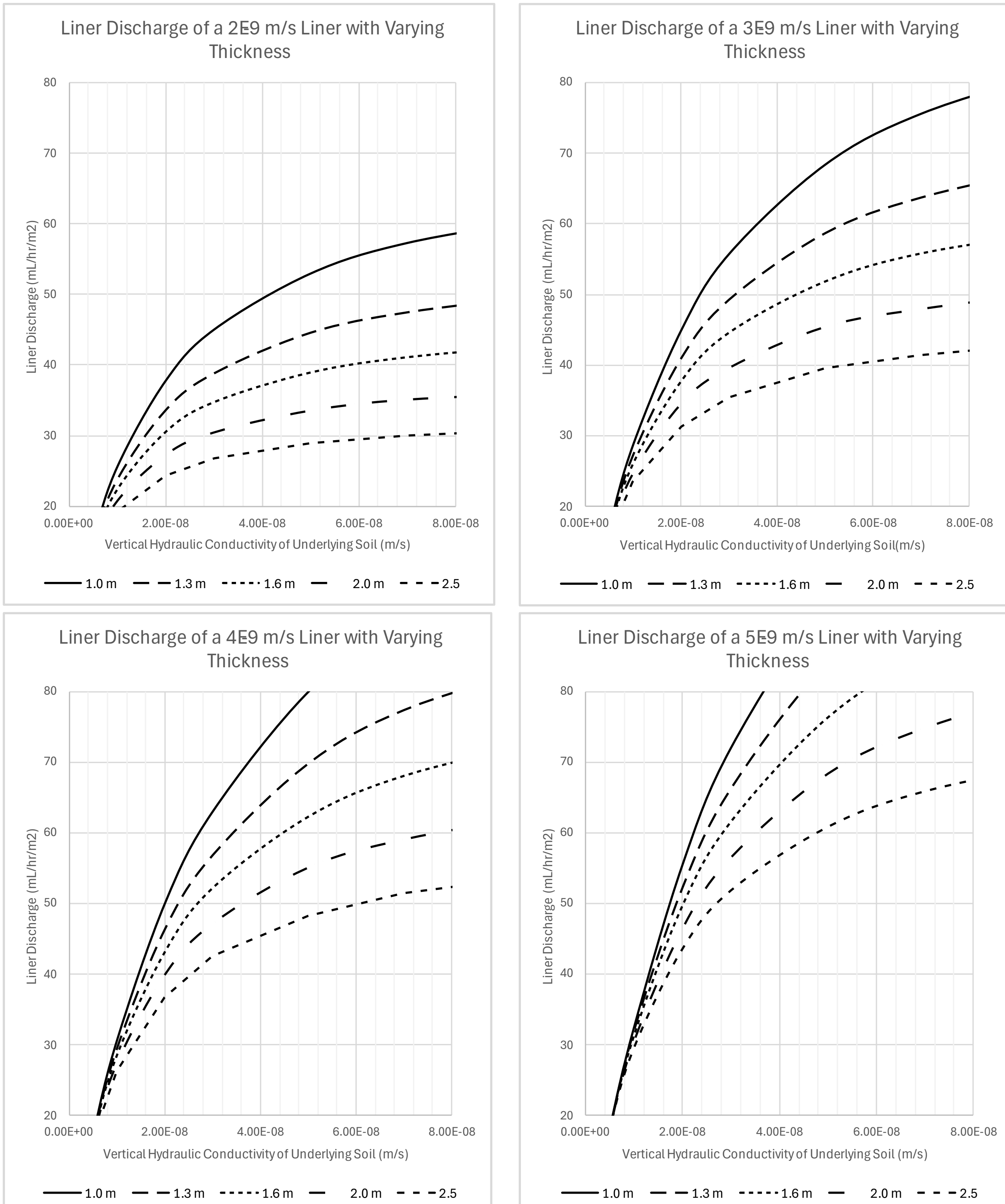

Figure 20 - Liner Discharge Curve Sensitivity with Liner Thickness

Table 10 provides a condensed summary of estimated liner discharge based on the combinations of hydraulic conductivity of the liner, underlying soil conditions, and liner thickness. A detailed table including a baseline a higher resolution of the underlying soil conductivity is provided in Appendix C.

Table 10 - Condensed Liner Discharge Summary

Liner Conductivity (m/s)	***Underlying Conductivity (m/s)***	***Liner Thickness (m)***	***Liner Discharge (mL/hr/m2)***
2E-09	1E-07	1.0	61
		1.3	50
		1.6	43
		2.0	36
	5E-08	1.0	53
		1.3	45
		1.6	39
		2.0	34
	1E-08	1.0	26
		1.3	24
		1.6	22
		2.0	21
3E-09	1E-07	1.0	82
		1.3	68
		1.6	59
		2.0	50
	5E-08	1.0	68
		1.3	59
		1.6	52
		2.0	45
	1E-08	1.0	29
		1.3	27
		1.6	26
		2.0	25
4E-09	1E-07	1.0	100
		1.3	84

		1.6	73
		2.0	63
	5E-08	1.0	80
		1.3	70
		1.6	62
		2.0	55
	1E-08	1.0	31
		1.3	30
		1.6	29
		2.0	27
5E-09	1E-07	1.0	126
		1.3	106
		1.6	93
		2.0	81
	5E-08	1.0	94
		1.3	84
		1.6	76
		2.0	68
	1E-08	1.0	32
		1.3	32
		1.6	31
		2.0	30

9.3 Practical Example

The LDCs may be used to interpret data obtained on site and estimate the liner discharge. For example, an EMS facility in southern Manitoba may have the following properties:

- A 1 m thick compacted clay liner
- A hydraulic conductivity of 2.1×10^{-9} m/s, measured via a flexible walled permeability test
- Underlying high plastic clay with a hydraulic conductivity of 4×10^{-8} m/s, measured via a slug test during the geotechnical investigation

Based on provincial regulations, this site would not be eligible for commissioning based on the measured hydraulic conductivity of the liner being greater than $1x10^{-9}$ m/s.

9.3.1 Graphical Solution

Using Figure 18 developed in Section 9.1, the liner discharge may be estimated based on the measured parameters and is shown on Figure 21.

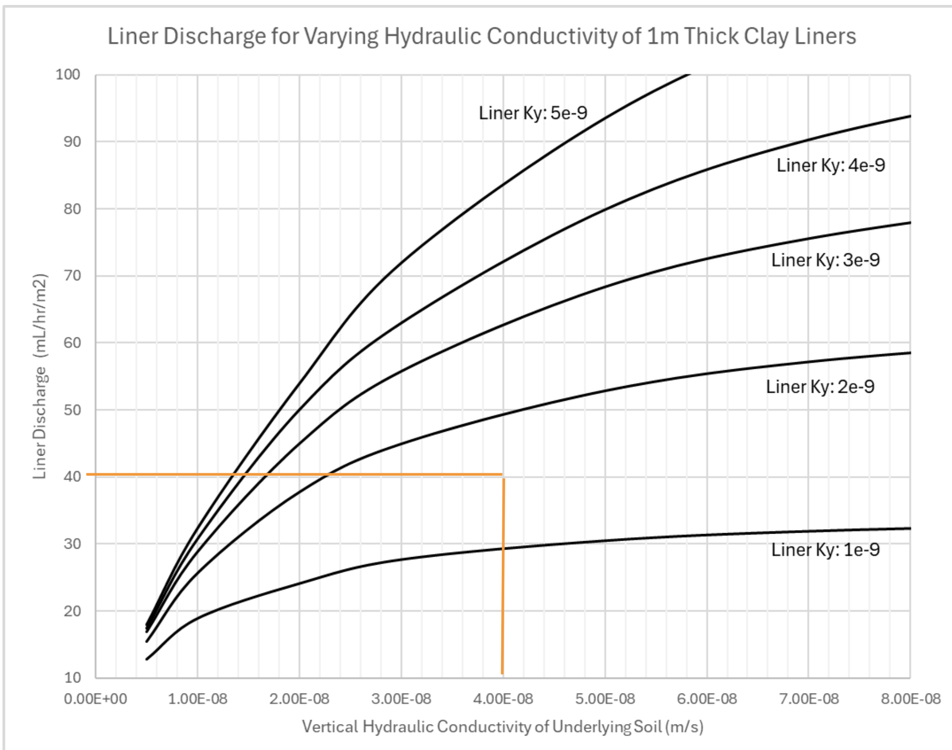

Figure 21 - Example Liner Discharge Estimation from Graphical Solution

Based on the Figure 21, the system would have an liner discharge of approximately 50 mL/hr/m^2, which is greater than the threshold limit of 40 mL/hr/m^2 established in Section 6.2.

To achieve the threshold limit, the thickness of the liner may be increased, as shown on Figure 22.

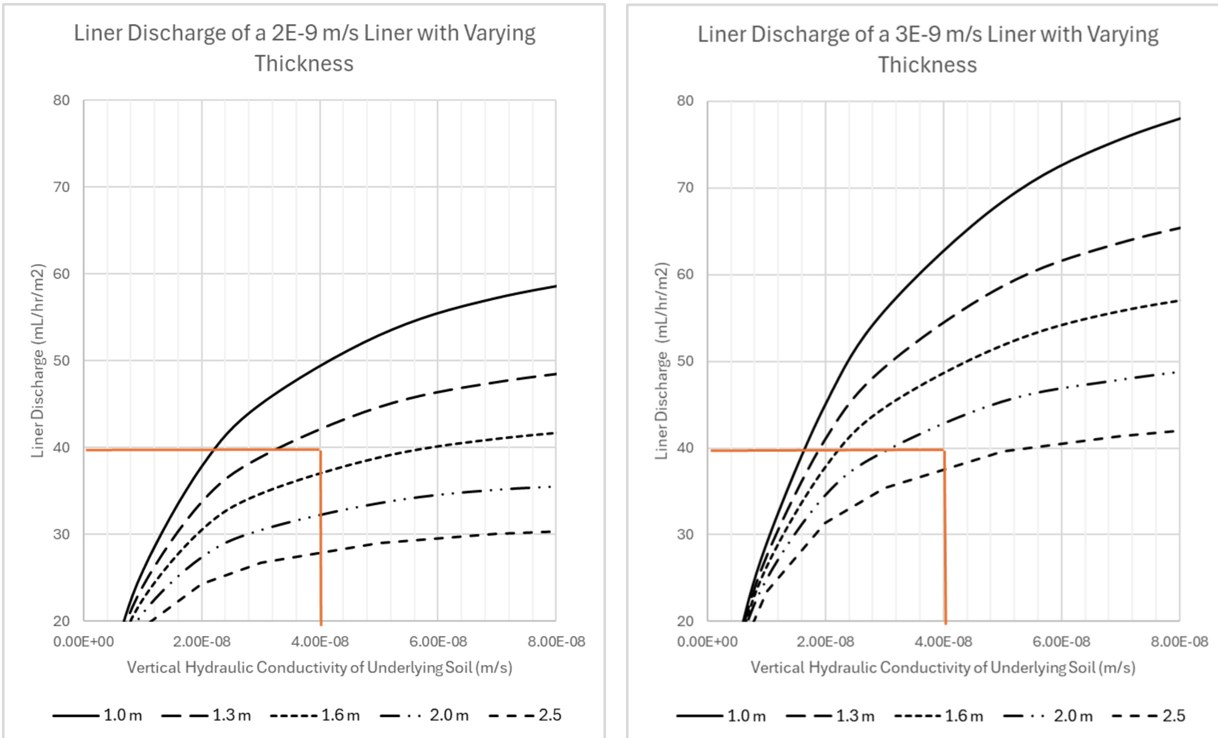

Figure 22 - Example Design Thickness from Graphical Solution

Based on the graphical solution, the equivalent liner thickness would be between 1.4 m and 2.3 m thick. As the measured hydraulic conductivity of the clay liner is 2.1×10^{-9} m/s, a value closer to 1.4 should be selected. For this site if the thickness of the liner was increased to approximately 1.5 m, a hydraulic loading equivalent to provincial regulations may be achieved.

9.3.2 Tabular Solution

Table 10 developed in Section 9.2 may also be used to conduct the analysis for the example site. An excerpt of the expanded table provided in Appendix C is used for the calculation of the liner thickness by interpolation.

Liner Conductivity (m/s)	Underlying Conductivity (m/s)	Liner Thickness (m)	Liner Discharge (mL/hr/m2)
2E-09	7E-08	1.0	57
		1.3	48
		1.6	41
		2.0	35
		2.5	30
	5E-08	1.0	53
		1.3	45
		1.6	39
		2.0	34
		2.5	29
	3E-08	1.0	45
		1.3	39
		1.6	35
		2.0	30
		2.5	27
	2E-08	1.0	38
		1.3	34
		1.6	31
		2.0	27
		2.5	24
	1E-09	-	4
3E-09	7E-08	1.0	76
		1.3	64
		1.6	56
		2.0	48
		2.5	41
	5E-08	1.0	68
		1.3	59
		1.6	52
		2.0	45
		2.5	40
	3E-08	1.0	56
		1.3	49
		1.6	45
		2.0	40
		2.5	35
	2E-08	1.0	45
		1.3	41
		1.6	38
		2.0	35
		2.5	31
	1E-09	-	4

$$y = y1 + (x - x1) \times (y2 - y1) / (x2 - x1)$$

Y - Interpolated Load
Y1 - Lower Load
Y2 - Higher Load

X - Measured Underlying
X1 - Higher Permiable Underlying
X2 - Lower Permiable Underlying

K, Underlying	Thickness	Load
4.00E-08	1.3	42
	1.6	37

Y - Liner Thickness
Y1 - Lower Thickness
Y2 - Higher Thickness

X - Target Load
X1 - Higher Load
X2 - Lower Load

Target Discharge	Thickness	Design Thickness
40	1.3	1.49
	1.6	

Y - Interpolated Load
Y1 - Lower Load
Y2 - Higher Load

X - Measured Underlying
X1 - Higher Permiable Underlying
X2 - Lower Permiable Underlying

K, Underlying	Thickness	Load
4.00E-08	2.0	42
	2.5	37

Y - Liner Thickness
Y1 - Lower Thickness
Y2 - Higher Thickness

X - Target Load
X1 - Higher Load
X2 - Lower Load

Target Load	Thickness	Design Thickness
40	2.0	2.25
	2.5	

Y - Liner Thickness
Y1 - Lower Thickness
Y2 - Higher Thickness

X - Measured Liner Conductivity
X1 - Higher Conductivity
X2 - Lower Conductivity

Thickness Interpolation

K, Measured	K, Liner	Thickness	Design Thickness
2.1E-09	2.0E-09	1.49	1.57
	3.0E-09	2.25	

According to the tabular solution, if the thickness of the liner was increased to 1.6 m, a hydraulic loading equivalent to provincial regulations may be achieved.

9.3.3 Numerical Model Solution

A finite element numerical model was produced based on the results of the tabular solution with a 1.6 m thick liner. As the anisotropy of the liner is unknown from the flexible walled permeability test, a Ky/Kx value of 10 was assumed and the liner discharge was calculated to be 38.5 mL/hr/m^2. The numerical model was updated to consider if an additional thickness of 0.25 m with a hydraulic conductivity of $1x10^{-9}$ m/s was constructed on top of the existing liner, the equivalent liner discharge of the system would be 38.8 mL/hr/m^2. The output of the composite liner numerical model is shown in Figure 23.

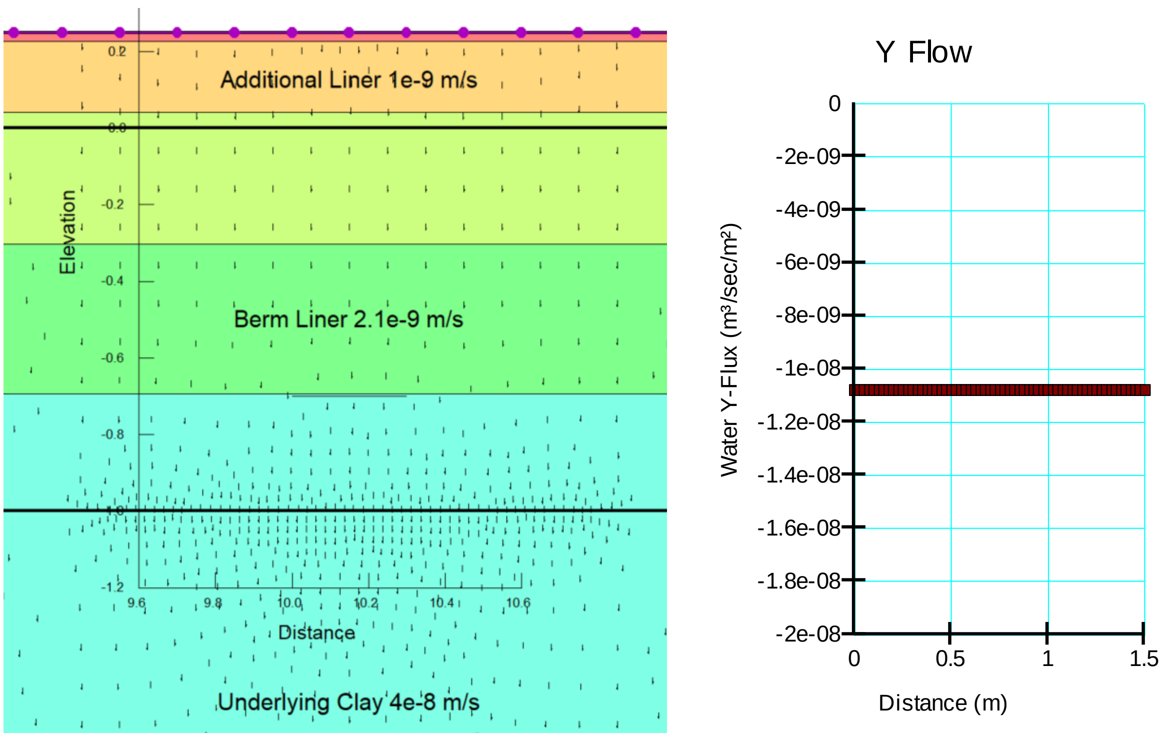

Figure 23 - Composite Layered Liner Discharge

A detailed output of the seepage model including soil parameters and pressure contours is included in Appendix B.

10.0 DISCUSSION

10.1 Interpretation of Results

The results of each testing program are consistent within the expected ranges for hydraulic conductivity for clay materials. For low hydraulic conductivity materials such as clay liners, the measured hydraulic conductivity may vary by multiple orders of magnitude between comparable samples under similar testing conditions. As expected, the floor and berm borehole infiltration tests experience similar flow rates compared to each other. The number of tests is too few to establish a statistically significant correlation between the in-situ and laboratory methods.

A high anisotropy of the soil was observed in the berm test with much higher vertical flows than horizontal flows, which is indicated by the k_y/k_x ratio of 20. The soil in the floor test was determined to be an order of magnitude less anisotropic than the berm test, which is indicated by the k_y/k_x ratio of 2. It is expected that during the construction of the liner, the reconstitution of the clay alters the varved structure of the particles and modifies the traditional flow of water through the soil. Many factors may influence the anisotropy of the soil including the mechanics of the soil's genesis, previous land use such as alfalfa growth, freeze thaw cycles, handling of the material during construction, and compaction methods. It may need to be considered in the development of a liner discharge model.

10.2 Methodology Strengths and Weaknesses

The in-situ measurement of the hydraulic conductivity of a soil liner may be time-consuming while on-site and requires qualified personnel for the installation and execution of the test.

Although imperfect testing conditions may be anticipated and mitigated factors such as weather, wildlife, and other external issues may have an influence on the test results.

The rootlet found in the laboratory test for the liner floor is an example of a preferential flow pathway being observed, however because of the small sample size it skews the data towards a higher hydraulic conductivity. As noted in the literature review, only a fraction of the total pore space is involved in active transport (Rogowski, 1990), and it is assumed that those pores are saturated in the beginning stages of the test. It is likely that due to the larger sample volume and potential for inclusions, in-situ testing would produce higher hydraulic conductivity result than the Shelby tube method; however, this result is also likely to be a better representation of site conditions. If rootlets, intrusions, or cracks are present in the liner, they should be accounted for instead of rendering a sample unusable.

Ultimately, the in-situ and laboratory testing are measuring different properties of the soil. The high induced pressure from the flexible wall permeameter measures the flow of water through saturated pores which does not represent the governing condition in which the site may experience. In-situ testing for measuring flow through the liner in EMS facilities has several advantages over laboratory testing in that the in-situ test involves measuring the flow of water through the actual liner in pursuit of accuracy, whereas laboratory testing involves testing small samples of the liner material in a controlled environment in pursuit of precision.

10.3 Comparison of Results with the Study Objectives

The result of the field and laboratory testing of the ASTM Method A of borehole infiltration is a viable alternative for assessing the hydraulic conductivity of an engineered clay liner. The method yields a horizontal and vertical hydraulic conductivity value required for the EMS commissioning requirements but also considers other site-specific conditions throughout the process, such as soil anisotropy, underlying soil conditions, preferential flow pathways, and inclusions in the liner material.

10.4 Limitations of the Study

The limitation of the study is based on the low number of tests successfully completed. Although the proof of concept was completed, an accurate correlation between the in-situ and laboratory tests is not yet clear. This is consistent with other large scale testing programs discussed in the literature review section which also did not establish a statistically significant correlation.

11.0 RECOMMENDATION

11.1 Summary of the Study

The study was conducted to test the viability for using the ASTM Method A of borehole infiltration to understand the discharge of an engineered clay liner for an EMS facility. The study determined that borehole infiltration can be an effective and economic alternative to traditional laboratory testing and that the properties being tested by an in-situ methods are more representative of the macro permeability of the liner system.

11.2 Recommendations for Future Studies

While the ASTM Method A of borehole infiltration has been shown to be a valuable tool for assessing the hydraulic conductivity of an engineered clay liner, further research is valuable in this area to improve the accuracy and reliability of the test. Examples of opportunities for future study include establish correlation between in-situ and laboratory testing, effects of chamber diameter, a calibration from underlying soil conditions, and development of loading curves.

11.2.1 In-Situ and Laboratory Testing Correlation

A correlation may exist between in-situ and laboratory hydraulic conductivity testing. Although each method measures different aspects of this parameter, further research in a controlled environment may better relate the micropermeability and macropermeability relationships. As concluded in the literature review this would require a very large sample size and due to the wide accepted variation in results. An emphasis should be made for establishing a trends between similar loading conditions, and numerical correlations for identical materials.

11.2.2 Chamber Diameter

The volume of soil being tested is a key factor in leveraging in-situ testing to achieve a high quality of data, however a large diameter chamber can increase cost and level of effort on site. There may be value in further investigating the effect of a smaller borehole diameter on the duration of testing, consistency of data, and overall quality of data.

11.2.3 Underlying Soil Calibration

As observed through the development of the liner discharge model, the flow through the liner was sensitive to the hydraulic properties of the underlying soil. Testing of the underlying soil by means of sample collection and laboratory testing or the use of a downhole slug test would provide a quantitative measurement for the calibration of an liner discharge model.

11.2.4 Anisotropic Behaviour

The anisotropic ratio of the clay liner varied between 2 and 20 for the borehole infiltration testing. A basic liner discharge model does not consider the hydraulic anisotropy of the soil, however for more complex model this parameter will be more critical. Further studies should investigate typical anisotropic ratio values for EMS liners constructed with Manitoba clay.

11.3 Recommendation for Practice

The engineering practice should consider using borehole infiltration as a tool for understanding the performance of a liner system and developing an LDC for commissioning of a clay-lined EMS. This tool may help the industry change its perspective on regulatory compliance from focusing on a single parameter to understanding the overall system and discharge to the environment. This tool may introduce a more accurate way of estimating the site-specific hydraulic conductivity for determining the acceptable liner discharge for the purpose of EMS facility commissioning in Manitoba. The use of a liner discharge model would allow Engineers to design more economical infrastructure and re-evaluate facilities through innovative techniques.

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Appendix A – Site Photos

University of Manitoba	Project Name: ASTM D6391-11 Borehole Infiltration	
	Project Location: Landmark, MB	
	Client: Manitoba Agriculture, Land Use	Project Code: A22516P
	Preparer: Alex Baker	Reviewer:
	Report Date: 03/08/2023	Page Number: 1 of 7

Picture 1: Site view of lagoon floor

Lat: 49.69063

Long: -96.77082

Bearing: N

Date Taken: 10/25/2022

Weather:

Taken By: Alex Baker

Tags: Site View

Picture 2: Site view of berm looking east

Latitude: 49.69056

Longitude: -96.77082

Bearing: N

Date Taken: 10/25/2022

Taken By: Alex Baker

Weather:

Tags: Site View

University of Manitoba

Project Name: ASTM D6391-11 Borehole Infiltration	
Project Location: Landmark, MB	
Client: Manitoba Agriculture, Land Use	Project Code: A22516P
Preparer:	Reviewer:
Report Date: 03/08/2023	Page Number: 2 of 7

Picture 3: Drilling borehole for berm test

Lat: 49.69063

Long: -96.77072

Bearing: N

Date Taken: 10/25/2022

Weather:

Taken By: Alex Baker

Tags: Berm Test

Picture 4: Setting up berm test apparatus

Latitude: 49.69057

Longitude: -96.77084

Bearing: N

Date Taken: 10/25/2022

Taken By: Alex Baker

Weather:

Tags: Berm Test

University of Manitoba

Project Name: ASTM D6391-11 Borehole Infiltration		
Project Location: Landmark, MB		
Client: Manitoba Agriculture, Land Use	Project Code: A22516P
Preparer:	Reviewer:
Report Date: 03/08/2023	Page Number: 3 of 7

Picture 5: Reamed surface of berm test

Lat: 49.69063

Long: -96.77072

Bearing: N

Date Taken: 10/26/2022

Weather:

Taken By: Alex Baker

Tags: Berm Test

Picture 6: Advancement of stage 2 of berm test

Latitude: 49.69010

Longitude: -96.77132

Bearing: N

Date Taken: 10/26/2022

Taken By: Alex Baker

Weather:

Tags: Floor Test

Picture 7: Ongoing berm infiltration test

Lat: 49.69059

Long: -96.77079

Bearing: N

Date Taken: 10/28/2022

Weather:

Taken By: Alex Baker

Tags: Berm Test

Picture 8: Leakage of Standpipe in floor test

Latitude: 49.69059

Longitude: -96.77070

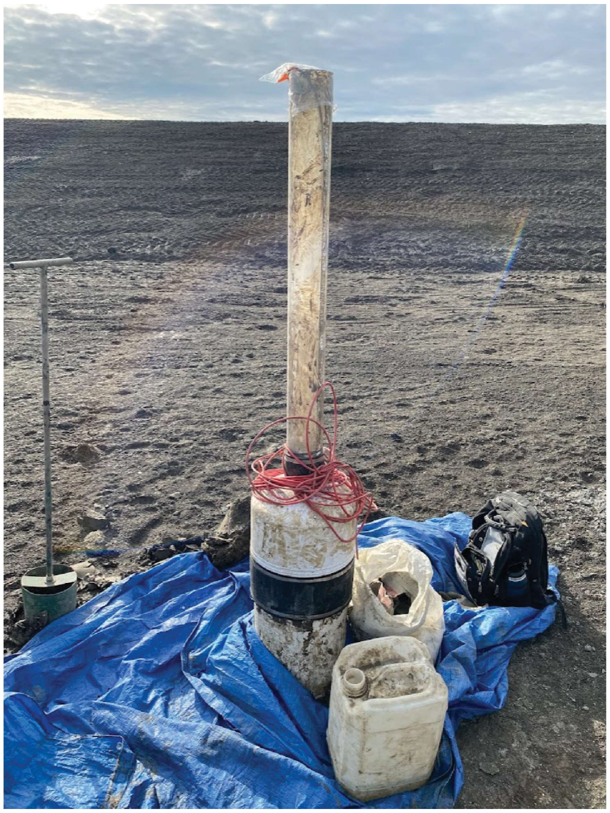
Bearing: N

Date Taken: 11/01/2022

Taken By: Alex Baker

Weather:

Tags: Berm Test



Picture 9: Floor BH Infiltration Test

Lat: 49.69012

Long: -96.77129

Bearing: N

Date Taken: 11/01/2022

Weather:

Taken By: Alex Baker

Tags: Floor Test

Picture 10: BH Reamer

Latitude: 49.69012

Longitude: -96.77130

Bearing: N

Date Taken: 11/03/2022

Taken By: Alex Baker

Weather:

Tags: Floor Test

Picture 11: Advancement of stage 2 in floor test

Lat: 49.69014

Long: -96.77128

Bearing: N

Date Taken: 11/03/2022

Weather:

Taken By: Alex Baker

Tags: Floor Test

Picture 12: Filling annulus with bentonite chips

Lat: 49.69014

Long: -96.77128

Bearing: N

Date Taken: 11/03/2022

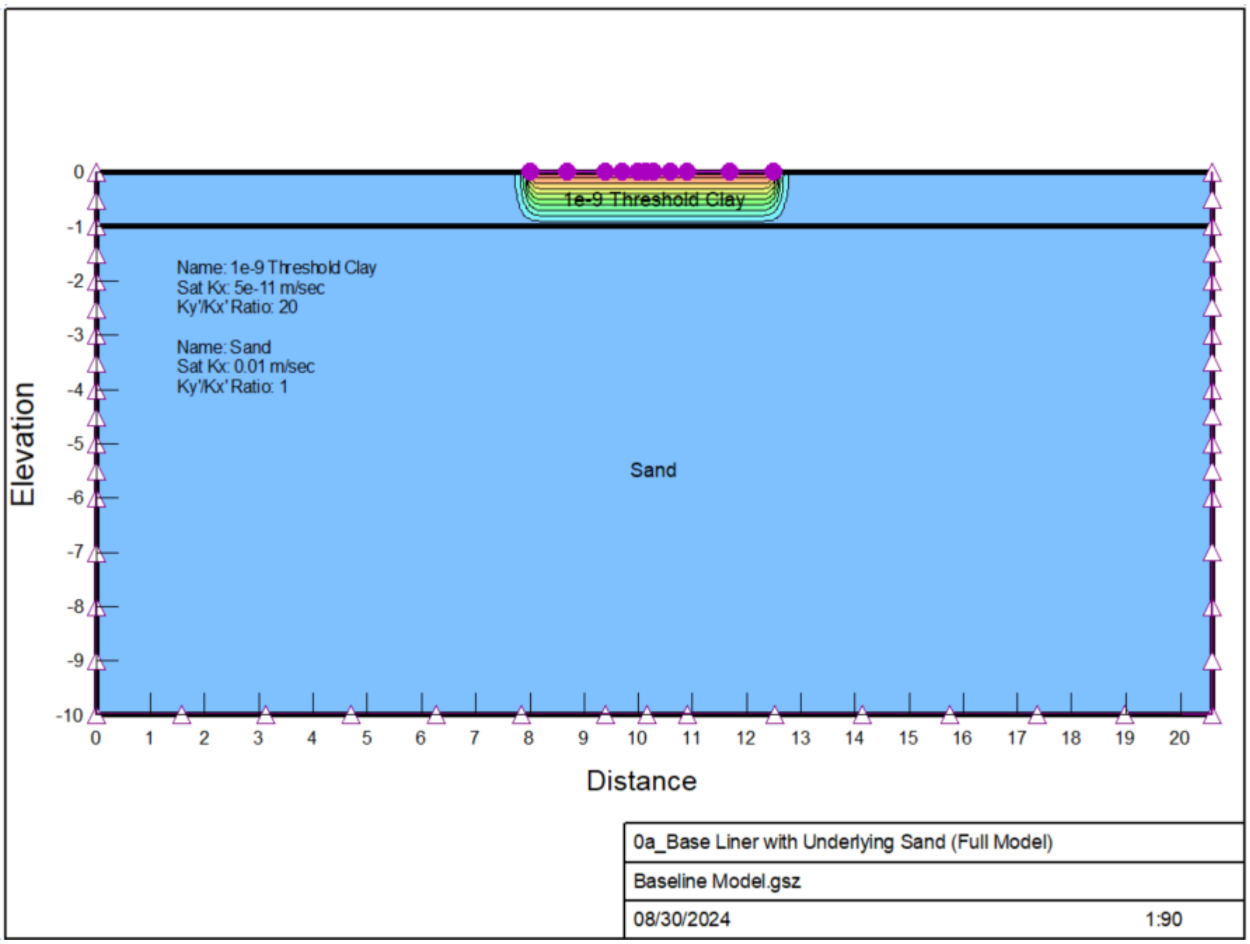
Weather:

Taken By: Alex Baker

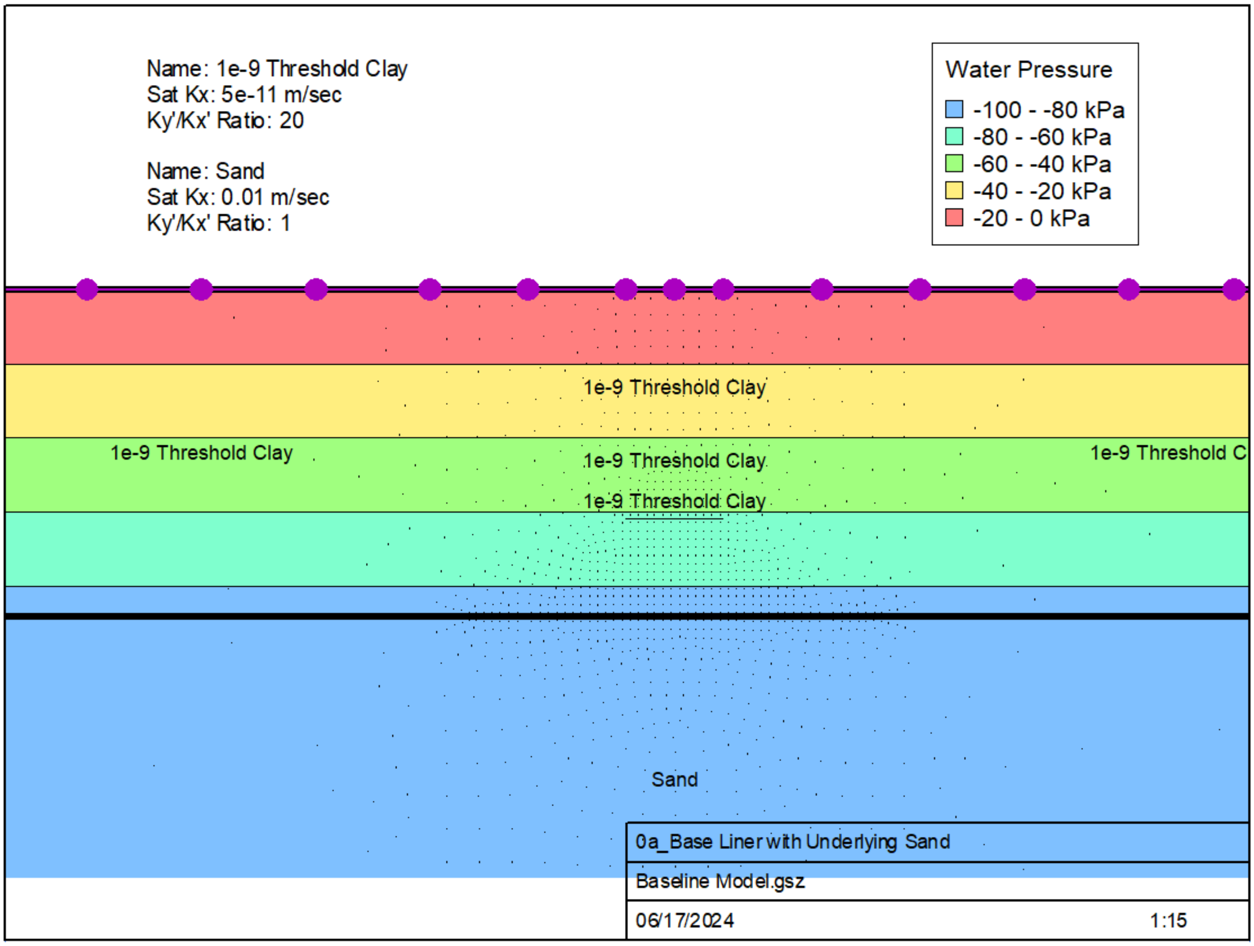
Tags: Berm Test

Appendix B – Typical Seep/W Model Outputs

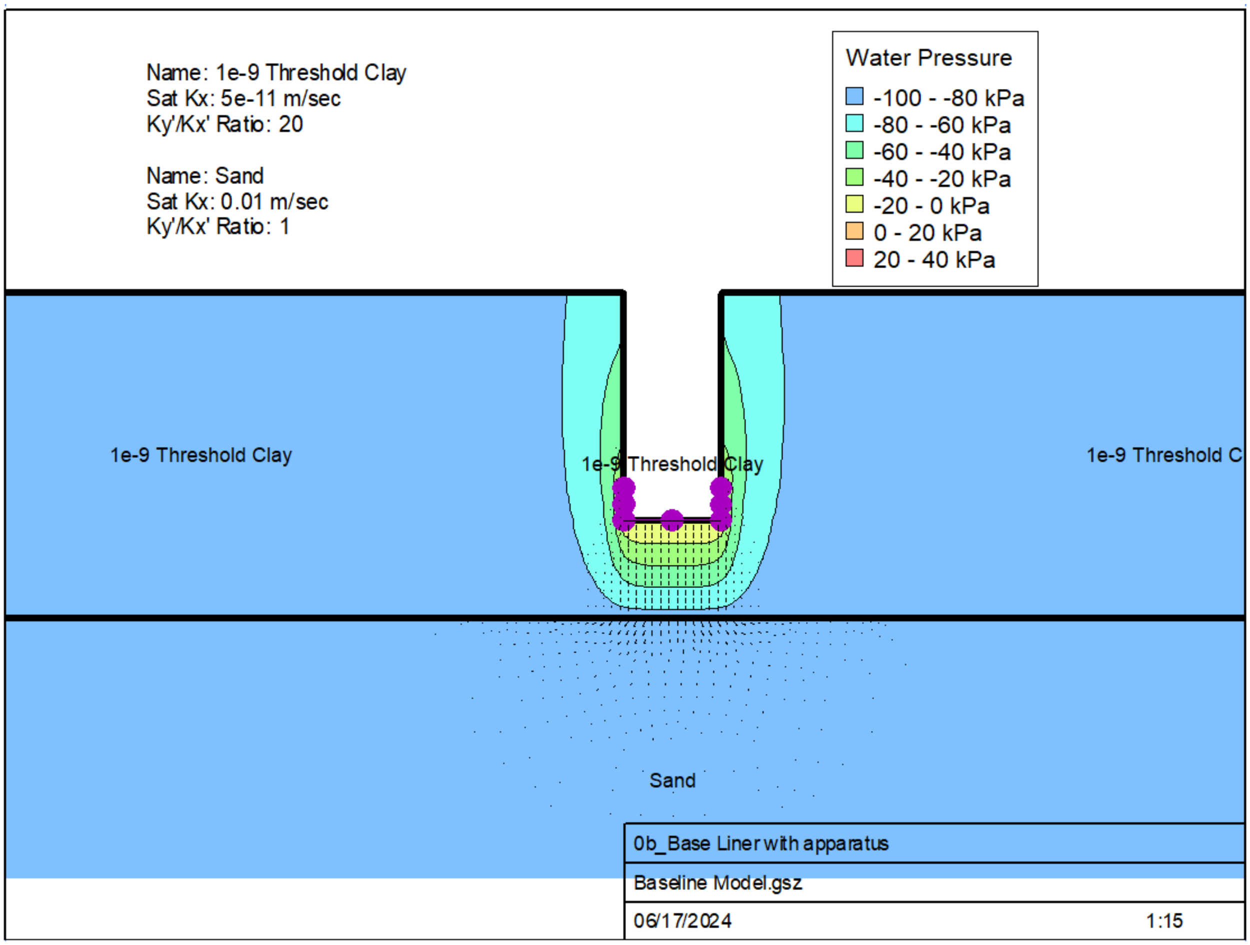
Establishment of a Baseline Threshold (Full Model)



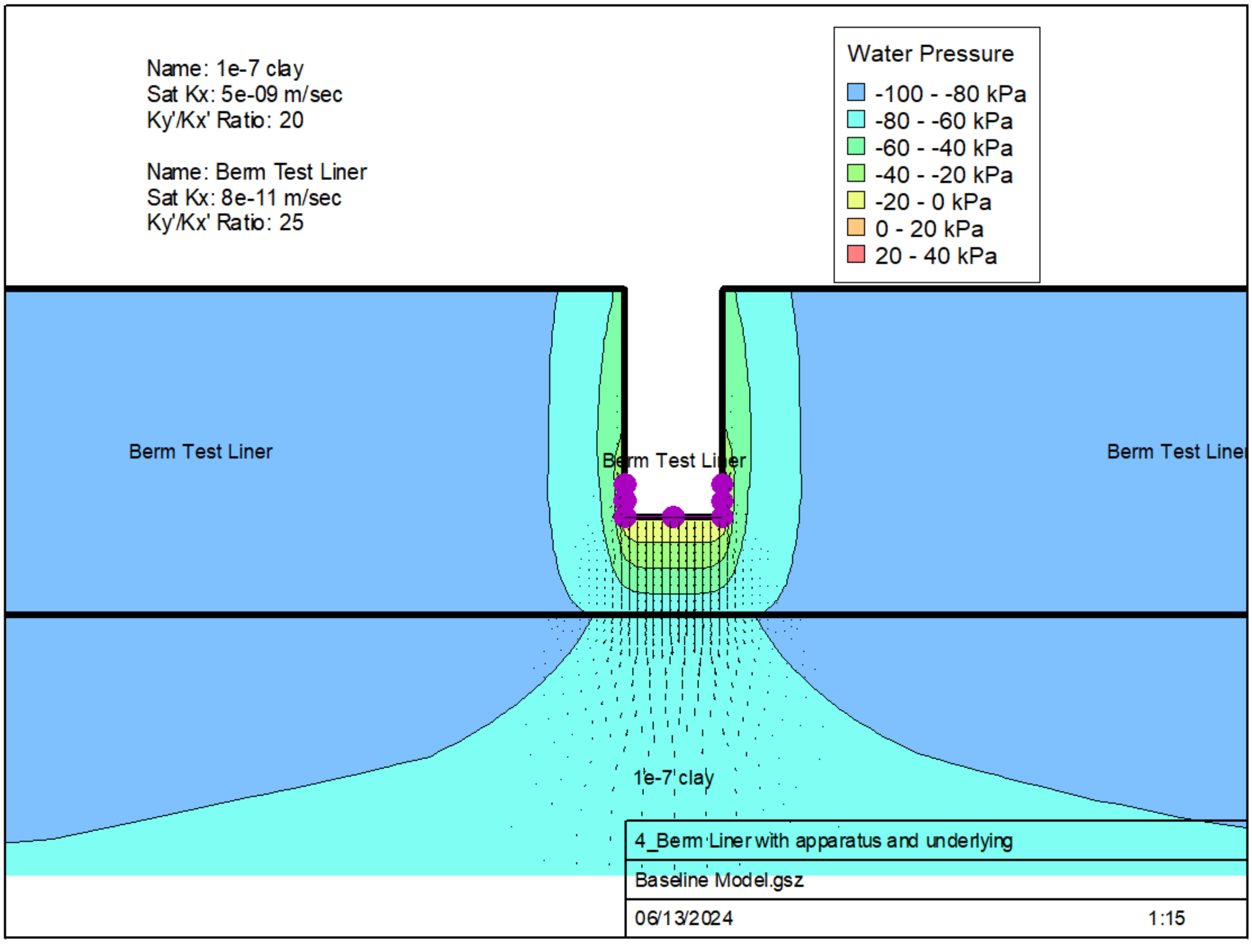
Establishment of a Baseline Threshold (Detailed)



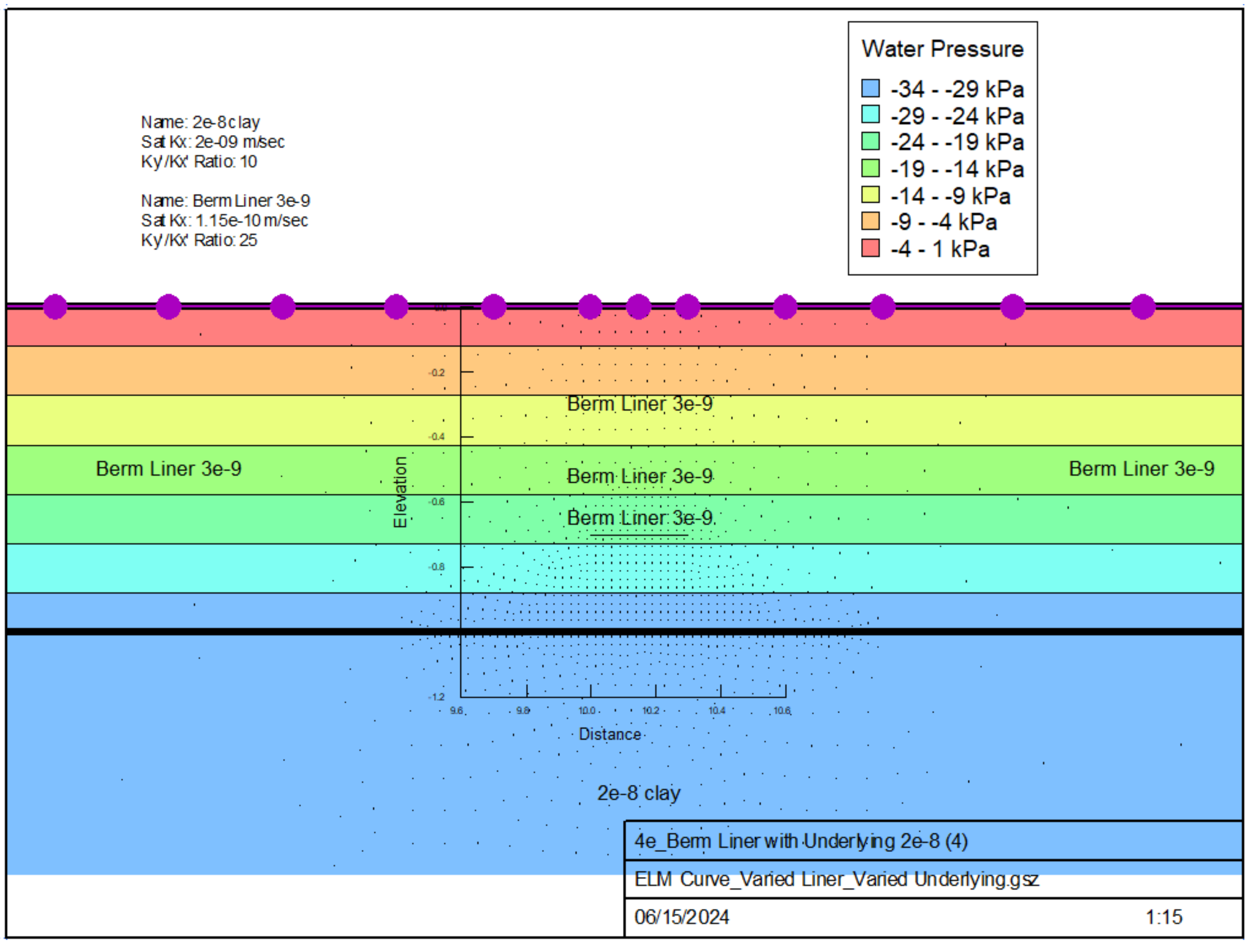
Calibration of Borehole Infiltration Test with Baseline Model



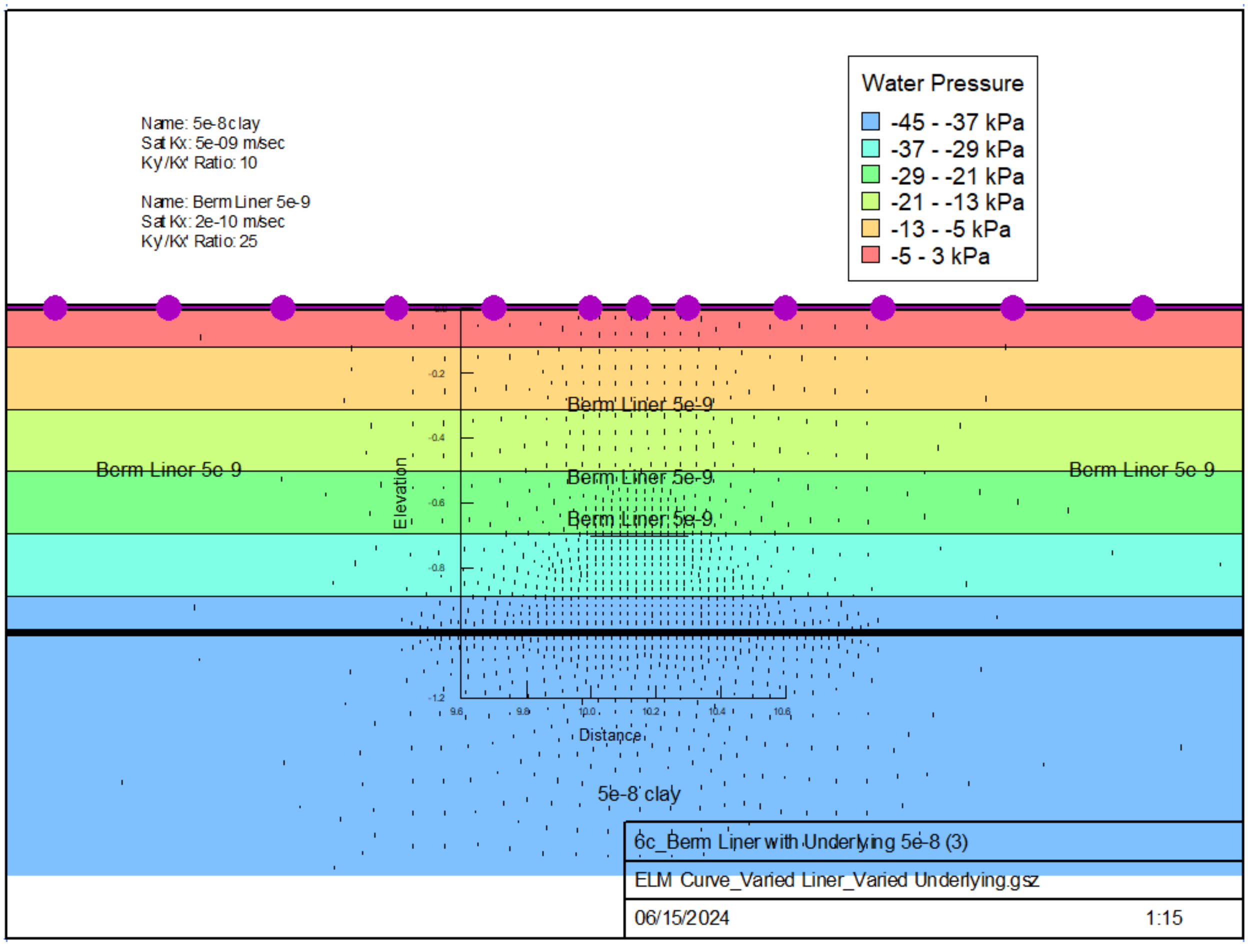
Application of Berm Infiltration Test Results



Typical Model for a Single Point of an LDC with Varying Underlying Conditions

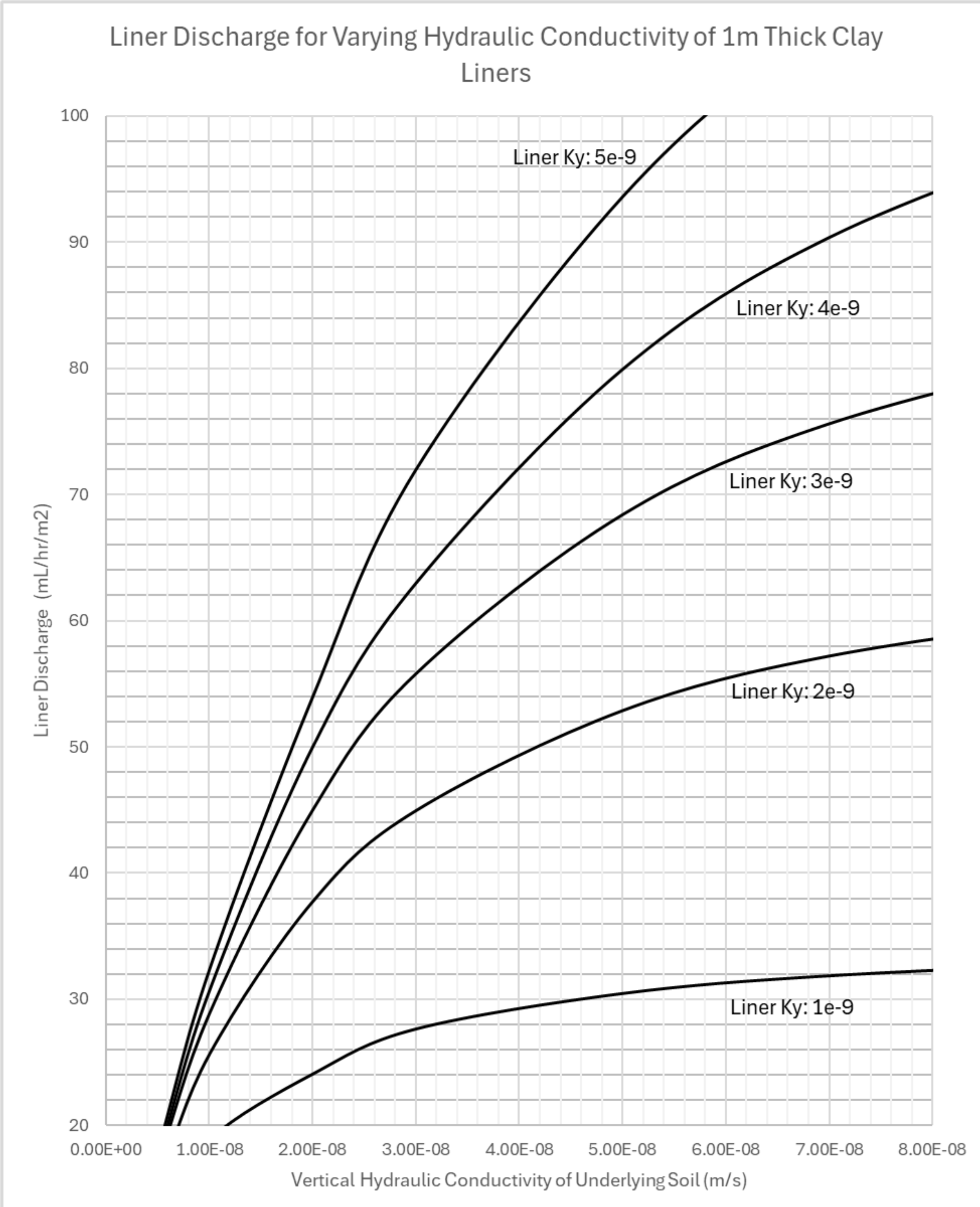


Typical Model for a Single Point of an LDC with Varying Underlying Conditions and Varying Thickness

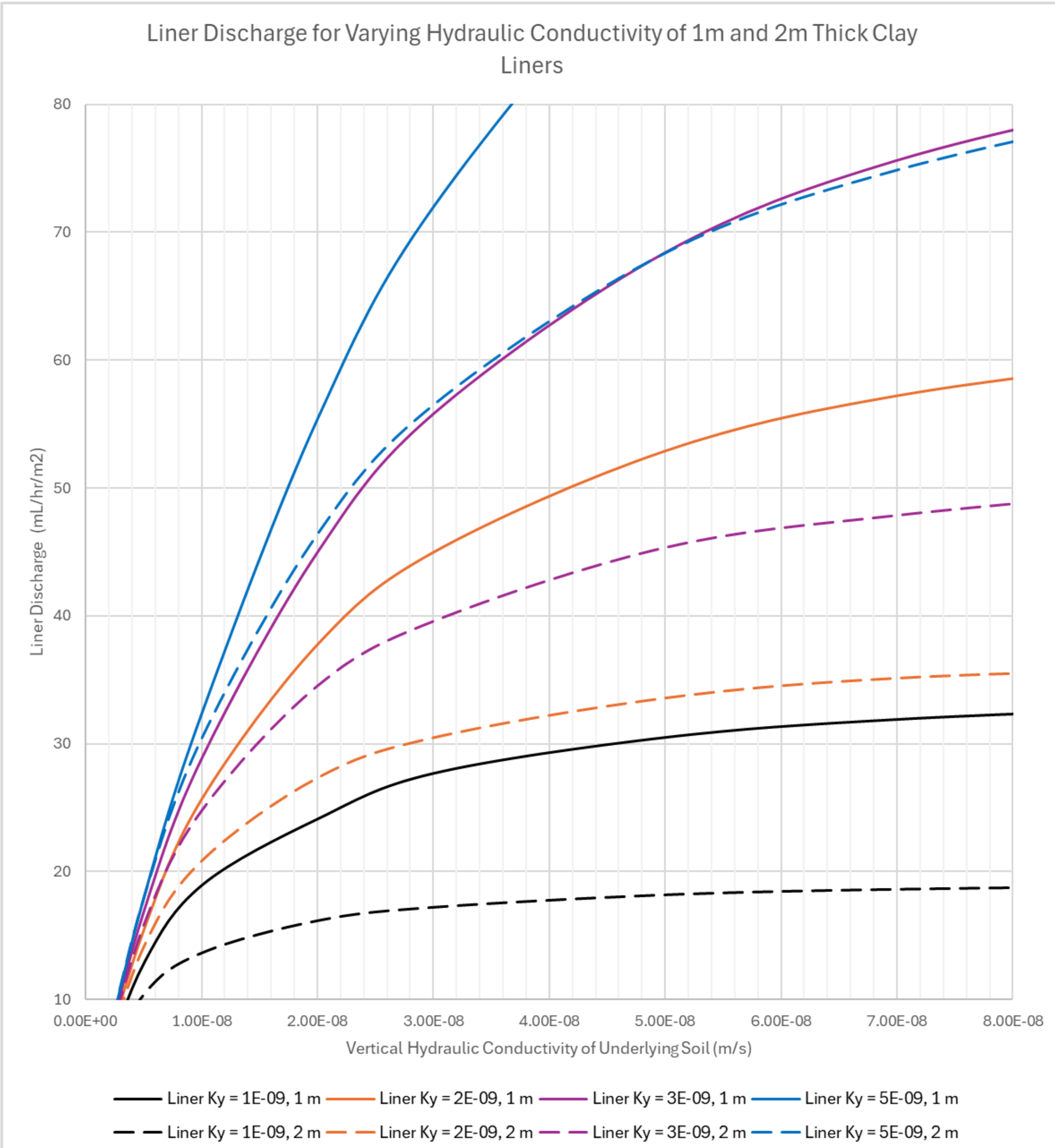


Appendix C – Liner Discharge Curves

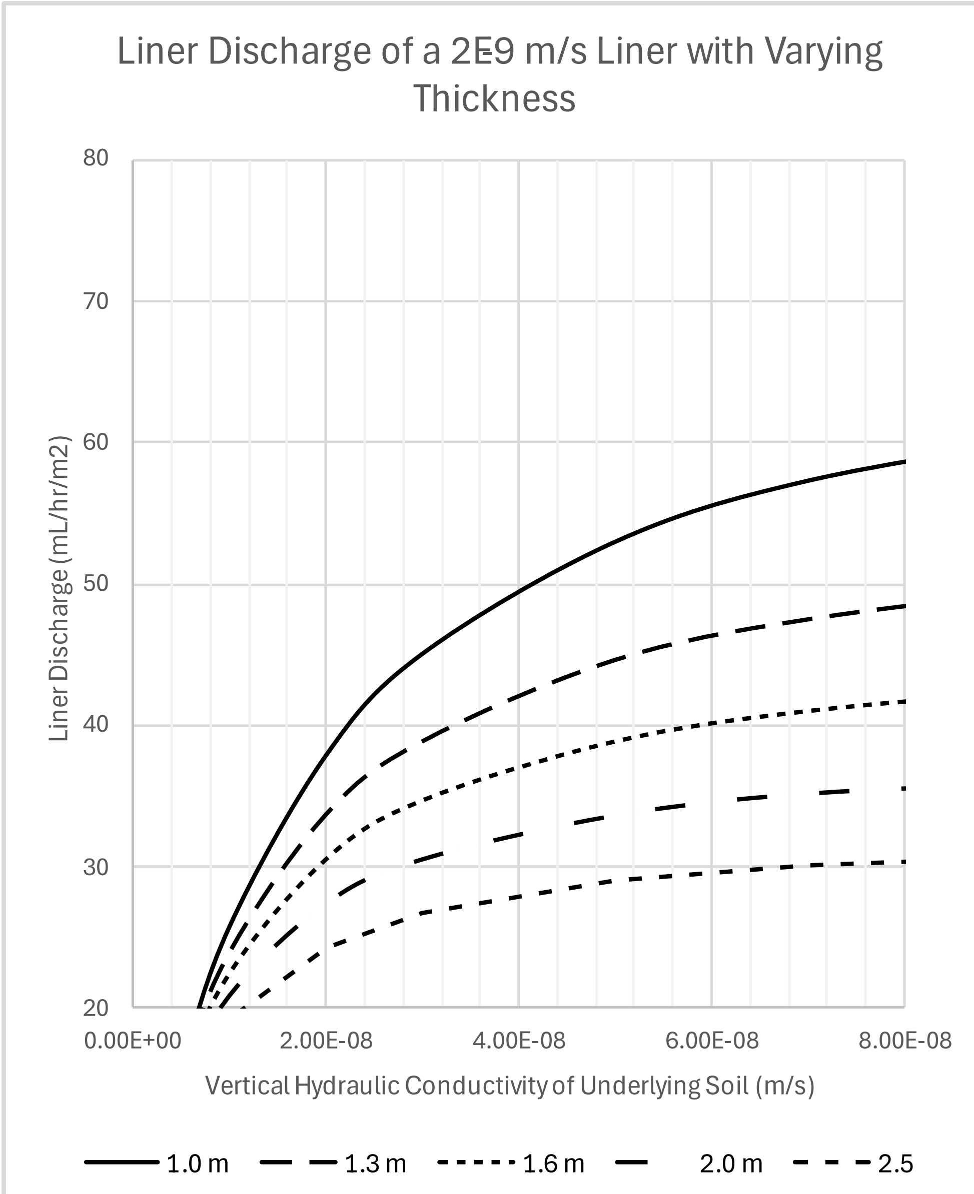
Appendix C – Environmental Loading Curves



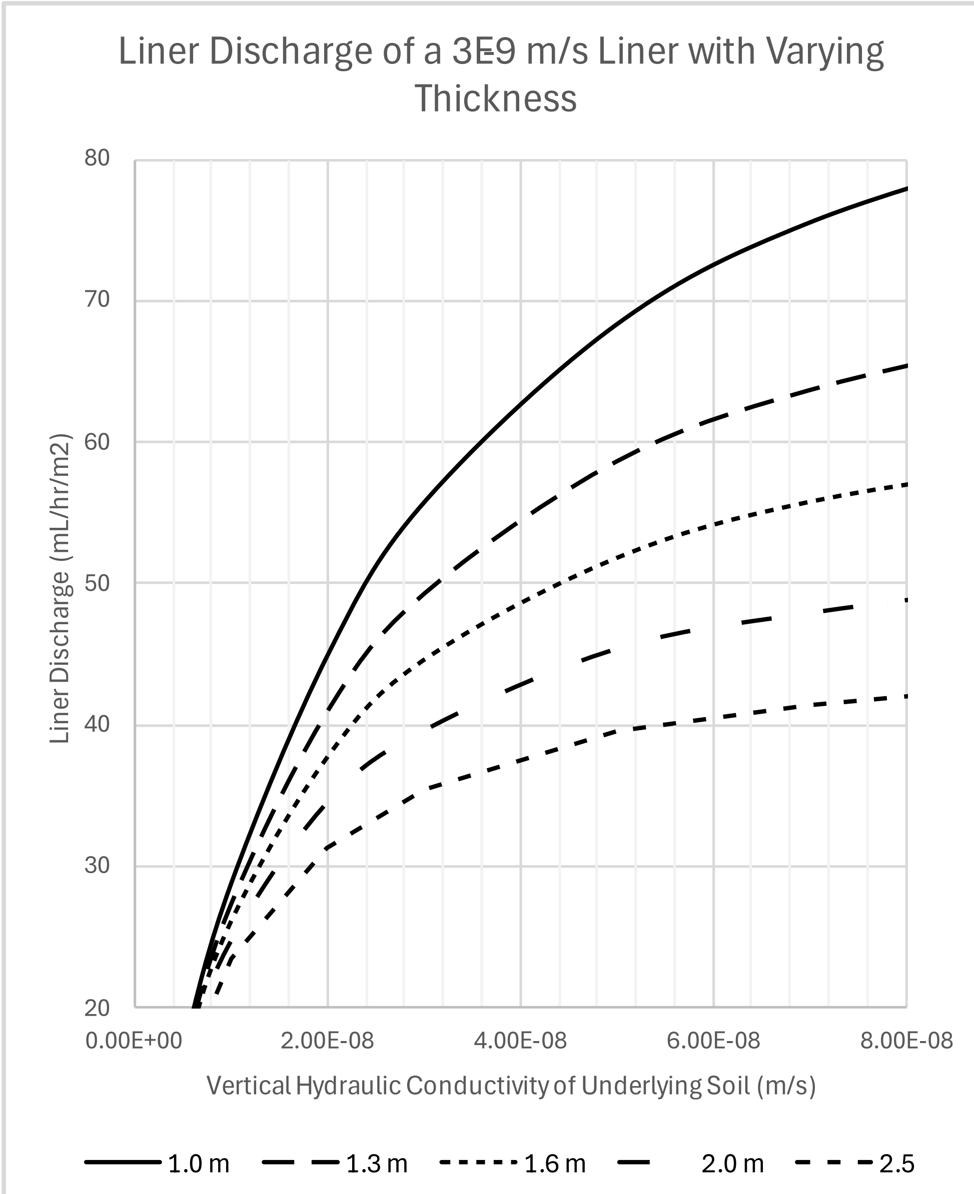
Appendix C – Environmental Loading Curves

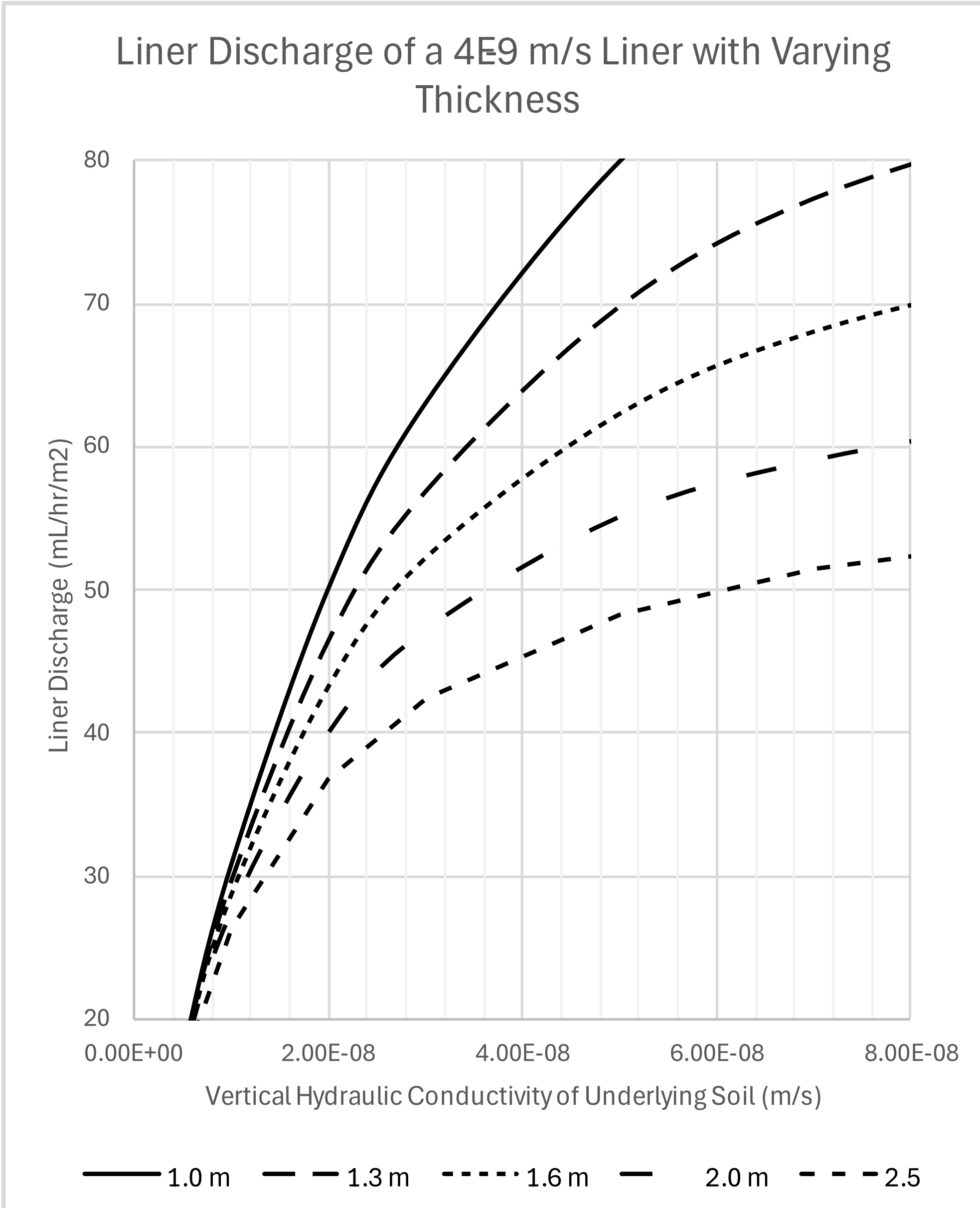


Appendix C – Environmental Loading Curves

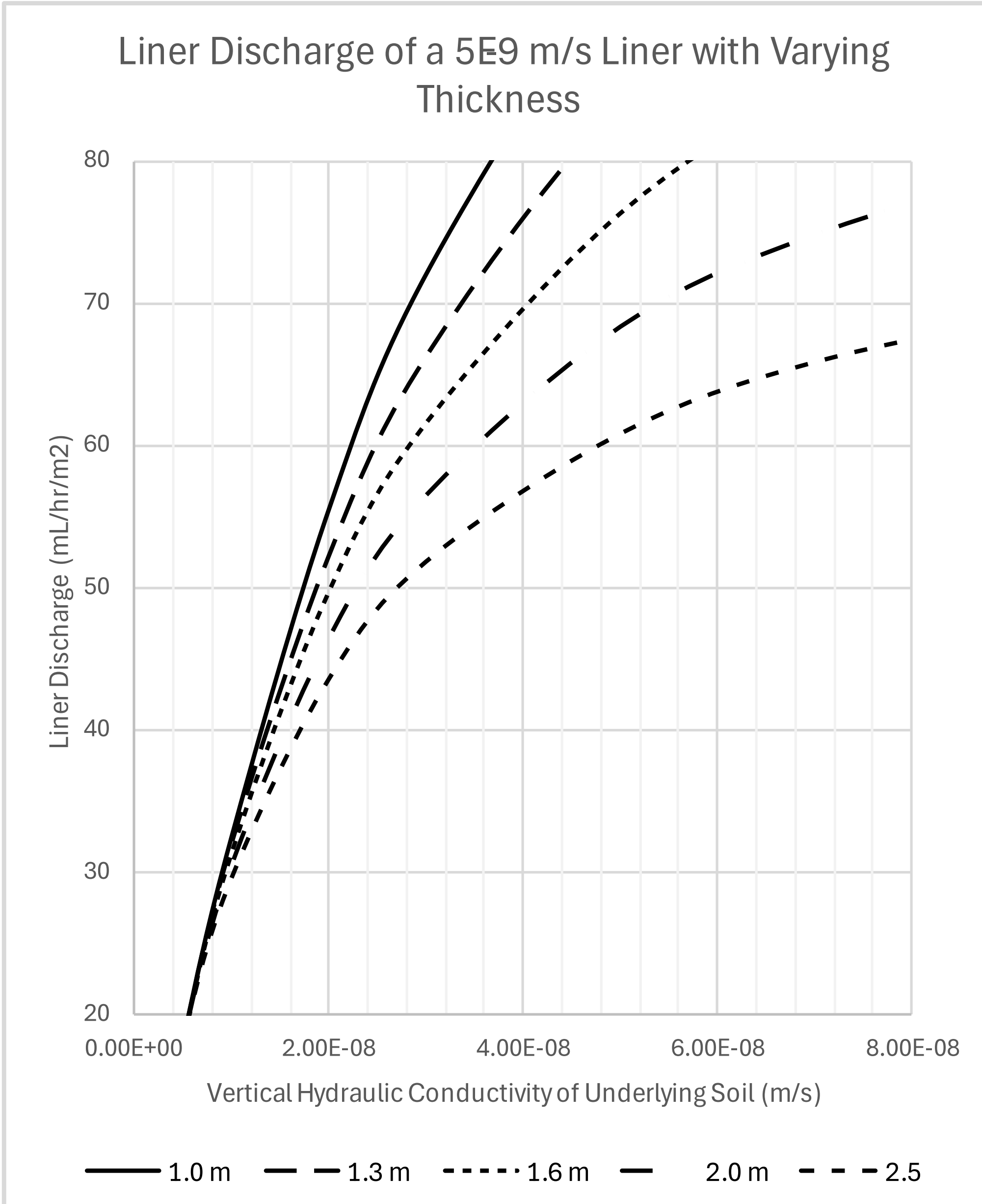


Appendix C – Environmental Loading Curves




Liner Discharge of a 4E-9 m/s Liner with Varying Thickness
80
70
60
50
40
30
20
Liner Discharge (mL/hr/m2)
0.00E+00
2.00E-08
4.00E-08
6.00E-08
8.00E-08
Vertical Hydraulic Conductivity of Underlying Soil (m/s)
1.0 m
1.3 m
1.6 m
2.0 m
2.5

Appendix C – Environmental Loading Curves



Liner Conductivity (m/s)	***Underlying Conductivity (m/s)***	***Liner Thickness (m)***	***Liner Discharge (mL/hr/m2)***
1E-09	1E-07	1.0	33
		1.3	27
		1.6	23
		2.0	19
		2.5	16
	7E-08	1.0	32
		1.3	26
		1.6	22
		2.0	19
		2.5	16
	5E-08	1.0	30
		1.3	25
		1.6	21
		2.0	18
		2.5	15
	3E-08	1.0	28
		1.3	23
		1.6	20
		2.0	17
		2.5	15
	2E-08	1.0	24
		1.3	21
		1.6	19
		2.0	16
		2.5	14
	1E-08	1.0	19
		1.3	17
		1.6	15
		2.0	14
		2.5	12
	5E-09	1.0	13
		1.3	12
		1.6	11
		2.0	10
		2.5	10
	1E-09	-	4
2E-09	1E-07	1.0	61
		1.3	50
		1.6	43
		2.0	36
		2.5	31
	7E-08	1.0	57
		1.3	48
		1.6	41
		2.0	35
		2.5	30
	5E-08	1.0	53
		1.3	45
		1.6	39
		2.0	34
		2.5	29

	3E-08	1.0	45
		1.3	39
		1.6	35
		2.0	30
		2.5	27
	2E-08	1.0	38
		1.3	34
		1.6	31
		2.0	27
		2.5	24
	1E-08	1.0	26
		1.3	24
		1.6	22
		2.0	21
		2.5	19
	5E-09	1.0	15
		1.3	15
		1.6	15
		2.0	14
		2.5	14
	1E-09	-	4
3E-09	1E-07	1.0	82
		1.3	68
		1.6	59
		2.0	50
		2.5	43
	7E-08	1.0	76
		1.3	64
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		2.0	48
		2.5	41
	5E-08	1.0	68
		1.3	59
		1.6	52
		2.0	45
		2.5	40
	3E-08	1.0	56
		1.3	49
		1.6	45
		2.0	40
		2.5	35
	2E-08	1.0	45
		1.3	41
		1.6	38
		2.0	35
		2.5	31
	1E-08	1.0	29
		1.3	27
		1.6	26
		2.0	25
		2.5	23
	5E-09	1.0	17
		1.3	16

		1.6	16
		2.0	16
		2.5	16
	1E-09	-	4
4E-09	1E-07	1.0	100
		1.3	84
		1.6	73
		2.0	63
		2.5	54
	7E-08	1.0	90
		1.3	77
		1.6	68
		2.0	59
		2.5	51
	5E-08	1.0	80
		1.3	70
		1.6	62
		2.0	55
		2.5	48
	3E-08	1.0	63
		1.3	57
		1.6	52
		2.0	47
		2.5	42
	2E-08	1.0	50
		1.3	46
		1.6	43
		2.0	40
		2.5	37
	1E-08	1.0	31
		1.3	30
		1.6	29
		2.0	27
		2.5	26
	5E-09	1.0	17
		1.3	17
		1.6	17
		2.0	17
		2.5	17
	1E-09	-	4
5E-09	1E-07	1.0	126
		1.3	106
		1.6	93
		2.0	81
		2.5	70
	7E-08	1.0	108
		1.3	95
		1.6	85
		2.0	75
		2.5	66
	5E-08	1.0	94
		1.3	84
		1.6	76

		2.0	68
		2.5	61
	3E-08	1.0	72
		1.3	66
		1.6	62
		2.0	57
		2.5	52
	2E-08	1.0	55
		1.3	52
		1.6	50
		2.0	46
		2.5	44
	1E-08	1.0	32
		1.3	32
		1.6	31
		2.0	30
		2.5	30
	5E-09	1.0	18
		1.3	18
		1.6	18
		2.0	18
		2.5	18
	1E-09	-	4