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## Long-term Field Performance of Geomembrane-Lined Cover Systems at Mine Waste Rock Piles

Deanna Hersey, *The University of Western Ontario*

Supervisor: Power, C., *The University of Western Ontario*

A thesis submitted in partial fulfillment of the requirements for the Master of Engineering Science degree in Civil and Environmental Engineering

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## Abstract

Mine waste rock piles (WRPs) are anthropogenically created landforms at active and former mining sites that can generate and release highly toxic acid mine drainage (AMD) to the environment. A common solution to control AMD generation is the use of cover systems over WRPs to isolate the reactive waste from water and oxygen in the atmosphere. Geomembranes exhibit the characteristics needed to be highly effective barriers to atmospheric fluxes; however, knowledge of their performance with in-service WRPs is limited. The objective of this thesis is to comprehensively assess the field performance of geomembrane-lined cover systems for limiting meteoric water to the waste rock. Four coal mine WRPs located in the Sydney Coalfield in Nova Scotia, Canada, were reclaimed with different cover systems and then extensively monitored for seven years. Defect leakage and water balance methods were employed to determine the daily water flux through the cover systems at each WRP over seven years. Results demonstrated that the inclusion of geomembrane liners in cover systems reduced the water influx from 28% of precipitation to as low as 0.05%. Furthermore, the composition of the drainage layer overlying the geomembrane influences the water influx, with native soil, granular material and geocomposite nets providing influx rates of 3%, 0.5% and 0.05%, respectively. This thesis highlights the role of geomembrane liners and drainage layers in engineered cover systems for significantly limiting the influx of meteoric water into mine waste rock.

*Keywords:* water balance, geomembranes, waste rock piles, defect leakage, water ingress

## Summary for Lay Audience

Mining produces a large amount of waste, which can come in many different forms, from liquid slurry to solid rock. Waste rock is commonly placed into large stockpiles on the ground, and can still contain small amounts of minerals that do not have much value. However, these little minerals can harm the environment. When these minerals interact with oxygen and water, they can cause a chemical reaction to take place and create a toxic fluid, called acid mine drainage (AMD). This can then be carried with water flow to the outside environment, and pollute the surrounding streams, rivers, groundwater and fields. The creation of AMD can be stopped by putting a cover around the waste rock, similar to putting saran wrap over a plate of food to avoid anything from getting in. A lot of different covers exist and can be made from sands, clays, gravels and plastics. The plastic option is very expensive but can be the best option; however, it is unknown if they work effectively over time. What if the plastic has holes in it? What will make the water flow faster or slower through these holes? This thesis looked at four different covers that were put over waste rock located in Nova Scotia, Canada. Seven years of data had been collected and needed careful compilation, analyses and interpretation. Results found that the plastic was very successful in stopping water infiltrating (rain/snow) to the waste rock. It reduced the yearly amount of water getting inside from 28% to only 0.05%. The results also showed that another layer for draining the water away from the plastic is very helpful, especially if the plastic has holes in it. This study shows that plastic covers, while more expensive, are a great solution to stop water infiltration and also prevent AMD pollution.

## Co-Authorship Statement

The candidate is responsible for the analysis of field data, as well as writing the drafts of all chapters of this thesis. Dr. Christopher Power provided the initial motivation for this research, provided suggestions for data analysis, and provided revisions for improvement of the thesis. The co-authorship breakdown of Chapters 3 and 4 are as follows:

*Authors:* Deanna Hersey, Christopher Power

*Contributions:*

Deanna Hersey conducted the analysis of field data, and interpretation of the results to prepare a draft of each thesis chapter. Christopher Power supervised analysis, provided insight and interpretation of results, and reviewed the draft chapters.



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Additionally, to the members of RESTORE, thank you all for being great friends. Despite the academic challenges we have faced these past couple years, I am very grateful to have formed the relationships with you we now share. Finally, I would like to thank my family for encouraging me to dream bigger, and to my friends who continue to inspire me to be my most authentic self. Lastly, a special thank you to my sister Becky, for always being my cheerleader.

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# 1 Introduction

## 1.1 Research Background

The mining sector in Canada accounts for approximately 5% of its GDP, contributing over 719,000 jobs in 2019 (Marshall, 2019). Throughout mining operations, waste is generated in both liquid (e.g., fine tailings) and solid (e.g., waste rock) states. In Canada, mining annually produces over 30 times the amount of solid waste that is generated by the entire population and industries combined (Marshall, 2019). This solid waste, also referred to as waste rock, is typically stored in large stockpiles on the ground surface. These waste rock piles (WRPs) typically contain sufficient amounts of reactive minerals that can interact with atmospheric oxygen and meteoric water, and cause a complex sequence of oxidation-reduction reactions that produces toxic acid mine drainage (AMD). AMD-impacted water is characterized by high acidity, low pH and high concentrations of sulfate, iron, aluminum, manganese, and other toxic metals. Once released, AMD can adversely impact the receiving environment, including pollution of adjacent surface water and groundwater resources and destroying aquatic life (John & Goyal, 2017; Acharya & Kharel, 2020).

AMD is one of the most serious pollutants in watercourses in Canada. The annual cost of AMD remediation in Canada is between two and five billion dollars, making it one of the largest environmental liabilities in the country (EMCBC, 2000). The prevention and/or control of AMD is a highly complex and challenging problem. One of the most commonly proposed solutions is the installation of an engineered cover system over the waste rock pile to isolate the reactive minerals from the atmosphere, including precipitation, thereby stopping the chemical reactions necessary to produce AMD (Figure 1-1). A diverse range of cover system configurations exist, ranging from a single layer of natural soil to multi-layer systems containing natural soils, geosynthetic-reinforced soils, geofabrics and geomembranes. Geomembrane liners are being increasingly used in WRP cover systems due to their effectiveness as a barrier to oxygen and water. However, their performance has typically been evaluated at the laboratory and pilot scale therefore the geomembrane is in pristine condition with no defects (e.g., Yanful et al., 2003; Adu-Wusu and Yanful, 2006). In actuality, the geomembrane liners are subject to holes or defects due to improper installation, heavy machinery traffic and aging among some of the many factors that

impact their integrity. Other studies have predicted water influx through assumed defects in geomembrane liners (e.g., Walton et al., 1997; Rowe, 2012; Touze-Foltz et al., 2000), but they were based on limited datasets and smaller laboratory scales over shorter study periods (e.g., Foose, 2001). While previous studies have demonstrated the benefits of geomembrane-lined cover systems, their performance for large, complex WRPs over a long time period has yet to be robustly evaluated. Therefore, despite their potential, knowledge is limited on the long-term behavior and performance of geomembrane-lined cover systems for mine WRPs.



*Figure 1-1: Engineered cover system being installed over a waste rock pile (WRP).*

This thesis focuses on the performance of geomembrane-lined cover systems following their installation at large, complex WRPs. As part of a large mine site reclamation program in the Sydney Coalfield in Nova Scotia, Canada, four WRPs were overlain with engineered cover systems, with three of these cover systems containing geomembrane liners with differing configurations and the other comprising a single soil layer. A comprehensive field monitoring program was subsequently performed at each WRP over a seven-year period. The performance of geomembrane-lined cover systems was first assessed through analysis of water influx by defect

leakage through the three geomembrane liners, which are overlain with differing drainage layers. The cover systems were then assessed for water and oxygen ingress through water balances and oxygen flux calculations. This research is expected to have significant industrial impact with conclusive findings on the benefits and limitations of geomembrane-lined cover systems for reducing atmospheric ingress to WRPs to prevent/control toxic AMD generation and release to the environment.

## 1.2 Research Objectives

The goal of this thesis is to provide new research to the mining industry on the performance of geomembrane-lined cover systems to reduce water influx to mine WRPs. This goal will be achieved through the following sub-objectives:

- 1) Assess the influence of drainage layer material on the water flux through defects in the geomembrane-lined cover systems
- 2) Perform extensive comparative analyses of four in-service cover systems, each with differing compositions and structures, to reduce water and oxygen influx to mine waste rock

## 1.3 Thesis Outline

This thesis is written in an “Integrated Article” format. A brief description of each subsequent chapter presented in this thesis is as follows:

- Chapter 2: summarizes the current scientific literature relevant to mine waste rock piles (WRPs), acid mine drainage (AMD), and engineered cover systems. The prevalence of mining in Canada as well as the generation, release, and impact of AMD due to mine WRPs is discussed. Previous performance studies of single and multi-layer cover systems and their material components are presented. A detailed description of the study sites in the Sydney Coalfield is also provided.
- Chapter 3: details various methods for determining water content above geomembrane liners within cover systems; the influence of drainage layer material on defect leakage through the geomembrane liner; and the fluid mechanics of leakage through defects in geomembrane liners. Presents final results on the impact of drainage layer systems in determining defect leakage at HDPE-inclusive cover systems. This research is intended to be published in *Geotextiles and Geomembranes Journal*.

- Chapter 4: presents an extensive comparative performance of in-service, geomembrane-lined cover systems to limit water and oxygen ingress. The water balance method was used to determine water influx, while oxygen concentrations and transport mechanisms were used to determine oxygen influx. This research is intended to be published in the Journal of Hydrology.
- Chapter 5: summarizes the findings of this research and outlines where these findings could be beneficial to the mining industry, while also providing recommendations for future work.

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## 2 Literature Review

### 2.1 Mining

#### 2.1.1 Mining in Canada

Mining in Canada began 40,000 years ago when the first Aboriginal peoples of the Western Hemisphere arrived. Utilizing various materials such as pebbles, chert, gold, silver and turquoise, they produced tools, weapons and decorative ornaments. In the following years, Vikings, British and French peoples arrived in the area now known as Newfoundland, and mined materials such as stone, sand, lime and gravel to construct local buildings (Cranstone, 2002).

Some of the first metals and minerals to be discovered in Canada were coal and iron. Later additional materials such as nickel and copper were revealed in a massive deposit in Sudbury, Ontario. This substantial deposit was a major contributing factor to Canada's success in becoming one of the world leaders in mining nickel. Canada also experienced a boom in gold with the largest rush in the country's history taking place in Yukon. However, during this period, the discovery of most mine deposits was still largely made by accident. It was not until after the 1880s and further into the mid 1900's that prospecting future mine sites became intentional with advancements in technology like the gamma ray spectrometer and airborne magnetometer.

Commercialization of the mining industry flourished with larger companies prospecting new areas to excavate resulting in the industry maturing from the 1950's onward (Cranstone, 2002). Today, mining in Canada is still an extremely significant part of our economy and ranks within the top 5 global leaders for producing 15 important metals and minerals (Figure 2-1) (Marshall, 2019). Additionally, Canada is also the leading global center for mining finance with the TSX Venture Exchange listing almost 50% of the world's publicly traded mining companies (Government of Canada, 2020).

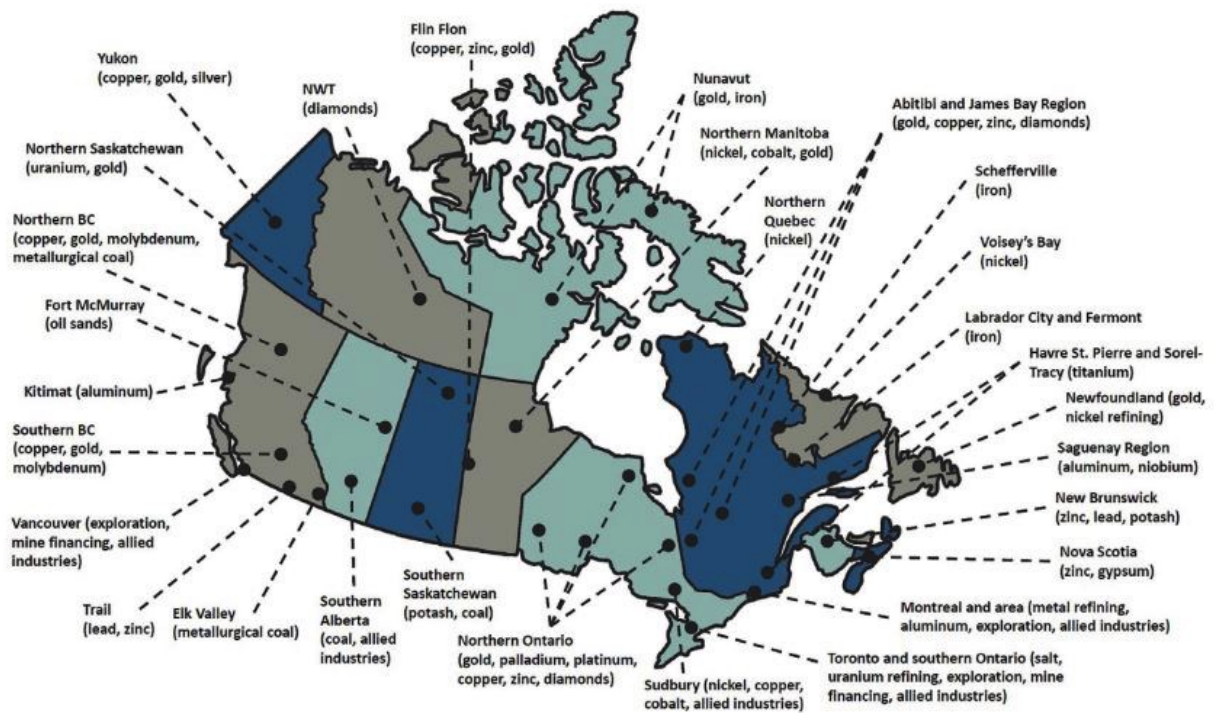
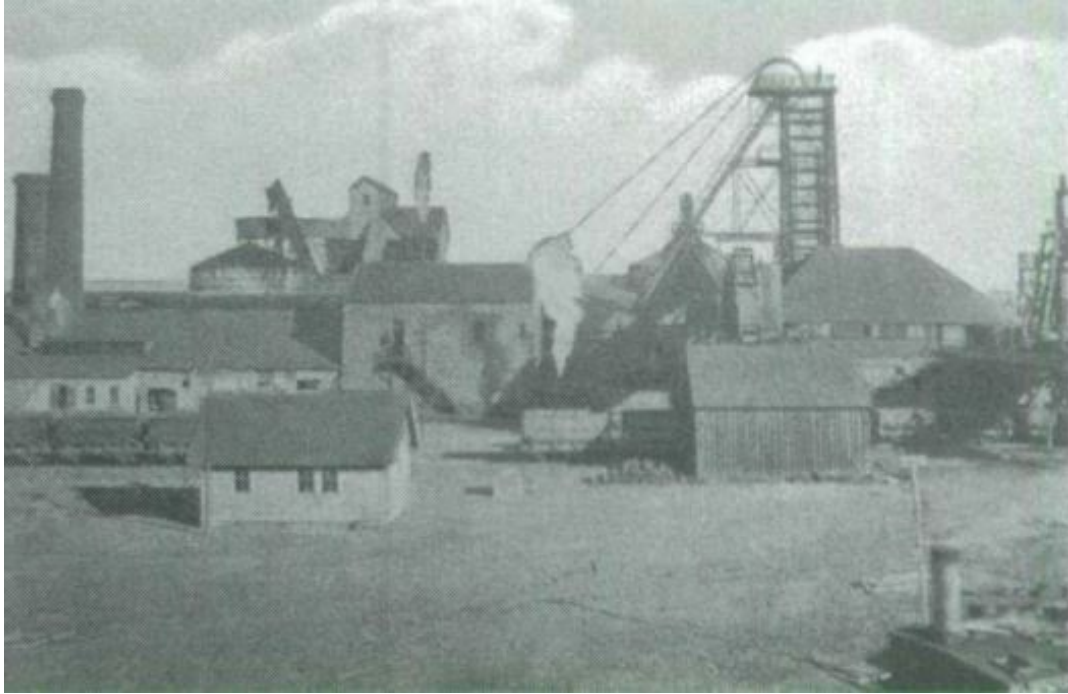


Figure 2-1: Geographic description of the variety of metals and minerals that Canada produces (source: Marshall, 2019)

### 2.1.2 Coal Mining

Coal was first prospected by Indigenous Peoples of Canada in Alberta as far back as 10,000 years ago. The mineral was commercially exploited later on in 1672 by Europeans on Cape Breton Island, Nova Scotia, shown in Figure 2-2 (Marshall, 2019). Here, expansive outcrops of coal seams along the coastline lead to the production of vast quantities of coal (Shea, 2009). Coal mining stretched out to other provinces in Canada such as British Columbia, Alberta and Saskatchewan towards the end of the 19<sup>th</sup> century. With the capability to transport the material by train, and the demand for coal to power their engines, the coal industry in Canada spiked in the 20<sup>th</sup> century. Canada's overall consumption of coal increased from 3.5 million tons in 1886 to peak in 1913 with 31.5 million tons per year. This trend was short lived however, and both output and consumption decreased until exportation to other developing countries at the time ensued (Muisse & McIntosh, 1996). Canada has now become the 4<sup>th</sup> largest exporter of metallurgical coal, coal of substantial quality to produce coke, an essential product for steelmaking, in the world with 37 million tons exported in 2019 (Government of Canada, 2019a). An additional 20

million tons of coal is produced and consumed locally, however drawbacks in this amount of expected to be seen as in 2018 the Government of Canada announced regulations to phase out traditional coal-fired electricity by 2030 (Government of Canada, 2019a).



*Figure 2-2: One of the many surface workings coal mines in Sydney, Nova Scotia (source: Muise & McIntosh, 1996)*

Currently there are 24 permitted coal mines across Canada in only four provinces (New Brunswick, Alberta, Saskatchewan and Nova Scotia), 19 of which are active (Figure 2-3). The majority of these mines are located in western provinces since more than 90% of coal deposits are located here (CAC, 2017). Most coal in Canada is mined using a process called strip or surface mining which removes overlying material temporarily to access the deposit. After collecting the coal, the overburden is then used to fill back in the space left (CAC, 2017; Hustrulid, 2011). This current method has higher productivity rates, which caused an increase in the price of coal when strip mining was first implemented (Cranstone, 2002).



Figure 2-3: Illustration of all coal mines in Canada (source: Government of Canada, 2019b)

### 2.1.3 Waste Products

All mining practices produce some sort of waste product. The waste from mining operations is characterized as high-volume material that is created through processes such as excavation and in-situ leaching (Szczepanska, & Twardowska, 2004). Waste is produced at multiple stages during the mining process and depending on the stage and practice utilized, waste can either be in a liquid or solid state. Liquid waste is a result of the use of water and chemical solutions to mine minerals contained within permeable ore. Mine water and sludge products are potential liquid waste pollutants due to their acidic chemical nature and possible inclusion of solid particles. Solid waste, such as solid waste rock, is produced after the initial excavation stage at a mine site to obtain access to the deposit. This material also presents similar environmental hazards due to the trace amounts of metals and minerals left behind in the waste product. Other forms of solid waste include gangue, which is formed during the mineral processing stage of ore. Gangue is reprocessed multiple times to further extract valuable minerals. Mine tailings are another form of solid waste that can be produced from mining practices. This form of waste is defined as the

finely ground rock that is leftover from mineral processing mixed with chemicals added during the extraction phase. (rest of this paragraph from (Lawson, 2020)).

The type of metal or mineral that is mined produces different amounts of mine waste. For example, for every ton of iron mined, over three tonnes of solid waste is produced (Mining Watch Canada, 2020). In 2013, the metal mining industry in Canada alone produced over 750 000 tonnes of tailings and mine waste rock (Statista Research Department, 2006). Overall, mining in Canada produces over 30 times of the amount of solid waste that is generated by the entire population and industries combined that the country produces on a yearly basis (Mining Watch Canada, 2020). With the vast quantities of mine waste being produced not only in Canada but globally, it is extremely important to monitor and dispose of it correctly to minimize environmental impact.

## 2.2 Acid Mine Drainage

Acid mine drainage (AMD) is the environmentally damaging toxic water that is released from active, inactive, or abandoned mine waste sites apart from liquid waste by-products from other chemical mining processes (Figure 2-4). The water contains toxic chemical leaching products that are stripped from waste rock through an oxidation-reduction reaction with the trace minerals left in the solid waste (Acharya & Kharel, 2020). In this section the process of generation, and factors affecting AMD as well as sources, release mechanisms and impacts that AMD cause will be discussed.



*Figure 2-4: AMD contaminated water resource (source: Akcil & Koldas, 2006)*

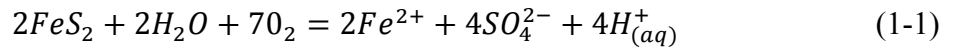
### 2.2.1 Generation and Factors Affecting AMD

AMD requires the necessary reactants of water, oxygen and sulfide minerals. Water and oxygen are both readily available in the atmosphere, and in the ground to some extent, whereas sulfide minerals can be present in mine waste rock as trace minerals. The amount of trace minerals left behind in waste rock depend on the type of material being mined and the economic viability of their extraction to the industry. Table 2-1 lists a number of different sulfide minerals that can exist.

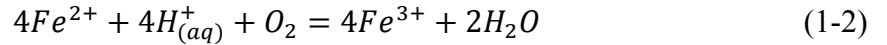
Table 2-1: Other sulfide minerals (Archarya & Kharel, 2020)

<b>Sulfide Minerals</b>
Pyrite
Pyrrhotite
Marcasite
Chalcopyrite
Galena
Millerite

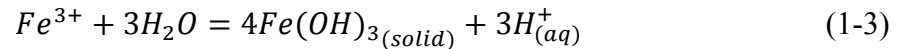
Using pyritic sulfur as an example, the mineral oxidizes in the presence of oxygen and water to form dissolved iron, hydrogen and sulfate seen in the reaction Equation (1-1).



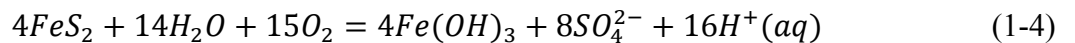
The dissolved iron reacts further, provided there is sufficient oxygen available, with hydrogen and oxygen to produce ferric iron ( $Fe^{3+}$ ) (Equation (1-2)).



Next, the ferric iron hydrolyzes to produce ferric hydroxide which will precipitate out of the solution as a solid (Equation (1-3)). The precipitate is often seen on shorelines and the surface of rocks as a white to yellow crust.



Another option for pyritic sulfur is to react with some of the ferric iron produced and water to create ferrous iron and sulfate (Equation (1-4)).



For many sulfides the production of hydrogen ions will decrease the pH of the solution and increase the acidity (Acharya & Kharel, 2020). Zinc sulfide is the one exception since the indirect



release of protons during oxidation of this mineral doesn't cause a large increase in acidity (Banks et al., 1997). Overall, however, there are various influences that can affect the production of AMD, including generation, physical and chemical factors (Acharya & Kharel, 2020).

### 2.2.2 AMD Influencing Factors

Factors affecting the generation of AMD include impacts on the reactants, physical factors and chemical factors (Acharya & Kharel, 2020; Akcil & Koldas, 2006; John, et al., 2017; Pat-Espadas et al., 2018). The reactants can be impacted by the presence of bacteria which cause an increase in the rate of sulfide oxidation. However, environmental conditions for these bacteria to survive are very specific, which can allow for AMD generation to be slowed down by forming an unfavourable habitat (Akcil & Koldas, 2006).

Physical factors such as the geographic location of the waste rock are particularly important since the climatic conditions, for example the amount of water available for the reaction, can affect the presence and pH of AMD (INAP, 2014). Therefore, the treatment of AMD must be site specific. Additionally, the physical characteristics of the sulfide minerals can affect the rate of production of AMD (Acharya & Kharel, 2020). Caruccio et al., 1997, found that coarse-grained pyrite particles with a non-framboidal crystalline structure decompose more slowly than fine-grained framboidal structures because of their limited surface area compared to the latter. The physical size of the waste rock itself can also affect AMD generation in terms of both the amount of surface area available for the reaction to occur as well as permeability. This waste rock dump pile permeability can also affect the reaction rate of AMD. The more permeable a waste rock pile is, the more space it has between the rock pieces and therefore has a larger allowance for oxygen flow. A positive feedback loop is created where more oxygen is able to enter the pile thereby increasing the reaction rates thus increasing the temperature within the pile creating convection within the structure and sucking more oxygen in. This effect can be minimized by crushing the rocks into smaller pieces thus decreasing the space between the rock therefore decreasing the amount of oxygen ingress to the pile (Akcil & Koldas, 2006).

Lastly, chemical factors such as the pH level, have the greatest impact on AMD (Acharya & Kharel, 2020). Equeenuddin et al., 2010, saw that the pH of AMD is negatively correlated with



the amount of dissolved sulfide present as well with additional dissolved metals such as iron and manganese. The high metal content that low pH AMD has can increase the electrical conductivity of the solution (Equeenuddin et al., 2010).

### 2.2.3 Sources and Release Mechanisms

Water and oxygen required for the AMD reaction to take place are readily available in the atmosphere. However, the reaction is not possible without the presence of sulfide minerals. This reactant is present in various mine waste products such as coal waste rock and emanates from both primary and secondary sources. Primary sources include tailings ponds, mine waste rock dumps and underground and open pit mine workings. Secondary sources are concentrated spills along roadways, treatment sludge ponds, rock cuts and emergency ponds (Figure 2-5) (Acharya & Kharel, 2020; Akcil & Koldas, 2006; John et al., 2017).

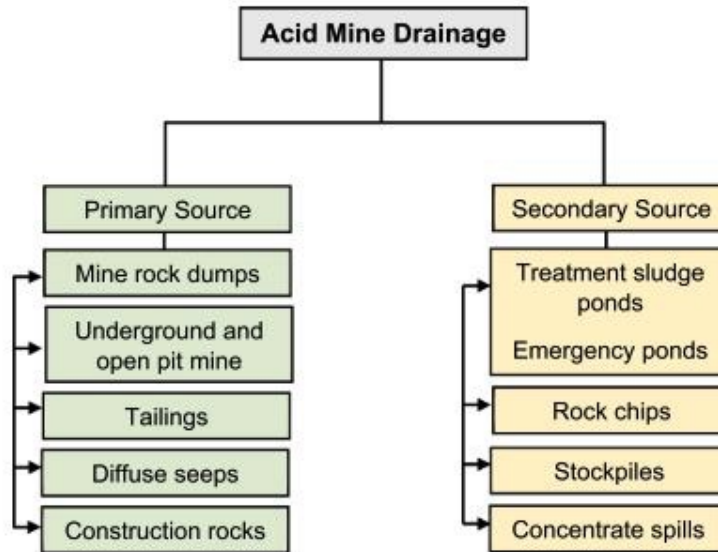


Figure 2-5: Primary and secondary sources of acid mine drainage (AMD) (source: Akcil & Koldas, 2006)

From these sources, the AMD product that is generated is released through the movement of water. After formation the AMD leachate that is contained within the waste rock will percolate through the depth of the WRP and seep out both at the base and on the sides, respectively denoted basal and toe seepage. Basal seepage will further percolate into the ground and contaminate groundwater resources such as aquifers. Toe seepage will flow off the pile onto the

ground surface and may contaminate surface water resources and soils (Acharya & Kharel, 2020).

#### 2.2.4 Impact of AMD

Effects due to acidic drainage vary from location, climate, land-use history, scale of mining, geochemistry of overburden material, and composition of mine water (Ayres & O’Kane, 2013; Acharya & Kharel, 2020). The impact of AMD is 4-fold, of which there are negative chemical, physical, biological, and ecological effects (John et al., 2017). Chemical impacts such as a reduction in pH to as small as a pH of 2, an increase in acidity and soluble metal concentration to the receiving aqueous environment relays a negative effect to the biology of life in the area through increased cell damage and death (Dutta et al., 2019, John et al., 2017). The resulting impact on ecological communities is detrimental with increased mortality in the animals that depend on these water resources. Thus, as a result water bodies contaminated are completely inhospitable to aquatic life except for extremophile species (John et al., 2017). Intake of heavy metals from AMD contaminated sources and bioaccumulation within the food chain has been seen as a result (Acharya & Kharel, 2020). Degradation of drinking water is also an issue as aquifers can be recharged with the contaminated water (Equeenuddin et al., 2010). However, humans are not impacted to the same degree as wildlife populations since the water can be treated before human use (Acharya & Kharel, 2020).

The difficulty in characterization, prediction, prevention, treatment and extent makes AMD one of the most serious pollutants in watercourses, and the impact is so severe that the U.S Environmental Protection Agency (EPA) stated the environmental risks are “second only to global warming and ozone depletion” (Acharya & Kharel, 2020; Pat-Espadas et al., 2018). Canada spends approximately 100 million dollars to collect and treat mine waste leachate and cost to remediate AMD in the mining industry is between two and five billion dollars annually, making it the largest environmental liability in Canada (EMCBC, 2000).

## 2.3 Cover Systems

### 2.3.1 Waste Rock Pile

Waste rock is disposed of in large, porous, partially saturated piles on the ground surface. The WRP is constructed by hauling the solid waste into piles nearby the mine site. However, depending on when the WRP is established, cover systems can be constructed beneath, on top of WRP's or utilize both options. Some WRPs have been further reprocessed to extract additional materials, and as a result have increased the footprint of the final pile. The geometry of the pile can change depending on how the waste rock is deposited. WRPs can have various formations such as having a sloped perimeter with a plateaued top (Figure 2-6), a cone shape or also be relatively flat. The geometry of the WRP can highly influence the performance of the cover system installed on top.



*Figure 2-6: Distinct slope and plateau area of a waste rock pile in Sydney, Nova Scotia.*

### 2.3.2 Cover System Types

Protective coverings, referred to as engineered cover systems or cover systems, have been implemented in various studies to limit interaction between reactive elements. Cover systems have been previously used at landfill sites, tailing ponds, nuclear waste facilities, etc (i.e. Ahn et al., 2011; Ashford et al., 2000).

Design of cover systems depend on multiple factors including the site conditions, topography, climate of the area, financial limitations, installation difficulty, and required performance criteria (Power et al., 2018). Due to the wide range of requirements necessary to consider in cover system design, a variety of systems exist to meet the requirements of engineered cover systems constructed globally (Kim & Benson 2004; MEND 2004). Cover systems are commonly distinguished by the number or types of layers they consist of, i.e. single layer, multi-layer and synthetic cover systems

Single cover systems are the most straightforward design and are aimed to function as a store-and-release mechanism for atmospheric ingress. Multi-layer cover systems are conversely more complex than single layer systems since, as their name suggests, consist of several layers which operate in unison to fulfill the performance objectives. Synthetic covers are unique from other designs because they are completely anthropogenically constructed. With this design, engineers are able to more accurately achieve cover performance goals than they would be with natural materials. Further insight into each of these cover system designs, where they are best implemented, their advantages and disadvantages are discussed in the following sections.

### 2.3.3 Single Layer Cover Systems

Single layer cover systems, as the name suggests, consist of only one layer. These covers are best implemented when the site objective needs are to store and release moisture from the atmosphere, without providing any function to limiting oxygen ingress (Scanlon et al., 2005). They can either be designed as a single liner or as a composite liner. Composite liners are cover systems which are comprised of two or more unique low-permeability materials that are in contact with one another (Giroud & Bonaparte, 1989). Most commonly, a composite liner uses a geomembrane, i.e. a fluid barrier that is thin and flexible, with a soil. Each material has individual hydraulic,

endurance and physical properties and both are combined to take advantage of each. Single layer cover systems objective is to delay the hydrologic cycle; therefore this design operates well in semi-arid or arid regions where precipitation is low and the cover is able to manage the influx of water through evapotranspiration before receiving more water (O’Kane and Ayres 2012; Scanlon et al., 2005; Bonstrom et al., 2012, Ayres et al., 2003). Single layer cover systems are easier to install and more cost effective than other designs making this an attractive option for a waste rock barrier (Power et al., 2017). The most common material to use for a single layer cover system is earthen till or soil, but other materials such as asphalt, cement and wax barriers have also been used in cover system designs (MEND, 2001).

Soil cover system can also be enhanced with other materials to aid in their retention and evaporative properties. Bentonite, a naturally occurring clay mineral, is a common additive that can display a wide range of properties depending on the circumstances with its formation but is used with soil to decrease the hydraulic conductivity (MEND 2002). Soil-bentonite mixtures are also attractive for use at water and waste containment facilities due to the unique crystalline structure of bentonite. When water is absorbed in this material the lattice swells, decreasing the void ratio thus decreasing the availability for water flow through the material. Studies by Claire et al., 1993 and Kraus et al., 1997 have shown that bentonite enhanced soils also have a considerable resistance to freeze-thaw cycles and only experience a slight increase in hydraulic conductivity during this period.

Similar properties are seen in other enhanced soil cover systems such as polymer modified soils. The same polymers that are used in the drilling industry to enhance the characteristics of drilling muds are also applied to enhanced soil mixtures to lower the hydraulic conductivity. Polymers are known to absorb 680 times their weight in water while bentonite only absorbs approximately 10 times (Zhou et al., 1993). For this reason, the use of polymer-soil mixtures in a simple soil cover design would be ideal to reduce infiltration of water and oxygen diffusion (MEND 2002). Asphalt covers have been used for mine tailings and waste disposal sites and are composed of mixtures of asphalt and mineral fillers. Hydraulic asphalt concrete (HAC) used for this purpose has a higher content of mineral fillers and asphalt cement but a lower air void content. HAC has the advantage of an extremely low hydraulic conductivity in perfect condition but degradation

through oxidation, microbial attack, freeze-thaw cycling, and aqueous leaching need to be considered when used for cover system design (MEND, 2002).

Similarly, cement covers like polypropylene fibre reinforced shotcrete, cefill, fly ash and geopolymers have been used on mine tailings sites, general acid generating waste, and waste rock to deliver the same low hydraulic conductivity traits (MEND, 2002).

#### 2.3.4 Multi-Layer Cover systems

Multi-layer cover systems implement several different layers to take advantage of the benefits of each material while also counteracting their disadvantages by using multiple mediums. These cover systems are extremely beneficial for use in various climates and are designed to minimize oxygen and water influx. Water is impeded by either the use of resistive “barriers” that are designed to repel water and transport it through interflow, runoff and evapotranspiration within the cover system or using moisture retention seen in the capillary barrier concept (Power et al., 2017). Oxygen is additionally repelled through the moisture retention because of low diffusivity of oxygen in water (Yanful, 1993). Multi-layer cover systems utilize a variety of materials such as soils and the modified mixtures mentioned in the previous section, gravel, and man-made materials like geofabrics, and plastics in a combination that is designed to achieve the long-term stability and performance goals of each specific WRP site.

Man-made materials will be discussed in the following section, however their use in combination with gravel drainage layers is an example of a multi-layered cover system which conveys the flow of water through the cover. The increased pore space in the gravel material allows for water to percolate through more easily than with a finer substrate such as sand or soil. The enhanced movement of water prevents build up on plastic “barrier” layers and decreases the likelihood of water influx while increasing interflow. Gravel has also been used on the surface of cover systems to decrease erosion of more finely grained upper layer materials (Woysner and Yanful, 1995). Other organic and biologic materials have been used in addition such as compost and sewage sludge to create a biocover which have previously been employed at landfill sites to limit the amount of methane release and increase the oxidation rates within the pile (Sadasivam & Reddy, 2014). A double liner is a multi-layer cover system design which uses a drainage layer

sandwiched by two liners. A more complex double liner utilizes the single layer composite liner design as both the upper and lower layers in the double liner design. The drainage layer can consist of high-permeability soils, sands, gravels, or synthetic materials like geotextiles, geofabrics or needle punched woven sheets (Giroud & Bonaparte, 1989).

### 2.3.5 Geomembrane & Synthetic Cover Systems

In both single and multi-layer cover systems synthetic materials, called geosynthetics, can be used. Some common geosynthetics are geomembranes, geotextiles, geosynthetic clay liners, erosion control blankets and geonets (Giroud & Bonaparte, 1989; Ogundare et al., 2019). Geomembranes are low-permeability plastic liners which are flexible and thin allowing them to be stored on large rolls for easy transport (Giroud et al., 2000). High-density polyethylene (HDPE), low-density polyethylene (LDPE) and polyvinyl chloride (PVC) are common geomembranes (Giroud & Bonaparte, 1989). Geomembranes have been highly successful at mining sites and landfill sites for liquid leachate containment (Lupo & Morrison, 2007). Under ideal performance, geomembranes have contributed to stopping volatile fatty acids, chloride, ammonia, lead, mercury, and many other contaminants from polluting the environment (Rowe et al., 2004; Rowe, 2005). However, their water flux performance can be impacted by holes created in the material through poor installation, heat damage, wrinkling and aging (Rowe, 2012).

Geotextiles are grouped into two categories; woven and non-woven but both are implemented in cover system design to increase stability and shear strength of overlying layers through resistive forces provided by the rough texture of the geotextile. These materials function to provide reinforcement, drainage, filtration, and separation to the cover system. Woven materials have a basket-weave pattern structure with a relatively smooth surface while non-woven geotextiles are made of random interlocking fibers that give a distinct “fuzzy” appearance (Figure 2-7). Additionally, geotextiles are important for use in cover systems that have layers intended for moisture storage since many natural soils decrease in strength with an increase in moisture content (Ogundare et al., 2019). The strength, i.e. the soil stability, is important in a cover system to maintain its structural integrity.



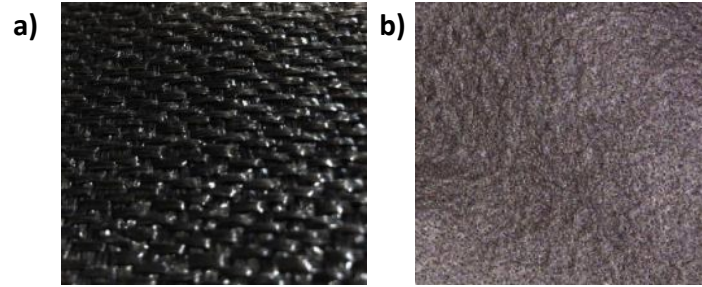


Figure 2-7: (a) woven, and (b) non-woven geotextile fabrics (source: Ogundare et al., 2019)

Geosynthetic clay liners (GCLs) can be used as the soil part in composite liners. It is made up of a thin layer of bentonite clay that could be adhered to a plastic layer that is sandwiched between two geotextiles. GCLs can be reinforced by needle-punching the clay and geotextile layers together which enhances its moisture retention and shear strength properties, making it the most common GCL (Rowe, 2012). Rowe, 2012 showed that GCL are more successful at limiting water influx compared to a traditional clay liner, and their performance continued in field settings for decades. GCLs are also popular for their faster installation time, ability to use lightweight construction equipment and the minimal volume they occupy (Renken et al., 2007).

A geonet is a plastic grid network sheet that is formed of a repetitive diamond pattern used to increase drainage (Figure 2-8) (Fannin et al., 1998). Since it is a man-made product, the sheet can be constructed with an exact transmissivity value known, unlike natural materials that are used for the same function. It is common for a geonet to be accompanied by a geotextile to prevent infiltration of smaller particles within the cover system that would clog the grid pattern. Geonets have also been used in other applications in multi-layer cover systems such as directly below geomembranes for use in leakage detection systems (Eith & Koerner, 1992).



Figure 2-8: Geometric repetitive pattern of geonet material (source: Eith & Koerner, 1992)



## 2.4 Cover System Performance

### 2.4.1 Key Performance Indicators

When a cover system is installed, different means of monitoring can be conducted to measure the performance of a cover at limiting AMD contamination over time. With knowledge of water and oxygen being the reactants to propel the production of AMD, the concentration or content of both these parameters are most commonly seen in cover system performance analysis and experimentation (e.g. Ayres et al., 2012). The long term performance of a cover system is dependent on the physical, chemical and biological processes detailed in Figure 2-9 that occur at the WRP site (Ayres & O’Kane, 2013).

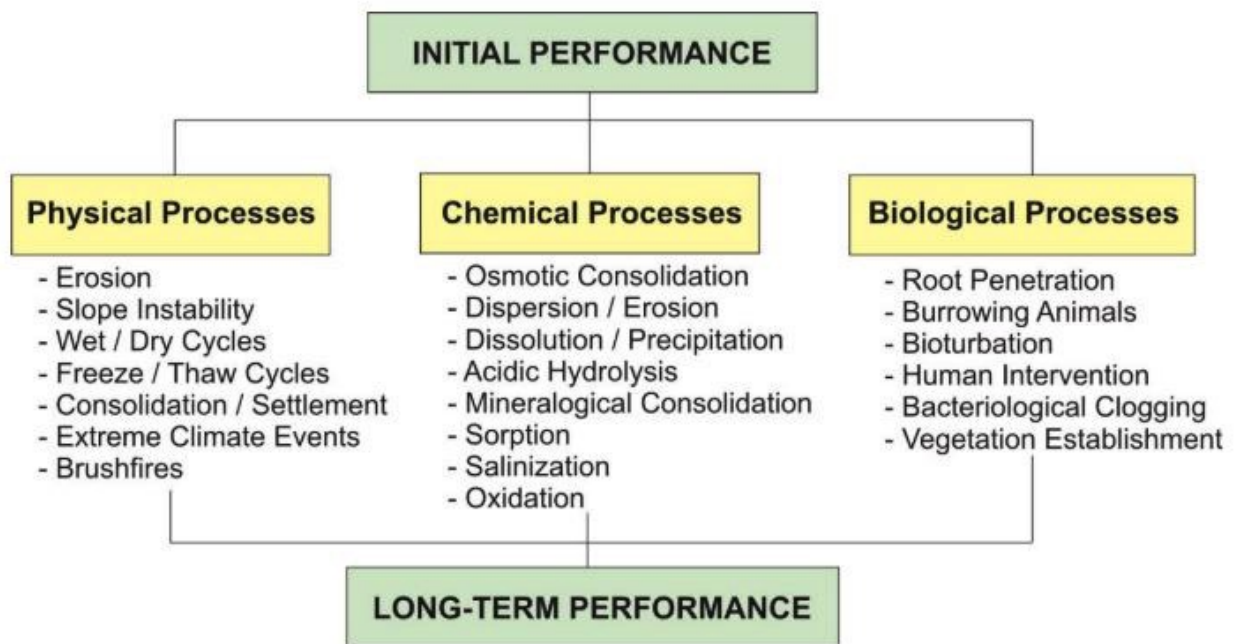


Figure 2-9: Processes that influence the performance of an engineered cover system (source: Ayres & O’Kane, 2013)

### 2.4.2 Measuring Water Influx

To measure water influx, or the net percolation, all water in the hydrologic cycle must be accounted for. With this system a water balance is commonly used to assess the amount of water that has accumulated from precipitation to other locations. A water balance for the site is often conducted for this method and can utilize systems such as a meteorological station, weirs, groundwater wells, automated net percolation measuring stations as well as stations for

determining the amount of soil moisture and pore-gas concentrations within the cover and WRP (Figure 2-10).

Meteorological stations have been used to measure all climatic conditions, including but not limited to air temperature and humidity, wind speed and direction, net radiation, and pressure (MEND, 2002; Tallon et al., 2013). A meteorological station is important to have at a WRP study since they are a simple yet effective tool to measure precipitation, which is the maximum influx that can occur for net percolation. Soil data including temperature, moisture content, has been analyzed using semivariograms (Tallon et al., 2013). A system to collect runoff like a v-notch weir is most common and can have the addition of collection ponds for further analysis of water contamination (Meiers et al., 2012; Power et al., 2018; MEND, 2015). Another vital instrument for determining water influx through a cover profile is the installation of moisture sensors, as seen in studies by Martin et al., 2019 and Power et al., 2018. Additional instrumentation like interflow devices constructed of geosynthetic sheets, and PVC piping are used to measure the water flow in cover systems that use geomembranes (Meiers et al., 2006).



*Figure 2-10: Monitoring equipment that can be used for cover performance evaluation (source: Ayres & O’Kane, 2013)*

A water balance has been used at sites like Whistle Mine near Sudbury, Ontario, to measure net percolation of a multi-layer cover system on the WRP over seven years (Ayres et al., 2012). Performance of various cover system designs using the Peak Gold Mines (PGM) field site have been analyzed using soil-atmosphere numerical modelling, experimental cover systems and

initial field testing. The PGM study by Ayres et al., 2003 showed that from a detailed water balance method analysis the soil-only cover was able to achieve successful evaporative results using the store-and-release principles. Experiments and testing using water balance are widely conducted on both field and in lab studies (Aubertin et al., 1997; O’Kane et al., 1998a; Meiers et al., 2009).

When studying performance of cover systems that include geomembranes, net percolation through the cover system can also be determined by the defect leakage experienced through the holes that are created in the plastic through the improper installation and aging of the product. Defect leakage is defined as the amount of liquid that flows through an opening in a cover system. These defects can occur in a variety of sizes ranging from pinholes to large tears and can result in a range of influx measurements (Giroud & Bonaparte, 1989). When considering defect leakage as a measurement of water influx, instrumentation that measures the water head above the geomembrane, like an OTT-pressure level sensor (PLS) or a HOBO logger, is necessary to include in the monitoring program. However, since the number and size of defects are not definitive and only highly estimated, the amount of defect leakage that could be calculated could vary from the actual measurement of net percolation (Giroud et al., 1992, Rowe 2012). The assumption is that as many as 15-20 defects of 2.5 – 15 mm in diameter are in every hectare of geomembrane (Rowe, 2012; Meiers & Bradley, 2017).

Considering all field studies and instruments utilized to measure water influx performance at WRPs, numerical modelling and simulations of cover performance have also been highly studied since it requires a fraction of the cost and time to analyze the results of various scenarios. However, like with most laboratory studies the results are not completely transferable to field sites due to the heterogeneity and complexity of in-situ cover performance (Meiers et al., 2009).

### 2.4.3 Measuring Oxygen Influx

Oxygen can be received to the waste rock through diffusion, advection, or dispersion. In the absence of defects, advective and dissolved transport mechanisms will not occur through geomembrane liner inclusive cover systems, the dominant mechanism being diffusion. An ideal cover system will combine the qualities to limit water ingress but share a balance with the traits

that limit oxygen ingress as well. This environment would display a cover system that is able to contain a layer near saturation to prevent diffusive oxygen flux, Ayres et al. (2003) found that oxygen flux is decreased substantially if at least 85% of the layer is saturated. A cover limiting oxygen ingress will also have a small amount of pore space to decrease the oxygen influx by using materials with the smallest surface area (Ayres et al., 2012). To measure the oxygen concentration within the cover system and waste rock, a NOVA Gas Analyzer, or similar device could be used (MEND, 2012).

## 2.5 The Sydney Coalfield

### 2.5.1 Background

The Sydney Coalfield is located in Nova Scotia, Canada on Cape Breton Island (Figure 2-11). The coal rich environment was formed approximately 300 million years ago in the Late Carboniferous period (Hacquebard, 1993). The first commercial mining of this area did not begin until 1672 later evolving into commercial mining in 1700's. The presence of war in the following years increased the production of coal and the Sydney Coalfield proved to be a successful venture. After the Seven Years War concluded, Cape Breton and coal production here was taken over by British who leased the mineral rights to the General Mining Association (GMA). GMA, in turn, relinquished the rights of the land back to the provincial government of Nova Scotia from 1826-1850. Until 1967 coal was still heavily mined alongside the demand from the growing economy. However, in 1967 the newly formed Crown corporation called the Cape Breton Development Corporation (CBDC) was formed to manage the coal industry in Sydney (Meiers, et al., 2012). With a decline in the demand for coal their objective was to develop new economic opportunities while phasing out coal mining (Parsons et al., 2012). However, the Oil Embargo of the mid 1970's resulted in continued coal mining at the Sydney Coalfield by CBDC until 2001 when the mine sites ceased operation (Campbell & Gauthier, 2010).

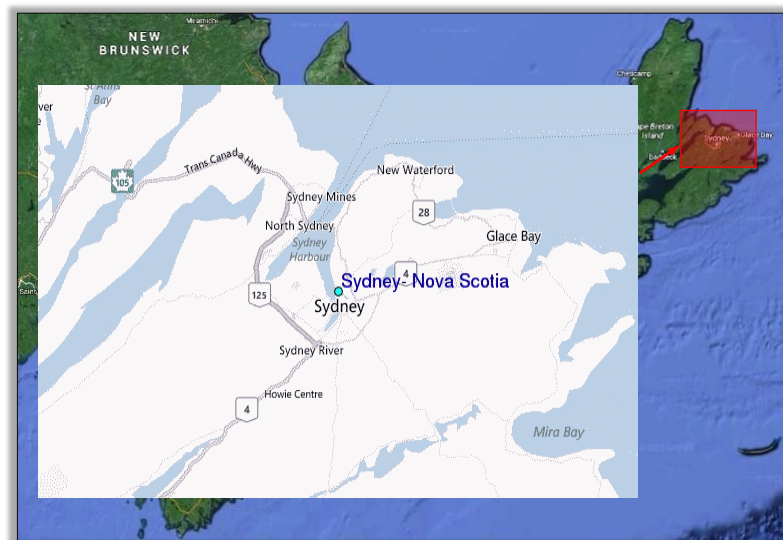


Figure 2-11: Sydney Coalfield, Nova Scotia, Canada (source: Google Earth, 2021)

### 2.5.2 Mine Site Reclamation Project

After almost 300 years of continuous mining, producing over 2.4 billion tonnes of coal, the CBDC inherited the Sydney Coalfield properties and retired the mine sites in 2001 (Forgeron, 2010). Working with Public Works and Government Services Canada (PWGSC), CBDC developed a program for remediating and closing former mine sites throughout the coalfield. The project spanned over 700 properties among 35 communities with multiple project managers (Parsons et al., 2012). PWGSC provided the engineering expertise including impacts associated with waste rock, GIS, and coal and industrial activity while CBDC were responsible for health and safety issues including human health, ecological risk assessments and mine workings hazards (Campbell & Gauthier, 2010). In 2009, CBDC dissolved, and the responsibility of the Sydney Coalfield Mine Site Reclamation Project was transferred to Enterprise Cape Breton Corporation (ECBC) (Ayers, 2010). Over the 10 years since this projects conception over 140 million dollars has been spent on planning, assessment, design, project management, demolition, construction, and environmental effects monitoring. The main objective was to return the land to its former or equal use through remediation practices that are economically viable while being the most passive method (Parsons et al., 2012).

### 2.5.3 Waste Rock Piles

To ensure the project site objectives for the Sydney Coalfield were being met, numerous waste rock piles sites were remediated through the installation of cover systems. Furthermore, at four WRP sites, state-of-the-art field monitoring instrumentation was installed alongside the cover system to allow for comprehensive performance monitoring and assess whether the site closure objectives were being achieved. Thsee four WRPs are Lingan, Victoria Junction, Scotchtown Summit and Franklin.

The first WRP is Lingan which is in New Waterford, Nova Scotia, centered nearby the Lingan and Phalen colliery sites. The clean up of the site resulted in 3 WRPs that have been covered with a soil cover and topped with sod grass. One of these piles was utilized in the mine site reclamation project and the improvements to the site are intended to restore the land to use as a recreational horse track for the surrounding communities (ECBC, 2014).

The Victoria Junction group of WRPs consists of 11 sites which includes both the tailings basin and the coal preparation plant. The Victoria Junction WRP site that was used in the project had the cover system constructed between May and December 2006 (MEND, 2012).

The Summit WRP group consists of 15 sites across New Waterford, Nova Scotia. Remediation was completed here in 2011 and 2012 with the creation of the main WRP and its accompanied cover system as well as a recreational trail network to restore the land to a new use (ECBC, 2014).

The Franklin WRP group consists of 6 sites spread across Florence and Bras d'Or, Nova Scotia. The main Franklin WRP that was included in the project is the largest of the 6 and was under operation from 1885 to 1957 where it produced approximately 1.4 million tonnes of coal (ECBC, 2014).

## 2.6 Summary & Data Gaps

Mining in Canada is still extremely prevalent with large amounts of waste rock being continuously produced through the mining of various metals and minerals. Furthermore, decommissioned mine sites, specifically coalfields, pose an environmental threat to nearby water resources and wildlife. The application of engineered cover systems has been focused mainly on test plot sites in laboratory settings which have resulted in increased knowledge of various materials performance in limiting atmospheric ingress. However, the ideal setting of lab studies doesn't show the reality of engineered cover system performance. Additionally, performance has generally only been studied for a handful of years, (e.g. Yanful & Adu-Wusu, 2006) and could be subject to skewed results due to the piles previous saturation prior to cover installation. Overall, few studies have been conducted at large-scale in field waste rock covers over an extended period of time to analyze how various systems perform through climatic variability and aging.

Therefore, there is a need to compare various types of engineered cover systems including several different materials to determine the best systems at limiting AMD. Additionally, the defects that can occur in HDPE-inclusive cover systems need to be evaluated as to determine the amount of water influx and thus the consequential potential AMD contamination. Chapters 3 and 4 of this thesis present a study focused on four WRPs at Sydney Coalfield in Nova, Scotia, Canada. Chapter 3 concentrates on the impacts of defect leakage on environmental receptors in HDPE cover systems. Chapter 4 focuses on an overall comparison of the four different engineered cover systems and their ability to limit both water and oxygen influx.



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## 3 Importance of Drainage Layers in Multi-Layer Geomembrane-Lined Cover Systems

### 3.1 Introduction

Mining operations produce massive quantities of waste rock that were not economically viable. The waste rock, which is typically deposited in large piles on the ground surface, can contain significant amounts of reactive sulfidic minerals such as pyrite and pyrrhotite. Exposure of these minerals to atmospheric water and meteoric oxygen can start a complex sequence of oxidation-reduction reactions that generates acid mine drainage (AMD) (Nordstrom et al., 2015). AMD leachate is characterized by low pH, high acidity and high concentrations of sulfate, iron, manganese and other heavy metals. As a result, these waste rock piles (WRPs) can be a long-term source of environmental pollution, particularly on water resources, soil and aquatic communities (INAP, 2014). A number of studies provide detailed reviews of ARD components, including geochemistry (e.g., Nordstrom et al. 2015), impacts (e.g., Simate and Ndlovu 2014) and remediation options (e.g., Johnson and Hallberg 2005).

A common approach to prevent and/or control AMD contamination is the placement of an engineered cover over the waste rock to isolate the reactive waste from the atmosphere. In addition to minimizing degradation of the surrounding environment, cover systems are also used to restore the WRP surface to a stable natural condition. A variety of cover system compositions and structures exist, ranging from a single layer of native soil to multiple layers of differing materials such as natural soil, geosynthetic-reinforced soil and geomembranes (e.g., MEND, 2014). A ‘store-and-release’ cover includes a growth medium layer that stores infiltrated water until atmospheric and biotic demands are able to remove the water through evaporation and transpiration (e.g., O’Kane & Ayres, 2012), while a ‘water-shedding’ system also contains an additional impermeable or low permeability layer to promote water-shedding when storage is overwhelmed in the growth medium.

Numerous studies have been performed to assess the effectiveness of various cover systems for limiting atmospheric influx based on numerical values of water and oxygen ingress. Furthermore, very few studies have monitored cover systems containing geomembranes. Geomembranes such

as high-density polyethylene (HDPE) can be a highly effective barrier to water and oxygen transport. While it has traditionally been used in lining systems at municipal waste landfills, it is now becoming a popular option within multi-layer cover systems being placed over WRPs. A recent monitoring project at a HDPE-lined cover system in Nova Scotia, Canada, confirmed the potential of HDPE-lined cover systems for reducing water and oxygen influx (Power et al., 2017a; Ramasamy et al., 2018); however, a detailed investigation of various HDPE-lined cover systems with differing compositions is necessary to better understand the robustness of HDPE and the optimal configuration.

While HDPE-lined covers are essentially impervious when devoid of defects, this is rarely the case at real field sites. Despite being pristine on arrival to the WRP, improper handling and installation commonly results in the creation of defects, whether it is a small hole or a long tear (Power et al., 2017). It is accepted in the literature that on average, 15 to 20 defects exist per hectare of the liner (Giroud et al., 1992; Forget et al., 2005). While it may not be possible to prevent the creation of defects and/or know the size/number of defects, it is possible to control the drainage layer on top of the HDPE liner. The absence or presence of a drainage layer above the HDPE liner, and the type of drainage material used can influence the movement and head of water above the HDPE liner, and therefore impact the amount of defect leakage in the cover system. While research has been performed on defect leakage rates through various defect sizes and shapes, no research has been performed on the influence of drainage material type on the water flux through HDPE-lined cover systems at WRPs.

The objective of this study was to assess the influence of the drainage layer and material type on the water flux through existing defects in HDPE liners within cover systems at WRPs by applying the defect leakage model. Three WRPs located in the Sydney Coalfield in Nova Scotia, Canada, were overlain with HDPE-lined cover systems with differing drainage layers. A comprehensive, seven-year field performance monitoring program was performed at each WRP to monitor the evolution of key parameters within the atmosphere, cover system and shallow waste rock. This extensive dataset was applied to determine the moisture dynamics within the cover system and the water influx into the underlying waste rock. A single layer soil cover was



also monitored to provide a reference to assess the general performance of HDPE-lined cover systems.

## 3.2 Site Description

### 3.2.1 The Sydney Coalfield

The Sydney Coalfield is located on Cape Breton Island in Nova Scotia, Canada, as shown in Figure 3-1. It is the oldest mined coalfield in North America, with underground mining occurring from the early 1700s to the early 2000s (Shea, 2009). These historic mining activities produced approximately 500 million tonnes of coal, but also left behind a legacy of contaminated sites containing mine WRPs (Meiers et al., 2014). Upon cessation of mining operations in 2001, a mine site closure and reclamation program was implemented by Enterprise Cape Breton Corporation (ECBC), and later Public Works and Government Services Canada (PWGSC).

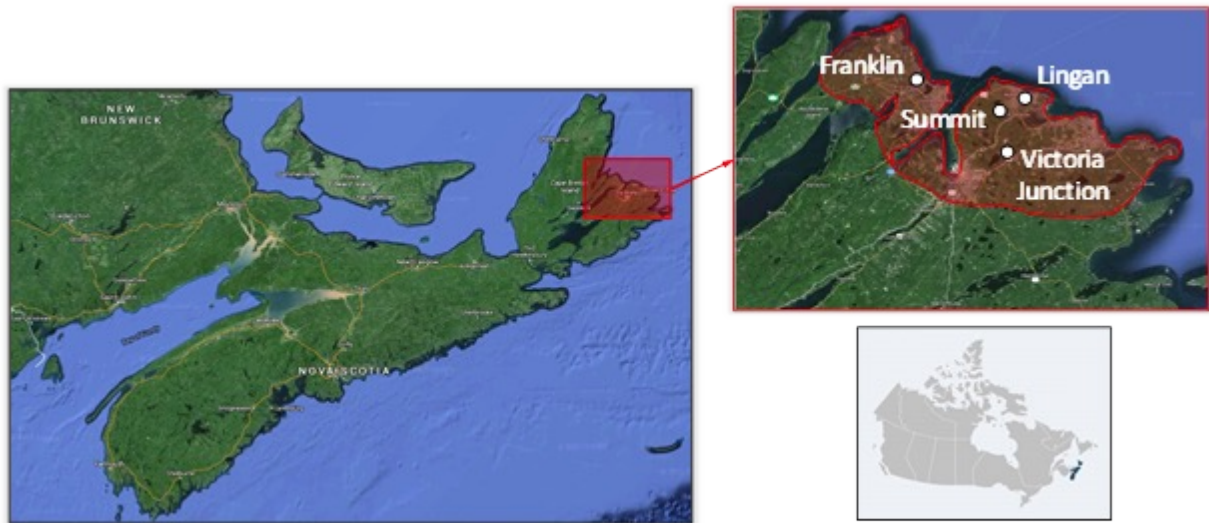


Figure 3-1: Site map of the Sydney Coalfield in Nova Scotia, Canada, indicating the location of the WRPs at Summit, Victoria Junction and Franklin

As part of this program, several WRPs were reclaimed with differing engineered cover systems, including single layer and multi-layer covers containing native soil, geosynthetics and geomembranes (e.g., Meiers et al., 2012). The three WRPs located at Summit, Victoria Junction and Franklin were each overlain with cover systems containing the same HDPE liner but differing layer compositions. Each site has a humid continental climate with an annual total precipitation of approximately 1500 mm and an annual potential evaporation of approximately 450 mm.

### 3.2.2 Summit WRP

The Summit WRP is located on the outskirts of Scotchtown, Nova Scotia, approximately 15 km north of Sydney. This WRP was created from the mine waste rock fill produced by the Dominion Coal Company from 1911 to 1973 and spread over an area of 44 hectares. In 2009, as part of the reclamation program, the WRP was re-shaped and consolidated, with the footprint reduced to approximately 37 hectares that was generally flat. The total volume of waste rock within the WRP is approximately 1.5 million m<sup>3</sup>, and ranges in thickness from 0.5 m to 10 m with the thickest deposits near the center. The plateau slopes range between 1% and 10%, and the side slopes range between 4% and 20%.

Between 2010 and 2011, an engineered cover system was installed. A 0.15 m thick layer of uniform bedding sand was first placed over the waste rock. A 60 mil (1.5 mm thick) HDPE liner was placed on top of the bedding sand, and then overlain with a protective layer geotextile fabric. The fabric increases shear strength and soil stability so cover system structure integrity is maintained on the sloped faces. The rough texture of this material resists horizontal movement of overlying material through friction (Bacas et al., 2015). The cover system was completed with a 0.5 m thick layer of imported till, which was then hydroseeded to establish a sustainable vegetative canopy and a geomorphically stable landform. Figure 3-2a presents an aerial photograph of the reclaimed WRP, while Figure 3-2b presents a cross-sectional profile of the cover system.

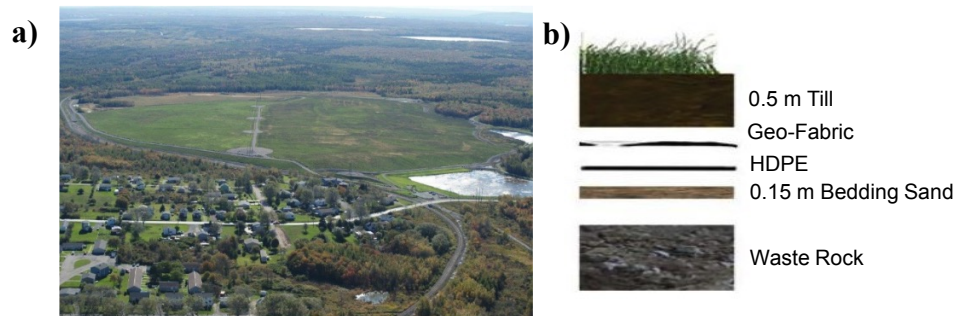


Figure 3-2: (a) aerial photograph of the reclaimed Summit WRP, and (b) 2D cross-section profile of the Summit cover system composition

### 3.2.3 Victoria Junction WRP

The Victoria Junction WRP is located approximately 3 km east of Sydney at the site of a closed coal preparation plant. The processed waste rock from the nearby Phalen Colliery resulted in the WRP containing 5.88 million m<sup>3</sup> of waste rock stretching over 28 hectares. The WRP has a well-defined plateau and slope of 33% and a maximum thickness of 40 m.

The cover system was installed between 2007 and 2008. A 0.15 m layer of uniform bedding sand was first placed over the waste rock, and then overlain with a 60 mil (thousands of an inch) HDPE liner. A 0.6 m thick layer of granular drainage material was then installed to promote lateral water flow and decrease the head of water on top of the impermeable HDPE liner. The resulting interflow was then directed towards a runoff collection system conjunctively. A final 0.6 m thick layer of natural till was placed over the granular drainage material to promote vegetative growth. Figure 3-3 presents an aerial photograph of the reclaimed WRP and a cross-sectional profile of its cover system.

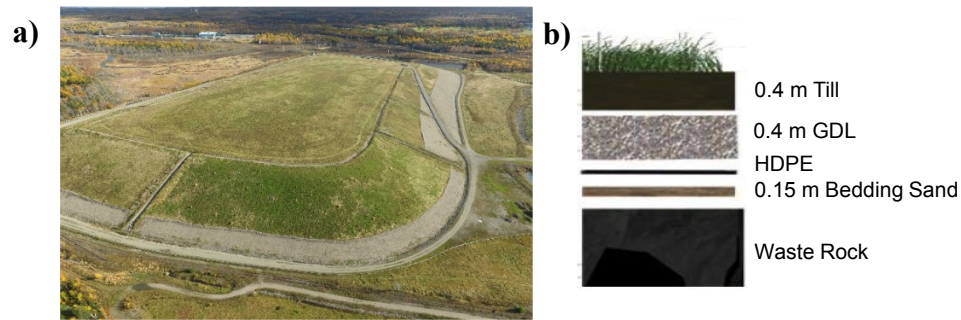
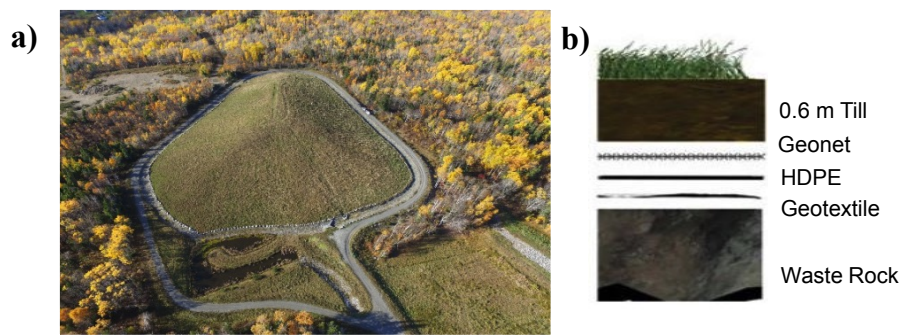


Figure 3-3: (a) aerial photograph of the reclaimed Victoria Junction WRP, and (b) 2D cross-section profile of the Victoria Junction cover system composition

### 3.2.4 Franklin WRP

The Franklin WRP is located in Bras d'Or, approximately 25 km north of Sydney. Over 187000 m<sup>3</sup> of waste rock from five nearby coal mines, including the Franklin mine, was deposited into the WRP. This WRP has the smallest footprint of the three WRPs in this study, spanning an area of 2.5 hectares. It has a small plateau on top with a maximum thickness of 13 m, and 25% side slopes.

The cover system was installed in 2011 and implements a geotextile fabric on top of the waste rock, that is then overlain with a 60 mil (i.e. thousands of an inch) HDPE liner. A geocomposite drainage system, referred to as a ‘geonet’ was placed on top of the HDPE liner. The geonet consists of two sets of HDPE strands intersecting at different angles and spacing that are heat-bonded with a nonwoven needle-punched geotextile to keep silt and soil particles from clogging the flow and increase the friction characteristics. A 0.6 m thick layer of imported till was placed on top and hydroseeded to provide a sustainable vegetative layer. Figure 3-4 presents an aerial photograph of the Franklin WRP and a cross-sectional profile of its cover system.



*Figure 3-4:* (a) aerial photograph of the reclaimed Franklin WRP, and (b) 2D cross-section profile of the Franklin cover system composition

## 3.3 Methodology

### 3.3.1 Defect Leakage

The primary mechanism for generating water flux through a cover system containing a HDPE liner is leakage through defects. Defects, also referred to as holes, tears or rips depending on the size and shape of the opening, are commonly present in cover systems (Giroud & Bonaparte, 1989). Defects can be formed in many ways at a WRP, including (i) handling, installation and seaming, (ii) subsequent placement of overlying cover material, (iii) heavy machinery traffic, and (iv) aging (Rowe, 2012). Giroud & Bonaparte (1989) were the first to outline concisely the presence of defects and the issues they cause in HDPE liner performance. Since their discovery, a number of studies like the ones by Rowe et al. (2012), Rowe (2012) and Touze-Foltz et al. (2021) have supported defect existence in HDPE and researched their impact on wrinkled and landfill liners and associated leakage rates. It is undisputed that defects occur within plastic liners and the number can range anywhere from 2 to 30 holes/ha upon initial HDPE placement. This value is applied to design calculations when constructing HDPE-inclusive cover systems however, it must be noted that further defects can arise over time through the aforementioned mechanisms (Giroud & Bonaparte 2001; Meiers et al., 2015).

Assessing the amount of leakage that can occur through geomembranes is a long-established and active area of research (Giroud & Touze-Foltz, 2005; Rowe, 2012; Foose et al., 2001; Touze-Foltz & Giroud, 2003). The leakage through defects is influenced by a number of different factors, including: (i) head of water above HDPE liner, (ii) slope angle of the HDPE liner size, (iii) size and number of defects within the liner, (iii) saturated hydraulic conductivity of the underlying medium, (iv) wrinkle dimensions (i.e. width and length) and connectivity, (iiv) transmissivity of the interface and (iiiv) contact quality between HDPE and underlying medium (Meiers & Bradley, 2017; Power et al., 2017).

A conceptual model of a single HDPE liner defect is shown in Figure 3-5 to illustrate how fluids travel through defects. The head of water that builds on top of the HDPE liner provides the gradient for flow through the defect. The slope of the cover system and the hydraulic conductivity of the underlying material also influences the flow rate through the defect. The quality of contact between the HDPE liner and the underlying material strongly influences the

total influx to the waste rock. Poor contact quality can be caused by wrinkles, uncompacted material and/or uneven surfaces and results in a gap between the interface of the HDPE and underlying material. In contrast, good contact quality occurs when strong adherence exists between both layers (Touze-Foltz & Giroud, 2003). The interface gap between the two layers influences the rate of lateral flow and spreading before percolating into the underlying medium. Area of the defect will also determine the rate of leakage through the HDPE liner. The area of a defect is directly related to the interface flow experienced. Therefore, large areas yield a greater surface area for interface flow and thus greater leakage rates. The converse occurs when the area of a defect is smaller. The head of water above HDPE liners is another key parameter in measuring defect leakage. A large hydraulic head experiences greater pressures and forces water through the defect more efficiently than with a small hydraulic head experiencing lower pressures. Finally, the saturated hydraulic conductivity ( $K_{sat}$ ) of the medium below the HDPE will dictate how fast the resulting leakage will be able to flow through towards the underlying waste rock. A material with a high  $K_{sat}$  is more permeable than a material with a low  $K_{sat}$ . Consequently, water travels more slowly through the latter as a result of the tightly packed saturated pore space. Opposingly, there is greater ease for water movement when the material has a high  $K_{sat}$ .

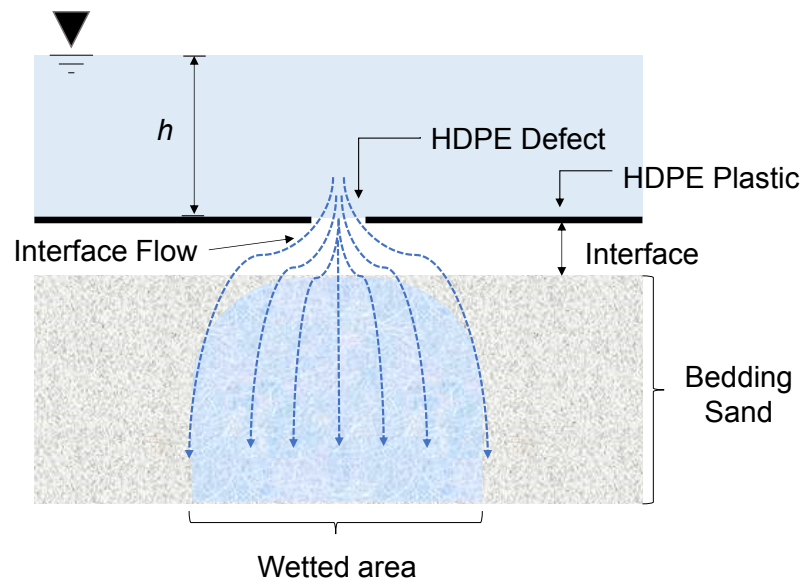


Figure 3-5: Conceptual model of fluid mechanics surrounding a defect in a HDPE liner (modified from Touze-Foltz & Giroud, 2003).

Several equations have been developed to measure the leakage flux through geomembrane defects installed at landfill and WRPs (e.g., Rowe, 2012; Foose et al., 2001 ). Some of the most well accepted and widely used equations for estimating leakage through a defect were developed by Giroud et al. (1992), McEnroe et al. (1981), Foose et al. (2001), Touze-Foltz et al. (2001) and Rowe (2012). Touze-Foltz et al. (2001) and Rowe (2012) specifically examined holes within wrinkles on a geomembrane surface. Wrinkling occurs during thermal heating and aging of the material causing a decrease in the contact quality. Analytical solutions of several scenarios were modelled that varied in the shape of the defect, size and connectivity of wrinkles as well as the flow boundary (Touze-Foltz et al., 2001; Rowe, 2012). Equations from Foose et al. (2001) were comparatively more general, allowing the use of the equation to be more adaptive to various geomembrane conditions (i.e. wrinkled and non-wrinkled). McEnroe et al., 1981 developed an equation for defect leakage on areas where the slope is less than 10%. Compiling the information of defect leakage equations available, the equation that was most suitable to this study was developed by Giroud et al. (1992). The analytical solution for the leakage rate  $Q$  (m<sup>3</sup>/sec) is as follows:

$$Q = C_{qo} \cdot A^{0.1} \cdot h^{0.9} \cdot K_{sat}^{0.74} , \quad (3.1)$$

where  $C_{qo}$  is the contact quality factor (ranging from 0.21 for good contact to 1.15 for poor contact) [-];  $A$  for area of the defect [m<sup>2</sup>];  $h$  is the head of water above the defect [m]; and  $K_{sat}$  is the saturated hydraulic conductivity of the underlying material [m/s]. This equation has been widely used in previous studies (e.g., Power et al., 2017, Qian et al., 2004) since it is general enough to capture a number of leakage scenarios with different geomembrane conditions, and topographies while being liberal with the amount of flow experienced to most accurately calculate water influx. The sensitivity of the various parameters involved in this equation are further discussed in section 3.4.5. Applications have involved determining defect leakage for wrinkled HDPE liners as well as on constructed landfill liners testing varying degrees of contact with a 3D model.



For the base case, a moderate contact quality of 0.68 was assumed, while the frequency of defects was assumed to be 20 per hectare ( $\pm 5$ ) with a diameter of 10 mm ( $\pm 7.5$ ). These assumptions are similar to those in previous studies (e.g., Giroud et al., 1992; Meiers and Bradley, 2017; Power et al., 2017). Following field placement, the  $K_{sat}$  of the bedding sand was measured to be  $1 \times 10^{-7}$  m/sec from calculations performed by O’Kane Consultants Inc. To monitor the moisture dynamics within the cover system, including the head of water, an extensive field monitoring program was conducted between January 2012 and December 2018 at all three WRPs.

### 3.3.2 Field Monitoring

During installation of the cover system at each WRP, state-of-the-art monitoring instrumentation was installed alongside the cover systems to permit cover performance monitoring and confirm that site closure objectives were being met. For this study, key parameters in the atmosphere, cover system, and shallow waste rock were monitored and analyzed. The dataset of performance information spans from January 2012 to December 2018.

Figure 3-6 presents a schematic of the cover system and photographs to summarize the monitoring instrumentation installed by O’Kane Consultants Inc. A meteorological station was installed at each WRP to continuously measure numerous meteorological parameters. Rainfall and snow depth were of most interest in this study, with both parameters being measured every three hours. Rainfall was measured with a Hydrological Services Model CS700 tipping bucket gauge (Campbell Scientific, Canada), with a resolution of 0.2 mm. Snow depth was measured with a SR50A sonic ranging sensor. Total precipitation (PPT) was then calculated using a combination of both rainfall and snow depth equivalent data.

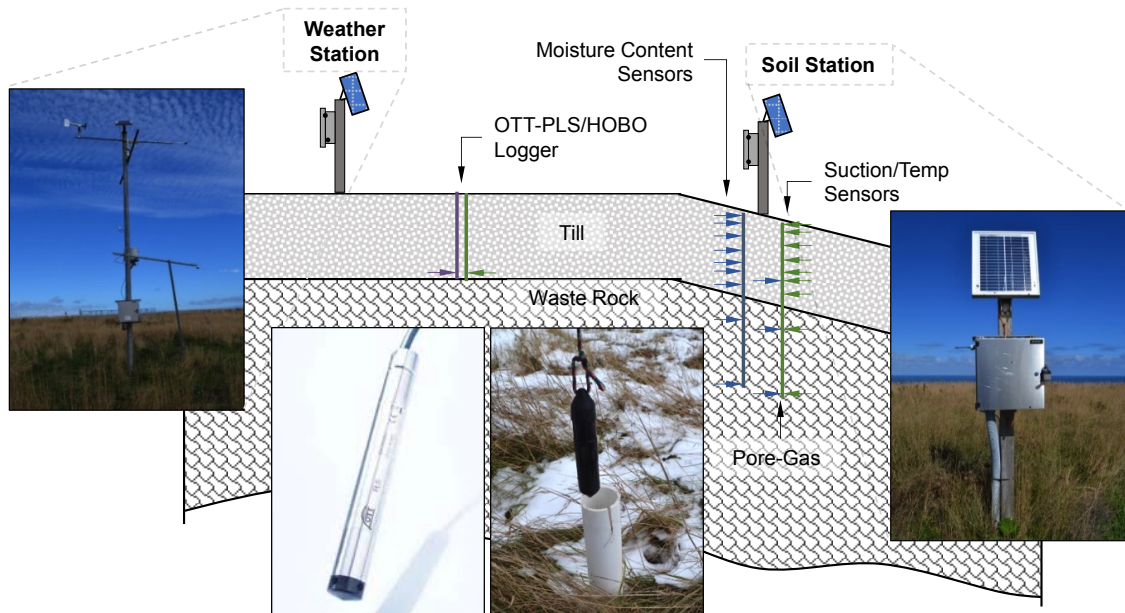


Figure 3-6: Cross-section of the WRP showing the profile of the cover system and the weather station, Soil Monitoring Station (SMS) and water level loggers, along with their associated photographs.

At each WRP, four soil monitoring stations (SMSs) were installed to continuously measure volumetric moisture content, matric suction, soil temperature and pore-gas at multiple depths within the cover system and shallow waste rock. Table 3-1 lists the specific depths of the moisture sensors at each WRP. Volumetric moisture content was measured every 3 hours using time domain reflectometry (TDR) sensors and was used to monitor the evolution of moisture dynamics within the cover system over time. Figure 3-6 shows the casing for the data acquisition system (DAS) for SMS.

OTT pressure level sensors (OTT-PLSs) and HOBO water level loggers were placed above the HDPE liner to measure the hydrostatic pressure and barometric pressure to determine the head of water on top of the HDPE liner. The OTT-PLS, as shown in Figure 3-6, is buried within the cover system and is connected to the nearest SMS where data is automatically recorded every 3 hours. This device has an operating range of 0 to 4.0 m and an accuracy of 0.05%. The HOBO loggers are placed inside a piezometer (Figure 3-6) that is fully screened across the entire depth of the cover system (i.e., from the HDPE liner to the surface), and also automatically record data every 3 hours with an accuracy of 0.1%. One OTT-PLS and five HOBO loggers were installed at

the Summit WRP, while one OTT-PLS and seven HOBO loggers were installed at the Victoria Junction WRP.

As no water level loggers were installed at the Franklin WRP, an alternative approach was needed to estimate the head of water on top of the HDPE liner. The drainage layer at Franklin is comprised of a geonet with a specific transmissivity, and the equation by Giroud et al. (2000) can be used to calculate the maximum head of water ( $h_{max}$ ) on a sloped surface as follows:

$$h_{max} = \frac{q_i L}{k_{sat} \sin \beta} \quad (3.3)$$

where  $q_i$  is the infiltration rate [mm/hr],  $L$  is the length of the slope [mm],  $K_{sat}$  is the saturated hydraulic conductivity of the geonet [mm/hr], and  $\beta$  is the slope angle [°]. This equation is highly suitable for the Franklin WRP as almost all its surface area is sloped. The infiltration rate was estimated from a water balance that was developed for the cover system, with the infiltration rate equal to PPT minus surface runoff, evapotranspiration and water storage (e.g., Power et al., 2018). The manufactured geonet transmissivity ( $1 \times 10^{-5}$  m/sec) and thickness (0.005 m) were used to determine the hydraulic conductivity of the geonet ( $1 \times 10^{-4}$  m/sec) The length and angle of the side slopes at Franklin is approximately 70 m and 60°, respectively.

Table 3-1: Depths of the moisture content sensors, OTT-PLS and HOBO loggers within each cover system for each SMS (m)

Summit	Victoria Junction	Franklin
<i>Growth Medium</i>		
0.05	0.05	0.05
0.10	0.10	0.10
0.20	0.20	0.20
0.30	0.30	0.30
0.40	0.40	0.40
0.49 <sup>a</sup>	0.59	0.50
<i>Drainage Layer</i>		

	0.65	
	0.94	
-	1.07	0.60
	1.29	
	1.30 <sup>a</sup>	
<hr/>		
<i>HDPE (60 mil, 1.5 mm)</i>		
<hr/>		
<i>Bedding Sand</i>		
<hr/>		
	1.35	
0.55		0.70
	1.40	
<hr/>		
<i>Waste Rock</i>		
<hr/>		
0.75	1.45	1.80
2.02	2.40	2.60
<hr/>		

<sup>a</sup> OTT-PLS and HOBO

The head of water estimates determined from Equation 3.3 can also be compared to the moisture contents that were monitored at Franklin. The moisture content and head of water that were both collected at Summit and Victoria Junction can be compared to develop a general understanding and correlation between moisture content and head of water above the HDPE liner, and this correlation can then be used to confirm that the estimated head of water at Franklin is supported by the corresponding moisture content.

## 3.4 Results and Discussion

### 3.4.1 Precipitation

The monthly cumulative precipitation (PPT) occurring at each WRP between January 2012 and December 2018 is presented in Figure 3-7. It is evident that the WRPs experienced a range of conditions throughout the monitoring period, with consistent seasonal fluctuations. As expected, the highest PPT occurs during the wet months in fall and spring (September to April) with the lowest PPT occurs during the summer months (May to August).

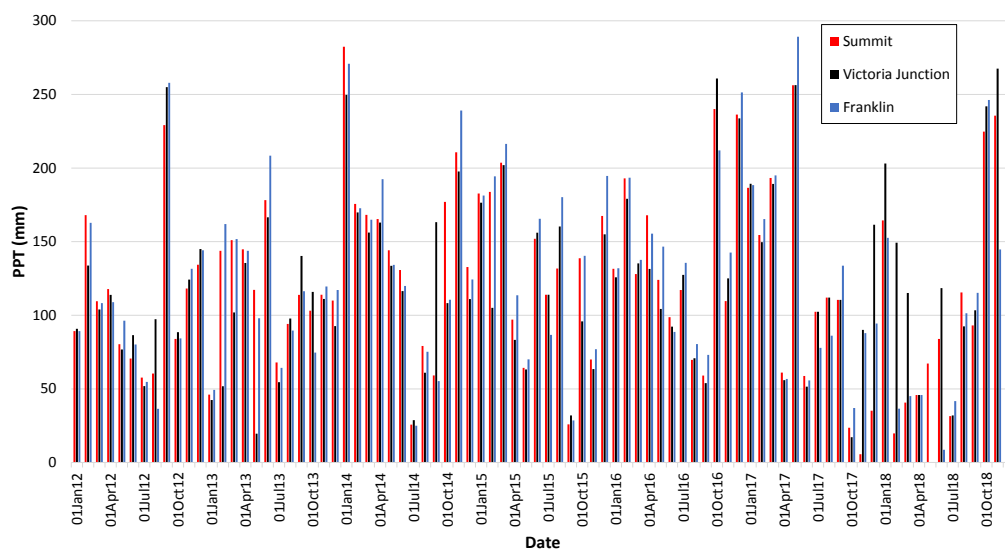


Figure 3-7: Monthly PPT occurring at Summit, Victoria Junction and Franklin

### 3.4.2 Volumetric Moisture Content

The volumetric moisture content measured at each sensor depth at the four SMSs were averaged to generate a depth profile of moisture content at each WRP that evolves through the monitoring period. Figure 3-8 presents a two-dimensional (2D) contour profile of average moisture content at each WRP site between January 2012 and December 2018. Red and blue regions indicate regions of low and high moisture content, respectively, white regions indicate when soil was frozen, and the moisture measurements were unreliable. While moisture content mainly varies due to water infiltration from both rainfall and snow water equivalents, it should be noted that since it is a function of porosity, moisture content can also vary due to material heterogeneity.

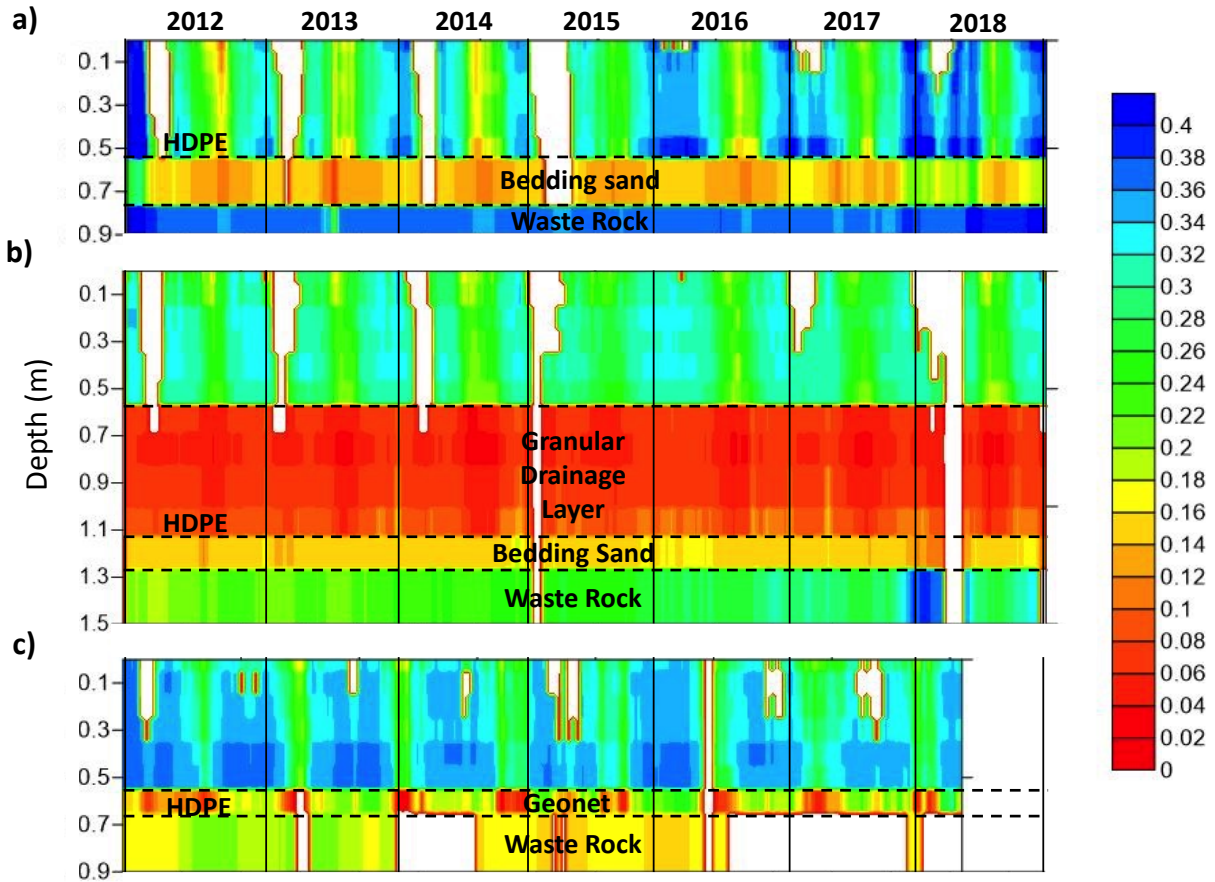


Figure 3-8: 2D contour plots of moisture content within the cover system and shallow waste rock at (a) Summit, (b) Victoria Junction, and (c) Franklin. White areas indicate moisture content data not recorded where soil was frozen.

At the Summit WRP (Figure 3-8a), the moisture content within the soil material overlying the HDPE liner (0 m to 0.55 m depth) follows the expected seasonal fluctuations: the moisture content is highest (blue regions) during highest PPT in fall and spring, while lowest moisture contents (yellow regions) occur during dry summer months. These moisture contents are relatively high as there is no distinct drainage layer and the downward percolating water builds on top of the HDPE liner. The repetition in the moisture content trends indicates that the cover material is consolidating and maturing over time. The bedding sand below the HDPE liner shows lower moisture content (orange) which indicates that the HDPE liner prevents water percolation (aside from defects).

Figure 3-8b demonstrates that the cover material above the drainage layer (0 m to 0.55 m depth) at Victoria Junction exhibits a lower moisture content than the Summit WRP but does follow the same seasonal fluctuations. The granular drainage layer between 0.55 m and 1.1 m depth indicates that the moisture content is very low over time (red) with little variability, though the moisture content is slightly higher near the HDPE liner, indicating a slight build-up on the liner. This demonstrates the effectiveness of the granular drainage layer to provide lateral water and limit the build-up of water on top of the HDPE. Below the HDPE, the moisture in the bedding sand was relatively low over time, similar to Summit.

At the Franklin WRP cover in Figure 3-8c, it is evident that the geonet drainage layer is also effective at maintaining lower moisture contents above the HDPE liner compared to Summit. Despite its small thickness, it is evident that the geonet can effectively drain the infiltrating water directly above the liner. During dry summer months, the moisture content in the top layer of soil is lower (green) and the geonet can rapidly reduce this moisture directly above the liner, while during the wetter months, the higher moisture contents in the soil layer are still rapidly reduced, though not to such a low level.

Individual moisture sensors can be further analyzed to focus on the evolution of moisture directly above and below the HDPE liner. Figure 3-9a indicates that the moisture content immediately above all liners fluctuates in response to seasonal trends. Due to the lack of lateral drainage and build-up of water above the liner, the moisture content at Summit is significantly higher than Victoria Junction and Franklin throughout the monitoring period, fluctuating between a low of 0.15 and a high of 0.35. Victoria Junction and Franklin exhibit lower moisture contents over time, fluctuating between 0.05 and 0.15, and 0.02 and 0.2, respectively. At all WRPs, the overall moisture content is slightly increasing over time, especially at Victoria Junction and Franklin. This is likely due to gradual clogging of the pore spaces within the granular and geonet drainage layers, thereby reducing its transmissivity. This result could also be due to compaction of the material, leading to smaller pore spaces and therefore enhanced capillarity, the materials ability to hold water at a greater moisture content.

Figure 3-9b plots the temporal evolution of moisture content directly below the HDPE at each WRP. At Summit and Victoria Junction, the moisture content lies within the bedding sand and it is evident that the moisture levels remain low over time. The bedding sand is uniform, and the measured moisture is likely the residual saturation retained around the sand grains. At Franklin, a protective geofabric was used which likely retains higher moisture content over time, though it is gradually decreasing over time, as shown in Figure 3-9b. At all WRPs, the moisture content remained relatively constant, which confirms that it is disconnected from the seasonal weather fluctuations.

Figure 3-9c presents the moisture content measured just below the surface of the waste rock to further analyze the efficacy of the cover systems for preventing water entering the waste rock. Prior to cover installation, the waste rock was exposed to the environment and direct water infiltration. As a result, the moisture content within the waste rock can be relatively high, especially in the immediate years after cover installation, which is confirmed in Figure 3-9c. The Summit and Franklin are slowly getting drier over time, which is expected. However, Victoria Junction is getting wetter over time, and demonstrates slight seasonal variation, which may be indicative of more substantial defects and associated leakage through its HDPE liner.



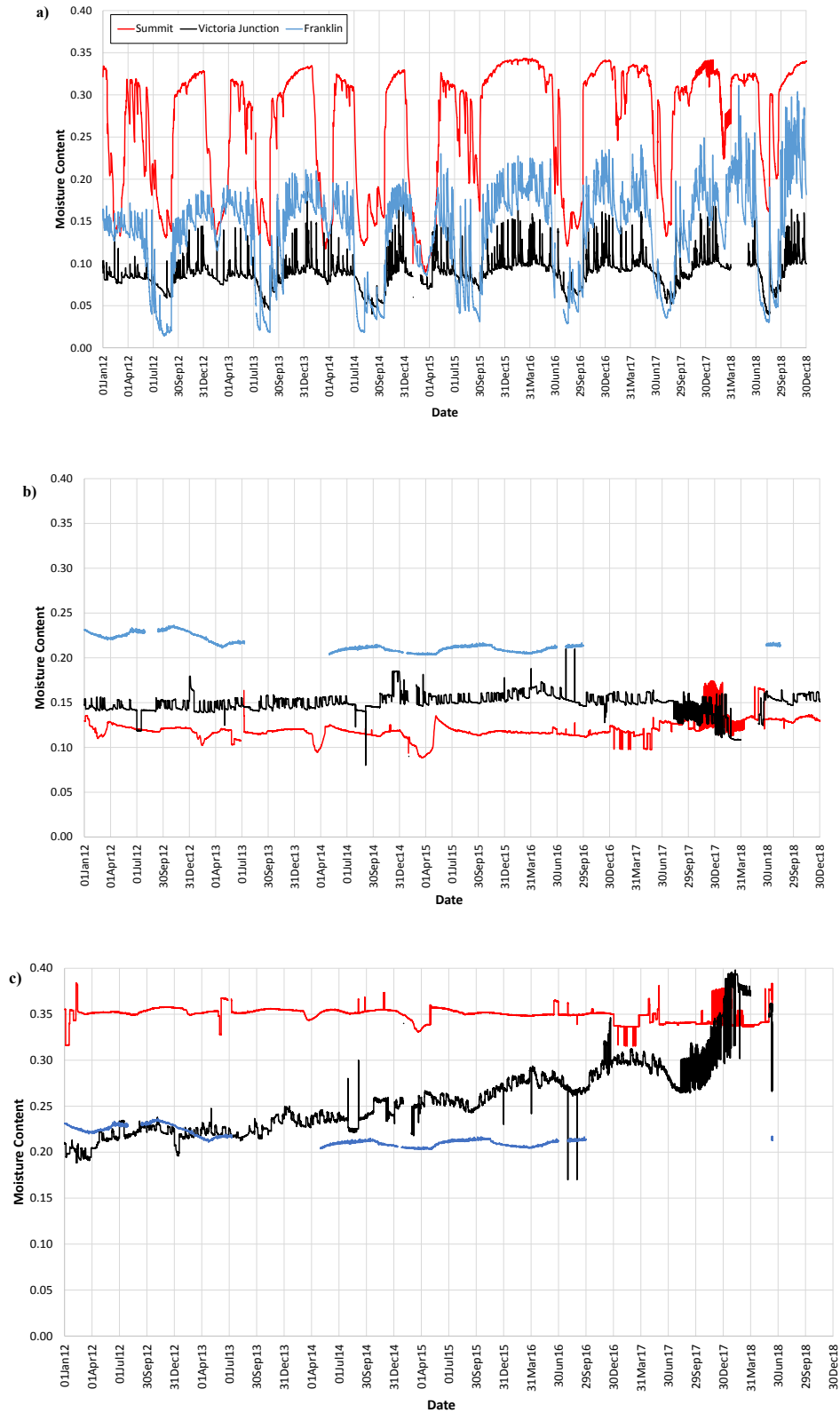


Figure 3-9: Evolution of averaged moisture content at each WRP across respective SMSs (a) directly above the HDPE liner, (b) directly below the HDPE liner, and (c) within the shallow waste rock

### 3.4.3 Head of Water above HDPE Liner

The head of water measured at multiple locations across the Summit and Victoria Junction WRPs by the OTT-PLSs and HOBO water level loggers were averaged to obtain a representative water height above the HDPE liner at both WRPs. The head of water at Franklin was estimated by Equation 3.3. Figure 3-10 plots the head of water over time at each WRP, and also shows the total volume of water in the cover material based on the moisture contents. It is evident that the head of water at each WRP varies over time in response to seasonal changes and is strongly correlated to fluctuations in PPT and moisture content, as shown in Figures 3-7 and 3-8. During wet periods, high PPT events leads to increases in moisture content and head of water events above the HDPE liner. Similarly, drier periods with low PPT results in decreases in moisture content and head of water. It should be noted that frozen ground conditions during winter can lead to a low head of water due to the lack of flowing water during this time period.

The head of water at the Summit WRP is significantly larger than Victoria Junction and Franklin, due to the lack of a drainage layer. At some periods, the head of water exceeded the height of the cover material above the HDPE liner, which was confirmed by the continual waterlogging observed at the field site. The lower head of water at Victoria Junction again confirms the effectiveness of the granular drainage layer to promote lateral flow of water. Similarly, despite the small thickness of the geonet, it was highly effective at promoting drainage and reducing head of water. This may be attributed to the uniformity and geometry that can be manufactured in geonets, which helps to maintain drainage performance, even under high compressive loads like heavy machinery traffic strengths (Yarahmadi et al., 2018; Jeon, 2019). Additionally, the small water head experienced at Franklin WRP is further supported by the low moisture content results from Figure 3-8c.

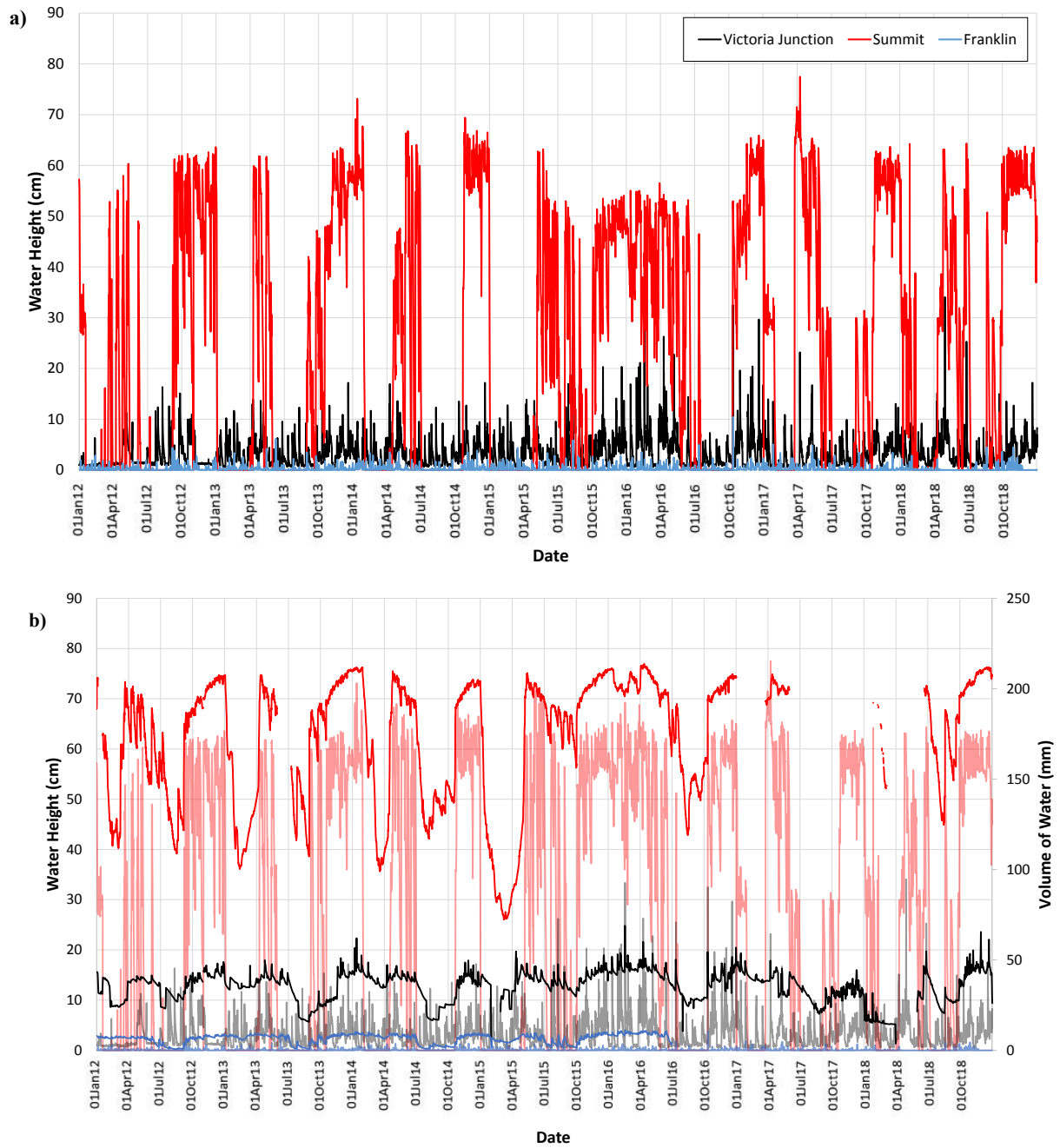


Figure 3-10: (a) Head of water above the HDPE liner and (b) total volume of water within the cover material measured at all 3 WRPs between January 2012 and December 2018.

### 3.4.4 Water Flux by Defect Leakage

The estimated defect leakage through each HDPE-lined cover system is plotted in Figure 3-11. The main variable in the fluid mechanics surrounding a HDPE defect (Figure 3-5) is the head of water; therefore, water flux through HDPE defects varies in direct response to changes in head. Defect leakage is significantly larger at Summit due to the larger head of water caused by the lack of an effective drainage layer. During dry periods, the head of water is negligible, no leakage occurs even when defects exist. Victoria Junction and Franklin have drastically lower leakage fluxes due to the lower head of water provided by their respective drainage layer. The variation in the material utilized below the geotextile at Franklin could also be contributing to the enhanced performance at this WRP. Further insight into the sensitivity and significance of the saturated hydraulic conductivity of the underlying medium beneath the HDPE is discussed in section 3.4.5.

Table 3-2 presents the cumulative PPT (mm), water influx due to defect leakage (mm), and water flux as a percentage of PPT (% PPT) at the end of each year between 2012 and 2018. As shown, the average water influx (% PPT) to the waste rock at Summit, Victoria Junction and Franklin is 2.01, 0.35, 0.08, respectively.

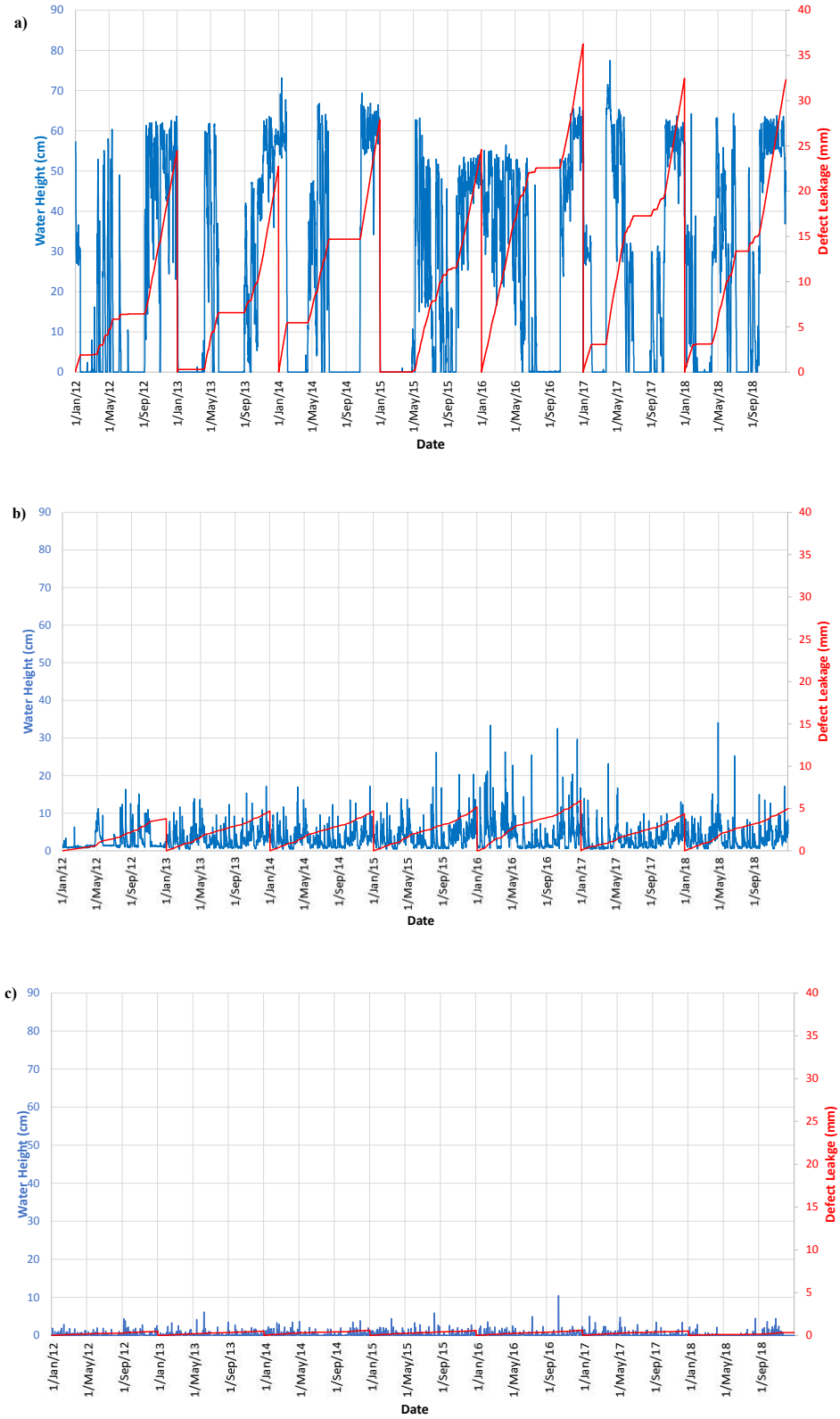


Figure 3-11: Water influx cumulative over each calendar year due to defect leakage through HDPE liner at Summit, Victoria Junction and Franklin WRPs.

Table 3-2: Water influx due to defect leakage

Year	Summit			Victoria Junction			Franklin		
	PPT (mm)	44.1.1 F % PPT	% PPT	PPT (mm)	44.1.1 I % PPT	% PPT	PPT (mm)	44.1.1 I % PPT	% PPT
2012	1319	24.45	1.85	1367	3.78	0.28	1355	0.48	0.04
2013	1384	22.79	1.65	1130	4.71	0.42	1395	0.49	0.04
2014	1751	27.93	1.60	1659	4.72	0.28	1684	0.59	0.04
2015	1531	24.61	1.61	1293	5.18	0.40	1649	0.57	0.03
2016	1675	36.30	2.17	1640	5.99	0.37	1749	0.61	0.03
2017	1276	32.50	2.55	1161	4.39	0.38	1467	0.51	0.03
2018	1206	32.36	2.68	1521	5.00	0.33	1364	0.33	0.02

### 3.4.5 Sensitivity Analysis of Defect Leakage

A sensitivity analysis was performed on the defect leakage flux equation in Equation (3.1) to assess how sensitive each parameter is on flux calculations. The baseline values for each parameter (contact quality, defect size, head of water, and  $K_{sat}$  of the bedding sand) were systematically modified one by one to realistic minimum and maximum values, as shown in Table 3-3. The baseline contact quality value was 0.68 (moderate contact), and was decreased to 0.21 (poor contact) and then increased to 1.15 (good contact). The baseline defect diameter was 0.01 m and was decreased and increased by 50% to 0.05 m and 0.02 m, respectively. A baseline head of water was 0.1 m (average head of water at Victoria Junction), which was then decreased and increased to 0.01 m (Franklin) and 0.5 (Summit), respectively. The  $K_{sat}$  of sand of  $1 \times 10^{-7}$  was decreased and increased by one order of magnitude.

Each scenario was evaluated as a percent change on the leakage flux compared to the baseline flux. The parameter that was most influential to defect leakage was a change in water head and saturated hydraulic conductivity of the bedding sand. Both parameters experienced a large % change in leakage with a larger % change in parameter. However, larger changes in these alternative scenarios could be seen with a greater % change in the parameter. The sensitivity of Giroud’s 1992 equation shows that the height of water above the HDPE plastic and the hydraulic conductivity of the underlying medium are most influential in determining the amount of defect leakage, therefore should be the parameters of most concern when constructing an HDPE-inclusive cover system.

*Table 3-3: Summary from sensitivity analysis of key parameters in the defect leakage equation. Baseline scenario:  $C_{q0} = 0.68$ ;  $d = 0.01$  (m);  $h_w = 0.1$  (m);  $K_{sat} = 1.0 \times 10^{-7}$  (m/s)*

<b>Scenario</b>	<b>New Value</b>	<b>% change in parameter</b>	<b>% change on leakage</b>
Increase $C_{q0}$	0.21	69.12	-69.12
Decrease $C_{q0}$	1.15	-69.12	69.12
Increase d	0.005 m	50	-12.94
Decrease d	0.02 m	-100	14.87
Increase $h_w$	0.5	-400	105.73
Decrease $h_w$	0.01	90	-93.92
Increase $K_{sat}$ of sand	$1.0 \times 10^{-8}$ m/s	90	-81.90
Decrease $K_{sat}$ of sand	$1.0 \times 10^{-6}$ m/s	-900	449.54

### 3.5 Conclusions

Cover systems that contain HDPE geomembrane liners are expected to provide a highly effective barrier to prevent meteoric water and atmospheric oxygen influx to mine waste rock, thereby halting the generation of environmentally toxic acid mine drainage (AMD). However, this is only achieved when the liner is in pristine condition, which is extremely difficult to maintain during handling, installation and placement of overlying cover material. As a result, HDPE liners are subject to defects in the form of holes or tears which can result in the flow of percolating water through these openings. One of the key parameters that controls the amount of leakage through defects is the head of water sitting on top of the liner. Furthermore, this is one of the only parameters that can be controlled prior to cover installation by designing and implementing a suitable drainage layer that promotes lateral drainage above the liner and limits the head of water.

This study assessed the performance of different drainage layer compositions within HDPE-lined cover systems at three reclaimed WRPs in the Sydney Coalfield in Nova Scotia, Canada. The cover system at each WRP implemented different drainage layer compositions: (i) Summit did not implement a specific drainage layer, instead relying on drainage through the overlying natural till material, (ii) Victoria Junction implemented a 0.6 m thick layer of natural granular material, and (iii) Franklin implemented a 5 mm thick layer of geocomposite drainage material (i.e., geonet). A comprehensive field monitoring program was conducted between January 2012 and December 2018 to monitor the moisture dynamics within each cover system every day over eight years, with the key parameters of interest including precipitation (PPT), moisture content and head of water above the liner.

While each WRP was subjected to similar amounts of PPT, the moisture levels and heads of water above the HDPE liner within each cover system differed significantly. During wet periods of high PPT (fall and spring), the Summit WRP was highly saturated with a large head of water and corresponding defect leakage flux (average annual of 10% PPT). Furthermore, the head of water frequently exceeded the total cover thickness, resulting in water ponding across the WRP and other cover performance issues such as poor vegetation and reduced erosion control. In contrast, the Victoria Junction WRP exhibited a low moisture content and head of water throughout the monitoring period, irrespective of heavy PPT events, and limited the leakage flux



to an average annual of 5% PPT. The geonet layer at the Franklin WRP also dramatically reduced the head of water above the HDPE liner and corresponding leakage flux (average annual of 7 %PPT), despite its small thickness.

Other well-known factors that influence defect leakage include contact quality and defect size/number but even with the most stringent quality control measures during installation, these factors can be difficult to control and observe during and following the placement of overlying cover material. One of the other key factors that can be controlled during design and installation is a drainage layer, with this study demonstrating that even if HDPE liners inevitably obtain defects, their high performance can still be attained if appropriate lateral drainage is achieved. This will limit the head of water above the liner, so even if defects exist, the leakage rate will be minimal.

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## 4 Comparative Field Performance of Engineered Mine Waste Rock Covers

### 4.1 Introduction

The mining industry in Canada is extremely prevalent, providing over 719,000 jobs across the country, and producing numerous valuable metals and minerals that count towards 19% of Canada's total domestic exports (Marshall, 2019). These activities produce significant quantities of mine waste rock which are deposited into large, partially-saturated, porous stockpiles on the ground surface, commonly referred to as waste rock piles (WRPs). These WRPs can pose a significant threat to the environment as trace amounts of sulfidic minerals can exist within the waste material. Exposure of these reactive minerals to meteoric water and atmospheric oxygen can ignite a complex sequence of oxidation-reduction reactions that produce a highly toxic leachate referred to as acid mine drainage (AMD) (Akcil & Koldas, 2006). Characterized by a low pH, high acidity, and high concentrations of sulfate, iron, manganese and other heavy metals, AMD leachate can percolate downwards through the WRP and discharge to the environment and contaminate surrounding groundwater and surface water resources (Acharya & Kharel, 2020). The characterization and remediation of AMD is highly complex and costly, with annual expenses between two and five billion dollars making it one of the largest environmental liabilities in Canada (EMCBC, 2000). Prevention techniques are essential to prevent, or at least, control AMD generation.

A common solution to limit atmospheric ingress and reduce AMD generation is the installation of engineered cover systems over the mine WRPs (Ayres, 2018). Cover systems are designed to minimize airflow, water flow and storage, across a wide range of environmental conditions. As a result, a large variety of cover system compositions exist to meet specific site closure objectives (Meiers et al., 2012). Complexity of cover systems can range from a single layer of earthen material to multiple layers of differing materials, including earthen material, geosynthetic-reinforced material and geomembranes (MEND, 2004). The simplest cover systems with a single layer of earthen material, usually native soil, are employed to store and release water; however, these covers work best in arid or semi-arid climates with little precipitation so any water influx can be effectively stored and then released back to the atmosphere via evapotranspiration (e.g.

Scanlon et al. 2005). Furthermore, simple soil covers provide a very weak barrier to oxygen influx.

Different compositions of multi-layer cover systems can be used to meet all climatic conditions (Giroud & Bonaparte, 1998). Geomembranes, such as high-density polyethylene (HDPE), are becoming increasingly used for impermeable barriers for a range of engineering and geoenvironmental applications, most notably at municipal waste landfills. Geomembranes provide a theoretically impermeable layer and when pristine, they have been proven to be very effective at limiting both water and oxygen flux (Rowe, 2012). Despite these properties, knowledge on their performance at in-service WRPs is limited. It is known that HDPE liners can be subject to imperfections such as wrinkles, holes and tears, because of poor handling and installation practices at field sites. Defects in these liners provides a pathway for water and oxygen influx to the underlying waste rock and further AMD generation. As seen in Chapter 3, the potential of HDPE liners is evident for limiting water ingress. However, while empirical defect leakage equations are widely used to represent defect leakage and estimate water flux rates, these equations rely on assumptions made on defect sizes and number. Therefore, the performance of HDPE-lined cover systems for limiting water influx shown in Chapter 3 can be validated through a comprehensive water balance analysis.

The objective of this study was to assess the performance of differing cover systems for limiting atmospheric ingress. Four coal mine WRPs located in the Sydney Coalfield in Nova Scotia, Canada were reclaimed with differing cover systems: three of the covers were multi-layer and each contained HDPE liners, while the other cover comprised a single layer of native soil. Seven years of field monitoring data were used to develop a comprehensive water balance, with parameters including precipitation, runoff, interflow, evapotranspiration, and changes in water and snow storage. The residual of the water balance was then assumed to be the net percolation into the underlying waste rock. Furthermore, oxygen concentrations measured within the cover material and underlying shallow waste rock were used to assess the effectiveness of each cover for limiting oxygen influx to the waste rock.

## 4.2 Site Description

### 4.2.1 The Sydney Coalfield

Four reclaimed mine WRPs were investigated for this study, all of which are located in former Sydney Coalfield in Nova Scotia, Canada (Figure 4-1). Significant mining operations were performed in the Sydney Coalfield for 300+ years, producing over 500 million tonnes of coal. However, these mining operations left behind a legacy of former mining sites containing large stockpiles of mine waste rock. Upon cessation of mining activities 2001, a multi-million dollar mine site closure and reclamation program was implemented by Cape Breton Development Corporation (CBDC), and managed by Public Works and Government Services Canada (PWGSC). This program included the placement of engineered cover systems over several mine WRPs, along with the installation of state-of-the-art field monitoring instrumentation to assess cover performance and confirm site closure objectives were being met. Of the four WRPs used in this study, one WRP at Lingan employed a simple cover with a single layer of local till material, while the other three WRPs at Summit, Victoria Junction and Franklin employed complex multi-layer covers that each contained a HDPE liner, but surrounding layers of different materials and thicknesses.

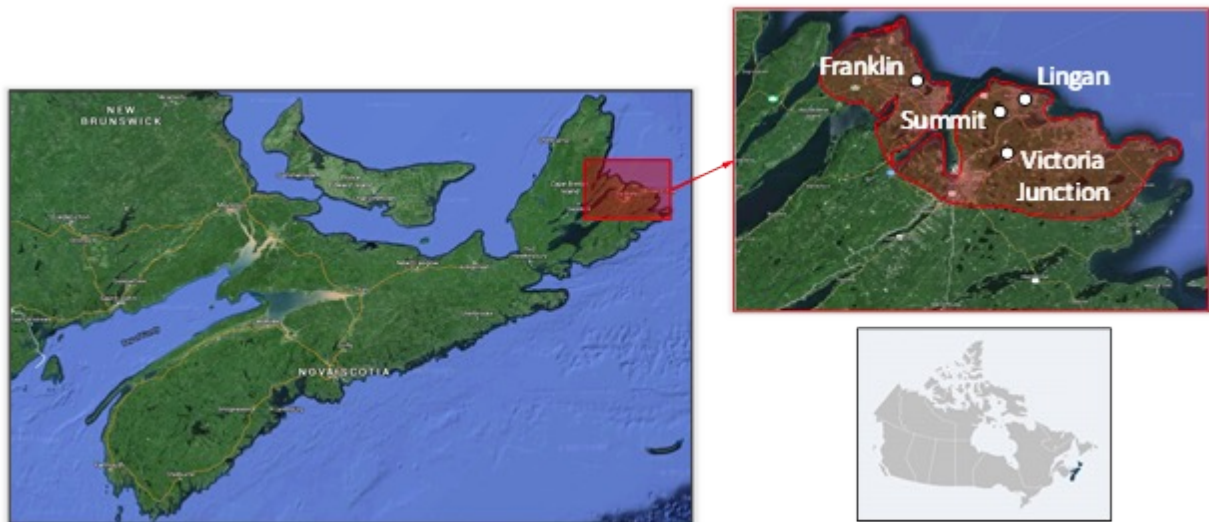


Figure 4-1: Site map of the Sydney Coalfield in Nova Scotia, Canada showing the four mine waste rock piles (WRPs).

### 4.2.2 Lingan WRP

The Lingan WRP is located in Lingan, Nova Scotia, approximately 16 km northeast of Sydney. This WRP is situated at the former Lingan Mine Colliery which was under operation for 25 years, and produced approximately 28 million tonnes of coal. The Lingan WRP contains 380,000 m<sup>3</sup> of waste rock and a surface footprint of 8.5 hectares. The pile has a well-defined plateau with a 3% grade, and 20% grade side slopes. The cover system consists of a 0.5 m thick layer of local till material that was graded and hydroseeded to provide a vegetative canopy, as shown in Figure 4-2. A drainage ditch exists along the perimeter of the pile plateau to capture surface runoff and divert it to catchment channels on the side slopes. A larger perimeter ditch around the pile then directs all runoff to an adjacent stream. The cover system was designed to control net percolation, through moisture store and release, and eliminate AMD-contaminated surface water runoff.

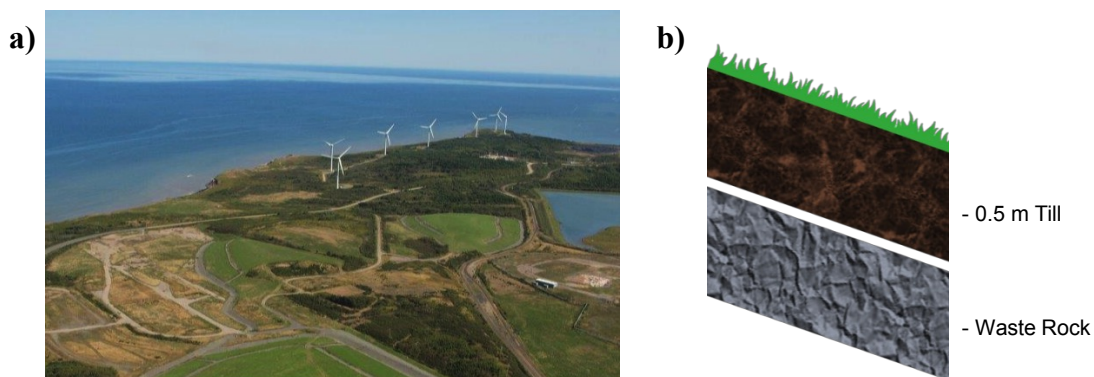


Figure 4-2: (a) Lingan WRP aerial view, and (b) the associated cover system

### 4.2.3 Summit WRP

The Summit WRP is located in the town of Scotchtown, approximately 15 km north of Sydney, Nova Scotia. This WRP contains 1.5 million m<sup>3</sup> of waste rock and covers an area of 44 hectares. The thickness of the pile ranges from 0.5 m to 10 m, with slight side slopes of 14%. As shown in Figure 4-3, the cover system consists of a 0.15 m thick layer of bedding sand placed first over the waste rock to prevent sharp edges from puncturing the overlying layer of 60 mil HDPE liner. Geotextile fabric was then placed over the HDPE liner to enhance friction and slope stability, and to protect the liner during the placement of the overlying till material. This final layer of till material is 0.5 m thick, which was graded and hydroseeded to promote vegetation and establish a strong root system.



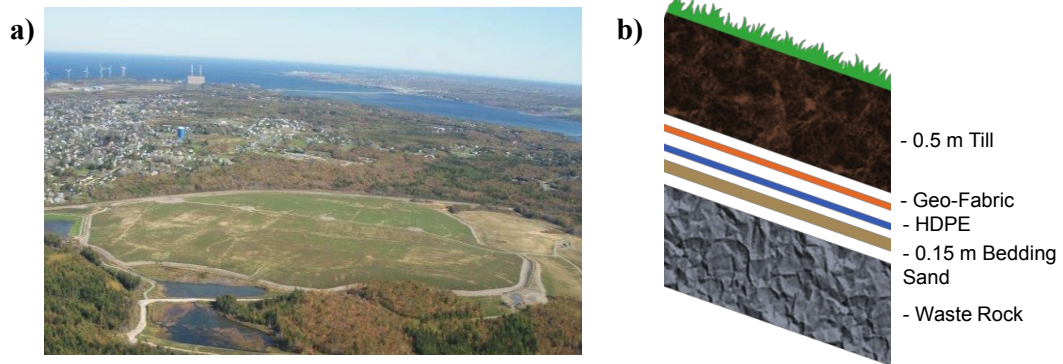


Figure 4-3: (a) Summit WRP aerial view, and (b) the associated cover system

#### 4.2.4 Victoria Junction WRP

The Victoria Junction WRP is located 3 km east of Sydney, Nova Scotia, on the site of a former coal preparation plant. The WRP pile contains 5.88 million m<sup>3</sup> of waste rock and has a footprint of 28 hectares. The pile has a defined plateau with a small slope, and significant side slopes with grades of 33%. The WRP has a general thickness of 40 m. As shown in Figure 4-4, the cover system comprises the same 0.15 m thick layer of bedding sand that was used at Summit WRP, which was again overlain with a 60 mil HDPE liner. The liner was then directly overlain with a 0.6 m gravel drainage layer to promote lateral water flow (or interflow) and limit excessive build up of water on top of the HDPE liner. A geotextile was placed over the gravel layer on the side slopes where slope stability could be most problematic. The entire WRP was then overlain with a 0.6 m thick layer of processed till (Figure 4-4).

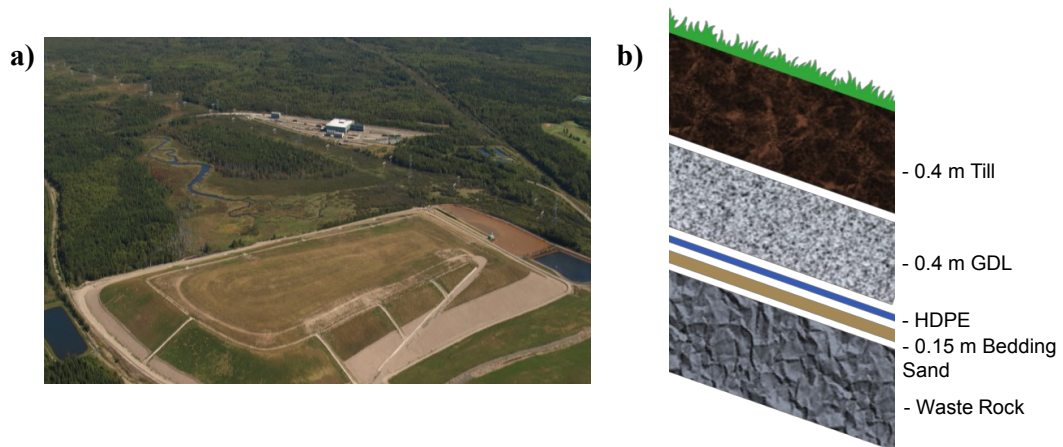


Figure 4-4: (a) Victoria Junction WRP aerial view, and (b) the associated cover system

#### 4.2.5 Franklin WRP

The Franklin WRP is located in Florence, approximately 25 km north of Sydney. The pile was used to compile 187 000 m<sup>3</sup> of waste rock from five nearby mining sites. The Franklin WRP is the smallest pile in this study, with a footprint of 2.5 hectares. The WRP has a cone like shape with a very small plateau and 25% graded side slopes. The thickness at the center of the pile is 13 m. As shown in Figure 4-5, a 60 mil HDPE liner was placed over the bedding sand layer. A geocomposite drainage layer, hereafter referred to as a ‘geonet’, was placed over the HDPE liner to provide an alternative approach to lateral drainage of water above the liner. A final 0.6 m thick layer of processed till was then placed on top, and hydroseeded.

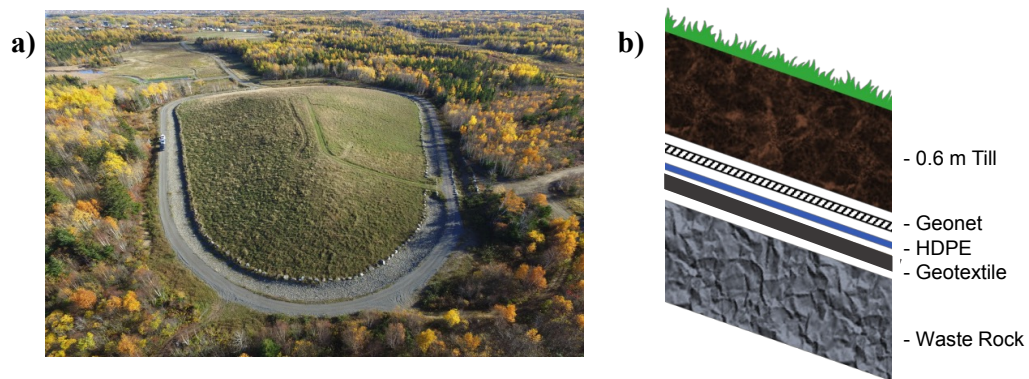


Figure 4-5: (a) Franklin WRP aerial view, and (b) the associated cover system\

### 4.3 Methodology

#### 4.3.1 Field Monitoring Program

Various field monitoring instrumentation were installed at each WRP to continuously monitor a large range of parameters within the atmosphere, cover system and shallow waste rock, throughout the seven-year monitoring period. Site photographs of key field instruments are shown in Figure 4-6, while Figure 4-7 presents a cross-sectional profile of the cover system and shallow waste and the respective measurement locations of each instrument. All instruments used in this study were provided by Campbell Scientific Canada.

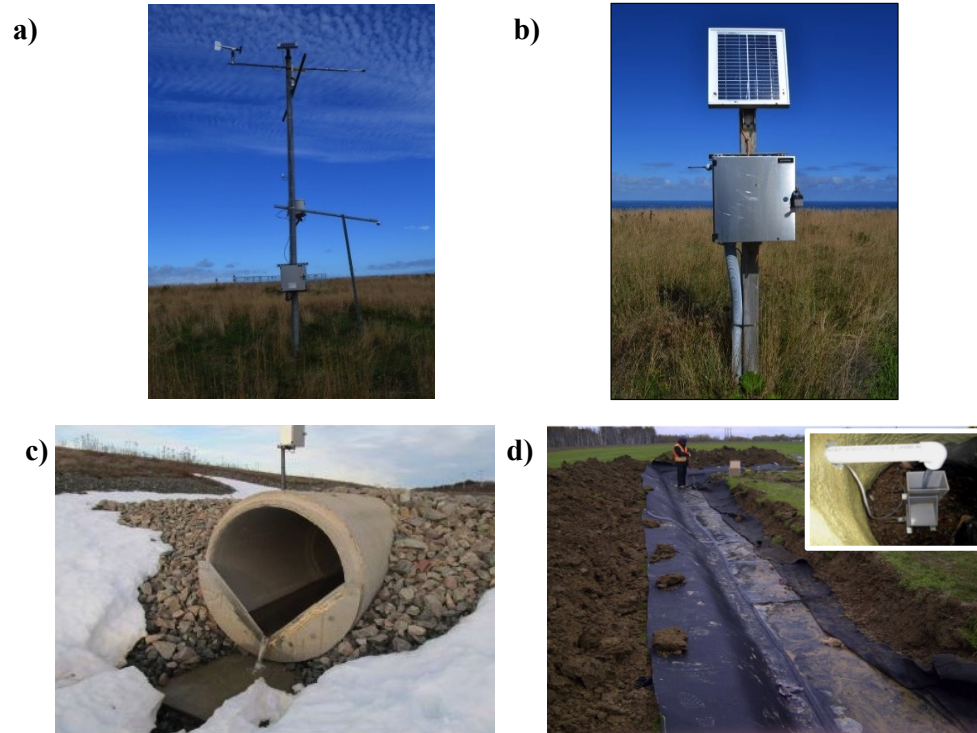


Figure 4-6: (a) meteorological station, (b) soil monitoring station (SMS), (c) weir, and (d) interflow collection system

A meteorological station, as shown in Figure 4-6, was installed at each WRP to continuously monitor rainfall, air temperature, relative humidity, wind speed and direction, barometric pressure, net radiation, and snowpack depth at each WRP. All parameters were measured hourly and daily from January 2012 to December 2018. In addition, weather stations used at the nearby airport by Environment Canada, were used to obtain any data that was missing from the site weather stations.

Four soil monitoring stations (SMSs) were installed at each WRP to continuously monitor volumetric moisture content, soil temperature, matric suction (negative pore-water pressure), and pore-gas concentrations within the various layers of the cover system and shallow waste rock (Figure 4-7). Table 4-1 presents the average depth of each sensor within the cover systems at each WRP. As shown, volumetric moisture content, soil temperature and matric suction were measured at every depth, while pore-gas concentrations were only measured at three sensor depth at each site. All parameters were recorded every 3 hours, except for pore-gas concentrations, which were measured manually with a NOVA gas analyzer each month.

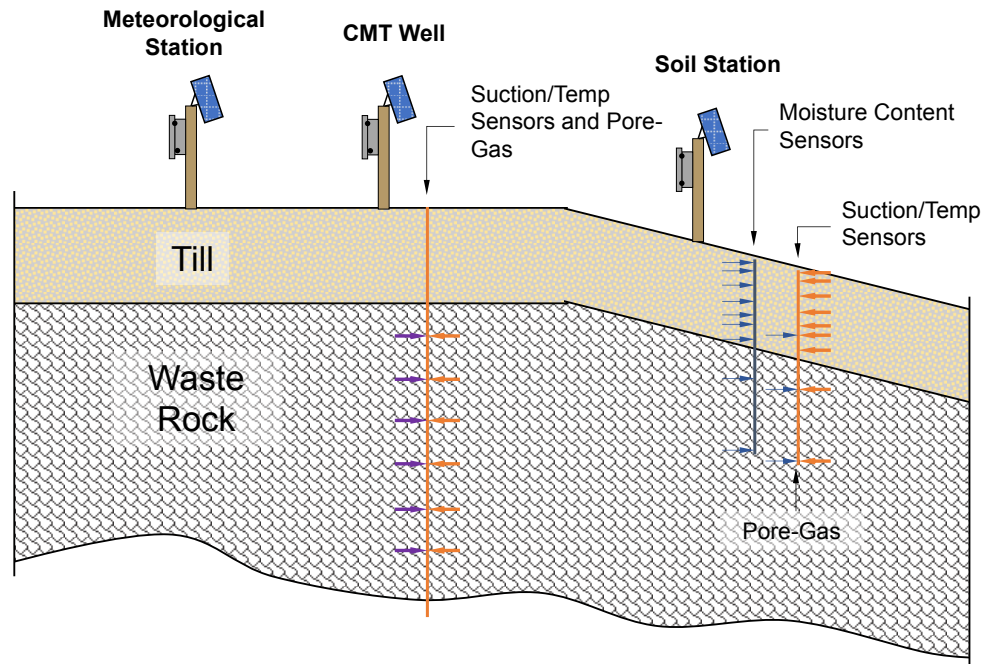


Figure 4-7: Cross section of WRP site with all monitoring devices installed.

Four continuous multi-channel tubing (CMT) wells were installed alongside the four SMSs at each site. As shown in Figure 4-7, these CMT wells are used to monitor parameters within the deeper waste rock, measuring soil temperature, differential pressure, groundwater levels, groundwater chemistry, and pore-gas concentrations. However, as this study focused on the water and oxygen fluxes within the cover system and shallow waste rock, parameters from the deeper CMT wells were only used to validate some of the observations in the shallow waste rock.

A weir was installed at all sites to measure the surface runoff from each cover system. A 60° notch weir was used at Summit and Franklin, with a catchment area of 25 000 m<sup>2</sup> and 15 850 m<sup>2</sup>, respectively. A 90° notch weir was used at Lingan and Victoria Junction, with catchments areas of 26 000 m<sup>2</sup> and 98 000 m<sup>2</sup>, respectively. A sonic ranger was installed at the top of each weir box to continuously monitor the stage height behind the weir, both hourly and daily, which would then be used to determine flow rates over the weir.

One interflow system was installed at the Summit WRP, while two interflow systems were installed at the Victoria Junction WRP (one for the plateau and one for the side slopes). An interflow system was not needed at Lingan as there would be limited lateral percolation, while at Franklin, the HDPE liner was keyed into the perimeter drainage ditch and diverted to the weir, meaning interflow would be measured as part of runoff. The interflow collection systems at Summit and Victoria Junction, as shown in Figure 4-6d, consisted of a HDPE-lined bank that was used to divert interflow water to a monitoring chamber with tipping buckets. The tipping bucket at Summit was calibrated to 0.65 L/tip, while the tipping buckets for the plateau and slopes at Victoria Junction were calibrated to 0.78L/tip and 1.18L/tip, respectively. When the tipping buckets reached full capacity, they would tip over to empty, and the number of tips were recorded by an adjacent sensor (both hourly and daily).

Table 4-1: Sensor depth locations at each WRP (m)

<b>Lingan</b>	<b>Summit</b>	<b>Victoria Junction</b>	<b>Franklin</b>
<i>Growth Medium</i>			
0.05	0.05	0.05	0.05
0.10	0.10	0.10	0.10
0.20	0.20	0.20	0.20
0.30	0.30	0.30	0.30
0.40	0.40 <sup>a</sup>	0.40 <sup>a</sup>	0.40 <sup>a</sup>
0.48 <sup>a</sup>	0.49	0.59	0.50
<i>Drainage Layer</i>			
-		0.65	
		0.94	
	-	1.07 <sup>a</sup>	0.60
1.25 <sup>a</sup>		1.29	
		1.30 <sup>a</sup>	

-	<i>HDPE (60 mil, 1.5 mm)</i>		
-	<i>Bedding Sand</i>		
	0.55 <sup>a</sup>	1.35	0.70 <sup>a</sup>
		1.40 <sup>a</sup>	
	<i>Waste Rock</i>		
	0.75 <sup>a</sup>	1.45 <sup>a</sup>	1.80
2.00	2.02	2.40	2.60 <sup>a</sup>

<sup>a</sup> Pore-gas measurement depth

A complete summary of all instruments and parameters measured is presented in Table 4-2.

Table 4-2: Summary of the site monitoring elements and parameters at each WRP site

Monitoring Element	Number	Parameters recorded	Location
Meteorological Station	1	Rainfall, air temperature, relative humidity, wind speed and direction, barometric pressure, net radiation, and snowpack depth	Atmosphere
Soil Monitoring Station (SMS)	4	Water content, temperature, matric suction, and pore-gas concentrations	Cover system and waste rock
Continuous Multi Channel Tubing (CMT) Well	4	Temperature, differential pressure, pore-gas concentrations, water level and chemistry	Cover system, waste rock and shallow bedrock
Weir	1	Runoff	Cover system
Interflow System	1,2*	Interflow	Cover system

\* Only at Summit and Victoria Junction WRP sites, respectively

### 4.3.2 Water Influx

The water balance method is a widely used and well accepted approach for examining the hydrological cycle and associated water budgets. In this study, it can be used to measure the net percolation into the waste rock, as long as all other parameters in the water balance are measured. The water balance for the WRP cover systems is shown in Equation (4-1) as follows:

$$PPT = R + AET + \Delta WS + \Delta SS + IF + NP \quad (4-1)$$

where, PPT is precipitation [mm], R is runoff [mm], AET is actual evapotranspiration [mm],  $\Delta WS$  is change in water storage [mm],  $\Delta SS$  is change in snow storage [mm], IF is interflow [mm], and NP is net percolation [mm]. PPT is the source for all water flux, while the other parameters are the sinks. If PPT is known, along with R, AET,  $\Delta WS$ ,  $\Delta SS$  and IF, then we can measure NP as the residual of the water balance.

#### *Precipitation*

This parameter was measured at each site meteorological station, monitoring rainfall with a CS700 tipping bucket rain gauge ( $\pm 0.2$  mm), and snow depth with a sonic ranger, which was then converted to snow water equivalent (SWE).

#### *Runoff*

The stage measurements continuously monitored behind the weirs at each site were combined with the geometry of the weir to calculate the flow rate from the weir discharge equation, as shown in Equation (4-2):

$$Weir\ Discharge = Cd \left(\frac{8}{15}\right) \tan\left(\frac{x}{2}\right) (stage\ height)^{5/2} \sqrt{19.62} \quad (4-2)$$

where  $Cd$  is the discharge coefficient [-], and  $x$  is the notch angle of the weir [°]. A 60° V-notch angle has a corresponding discharge coefficient of 0.654, while a 60° V-notch angle has a discharge coefficient of 0.694. It should be noted that accurate stage measurements were highly challenging in the winter months as existing water in the weir can freeze, and subsequent water

may flow over this frozen layer and provide non-representative measurements of stage height. As a result, careful consideration of water and air temperatures was needed, along with the use of periodic manual stage measurements. The calculated weir discharge measurements were then divided by the corresponding catchment area to obtain a flux measurement per meter.

#### *Actual Evapotranspiration*

AET was directly measured with an Eddy Covariance system installed at the sites during the summer months. However, since the AET was not measured at various periods of the year, it was estimated from empirical calculations of potential evapotranspiration (PET) determined from the widely used Penman (1948) equation:

$$PE = \frac{(m \cdot R_n + E_a \cdot \gamma)}{(m + \gamma)} \quad (4-3)$$

where,  $m$  is the slope of the saturation vapour pressure curve ( $\delta e^\circ / \delta T$ , where  $e^\circ$  is the saturated vapour pressure [Pa] and  $T$  is the air temperature [K]),  $R_n$  is the net radiation [ $\text{MJ}/\text{m}^2/\text{day}$ ],  $E_a$  is the vapour transport flux [ $\text{mm}/\text{day}$ ], and  $\gamma$  is the psychrometric constant [ $\text{Pa}/\text{K}$ ]. Each of these parameters were measured at the site meteorological stations.

#### *Changes in Water Storage*

The changes in water storage were calculated from the evolving moisture contents and water volumes within the cover system over time.

#### *Changes in Snow Storage*

The snowpack depth and snow density were used to calculate the SWE. Similar to changes in water storage, the change in the snow storage at each cover system was calculated.

#### *Interflow*

The total tips measured within the interflow were integrated with the contributing area to calculate the interflow per meter at each WRP.



### 4.3.3 Oxygen Influx

The pore-gas concentrations measured within the cover system and within the shallow waste rock can be used to indicate the effectiveness of the cover systems for limiting oxygen influx. While actual flux measurements were desirable, the pore-gas measurement tubes provided significant challenges with many of the tubes becoming blocked and providing unreasonable pore-gas concentrations. However, a simple analysis of any available and reliable pore-gas concentrations can still provide a general indication of the effectiveness of each cover system to act as a barrier to oxygen.

## 4.4 Results and Discussion

### 4.4.1 Water Flux

#### 4.4.1.1 Precipitation

Figure 4-8 presents the cumulative monthly PPT measured at each WRP between January 2012 and December 2018. Seasonal trends were consistent over time between all WRPs, which was expected due to their close proximity. It also confirms that the source of water to each cover system was similar, which was beneficial for this comparative study.

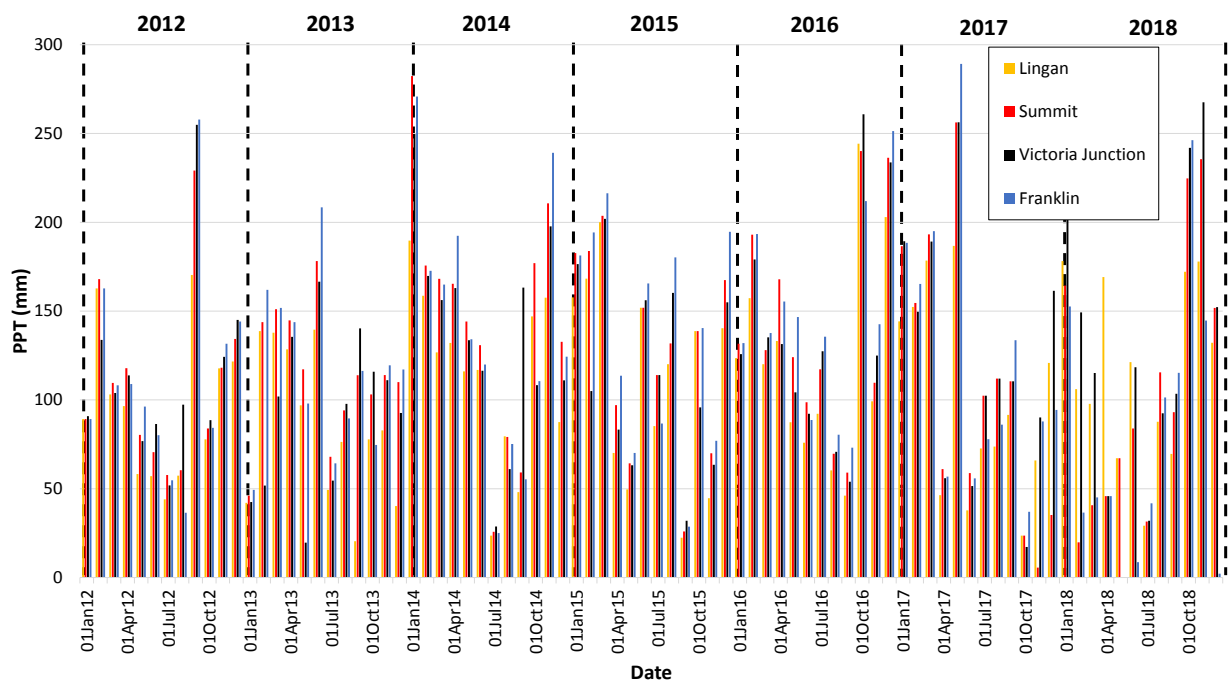


Figure 4-8: Cumulative monthly precipitation (PPT) at each WRP site

Figures 4-9 and 4-10 present the daily cumulative flux for each parameter in the water balance equation. These figures again confirm that similar variations in PPT (blue line) occurred at all WRPs.

#### 4.4.1.2 Runoff

As shown in Figures 4-9 and 4-10, runoff (orange line) follows the same trend as PPT. For example, runoff increased the most during spring and fall, which corresponds to periods of

highest PPT, while periods of low PPT resulted in little to no runoff, as shown by the plateau in runoff. The lowest runoff occurred at the Lingan WRP, with an annual maximum of 617 mm occurring in 2015 where the annual PPT was 1402 mm. The other WRPs sites had their highest annual runoff in 2014; however, Franklin was the only one to continually perform at this level for subsequent years. Victoria Junction and Summit had similar trends of decreasing runoff performance after 2014.

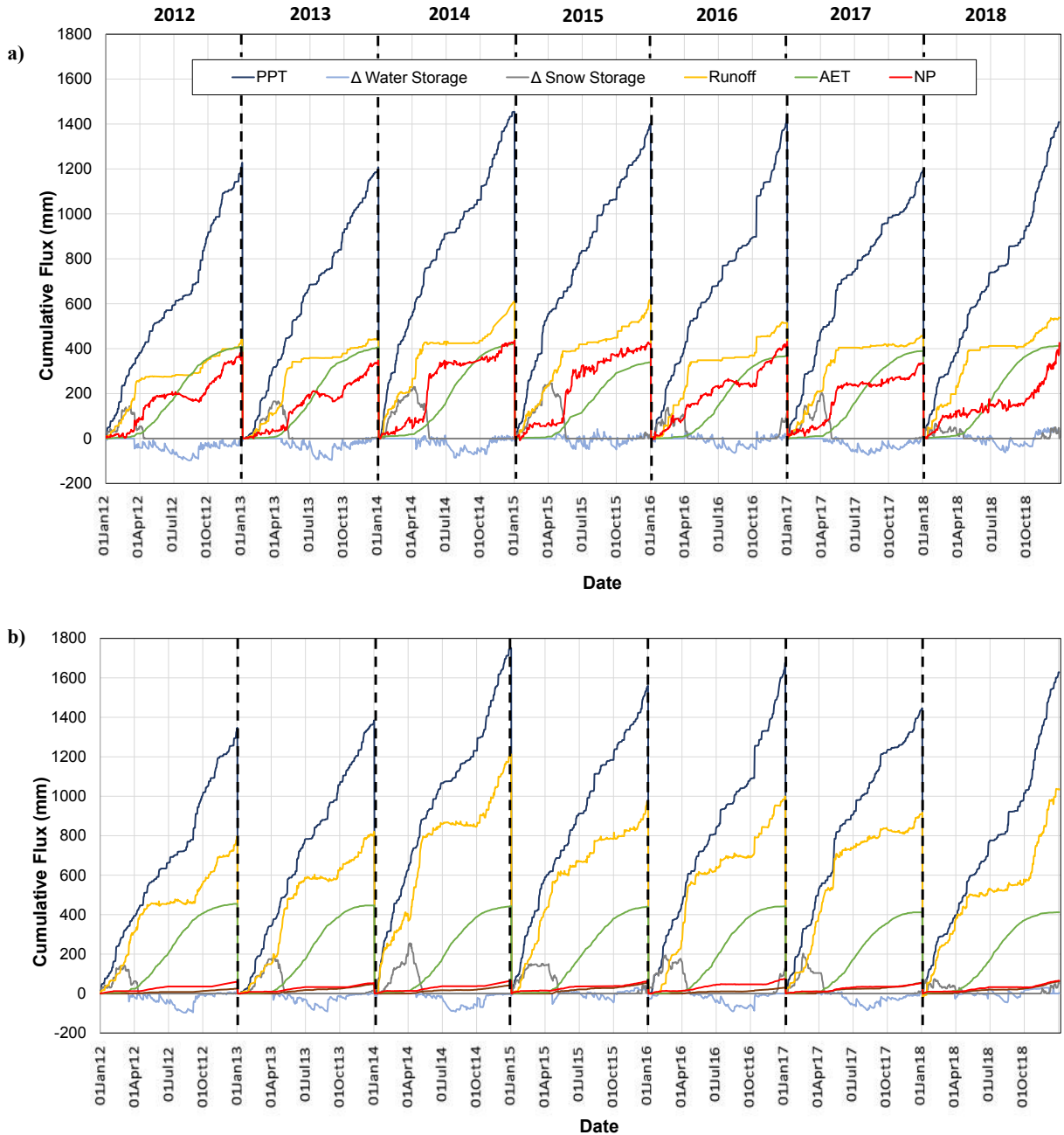


Figure 4-9: Final water balance at (a) Lingan, and (b) Summit

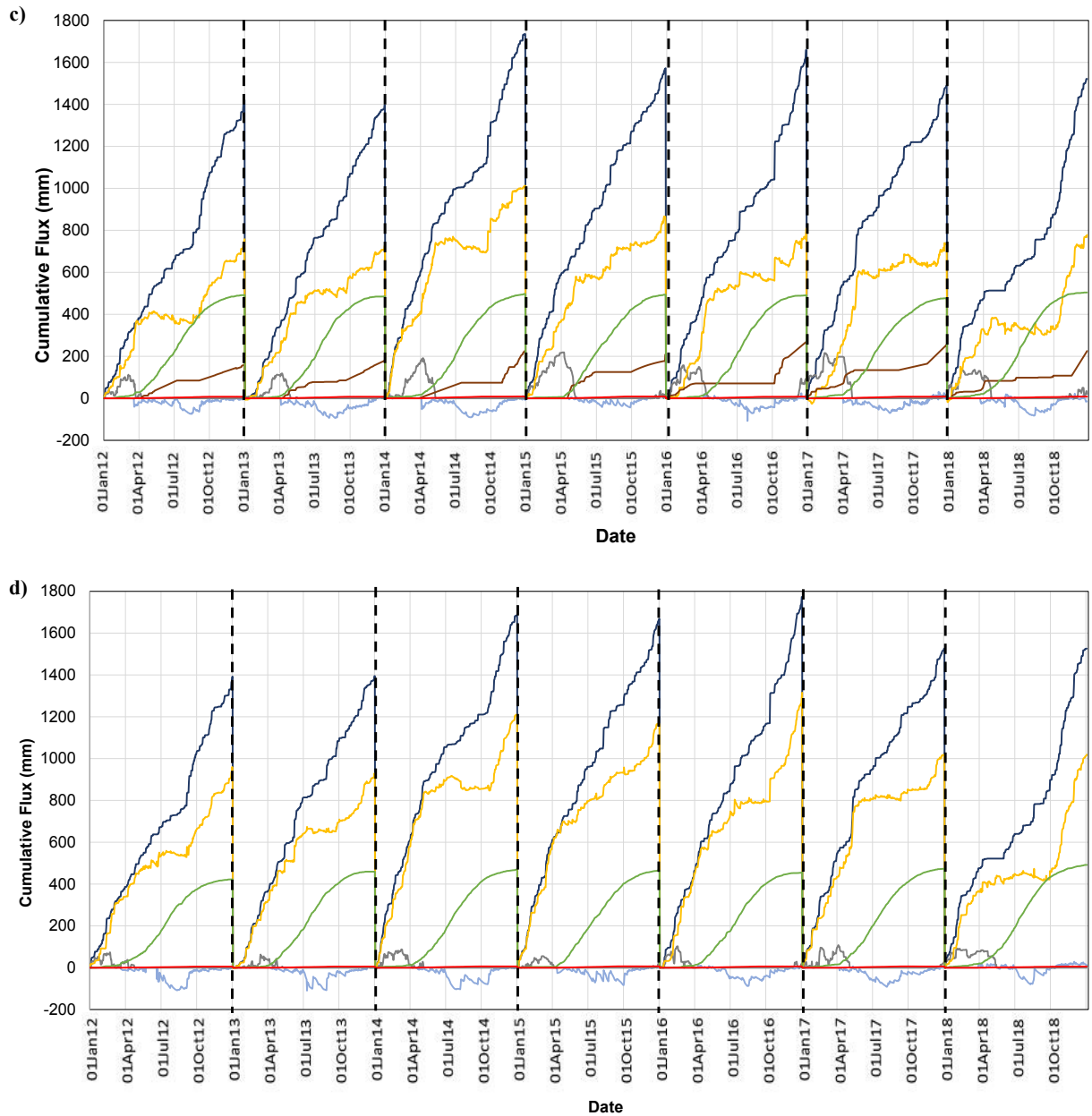


Figure 4-10: Final water balance at (c) Victoria Junction, and (d) Franklin

#### 4.4.1.3 Evapotranspiration

As shown in Figures 4-9 and 4-10, AET (green line) was relatively similar across all four WRP sites. During the colder periods at the beginning and end of each year, AET was very low, with the most significant periods of AET occurring between April and October. Lingan had the least amount of AET, despite its cover system design relying on moisture store-and-release behaviour. The AET at Summit gradually decreases over time, while Victoria Junction had consistency in

high AET levels throughout the seven year period. Franklin exhibits slight increases in AET levels over time, which can be related to the maturity and stabilization of the cover material and vegetation over time.

#### 4.4.1.4 Changes in Water Storage

Changes in water storage are related to evolving moisture contents in the cover material over time. Figure 4-11 illustrates the moisture content along the profile of the cover system and shallow waste rock at each site. As mentioned previously, the locations of each moisture content sensor and measurement were determined by the depth and thickness of different cover system layers, meaning each 2D contour plot in Figure 4-11 is unique. This is shown by the different depths of the HDPE liner at Summit, Victoria Junction and Franklin. It should be noted that moisture content is a function of porosity, and not just water saturation.

As shown in Figure 4-11, high moisture contents (blue regions) are evident in the top soil layer, especially above the HDPE liners at Summit and Franklin, which is due to the lack of, or minimal thickness of, a drainage layer. Low moisture contents (red regions) are most evident in the drainage layers at Victoria Junction and Franklin. White regions represent periods where the cover material was frozen and the corresponding moisture contents were unreliable. Overall, Lingan has a relatively consistent moisture content throughout the entire cover, and even the shallow waste rock (Figure 4-11a), while Summit WRP is more erratic with high fluctuations from dry to wet conditions each year.

Figures 4-9 and 4-10 present the cumulative change in water storage (light blue line) for each year. Since this cumulative change in flux is referenced to the water storage on January 1 each year, it is expected that little change to that reference value will occur in winter and fall periods, while large decreases in water storage will occur between April and October, where the cover material is drying out. Figures 4-9 and 4-10 confirm these expected trends with negative water storage occurring in the drier months, before water storage changes tend to return to zero as it approaches the end of the year.

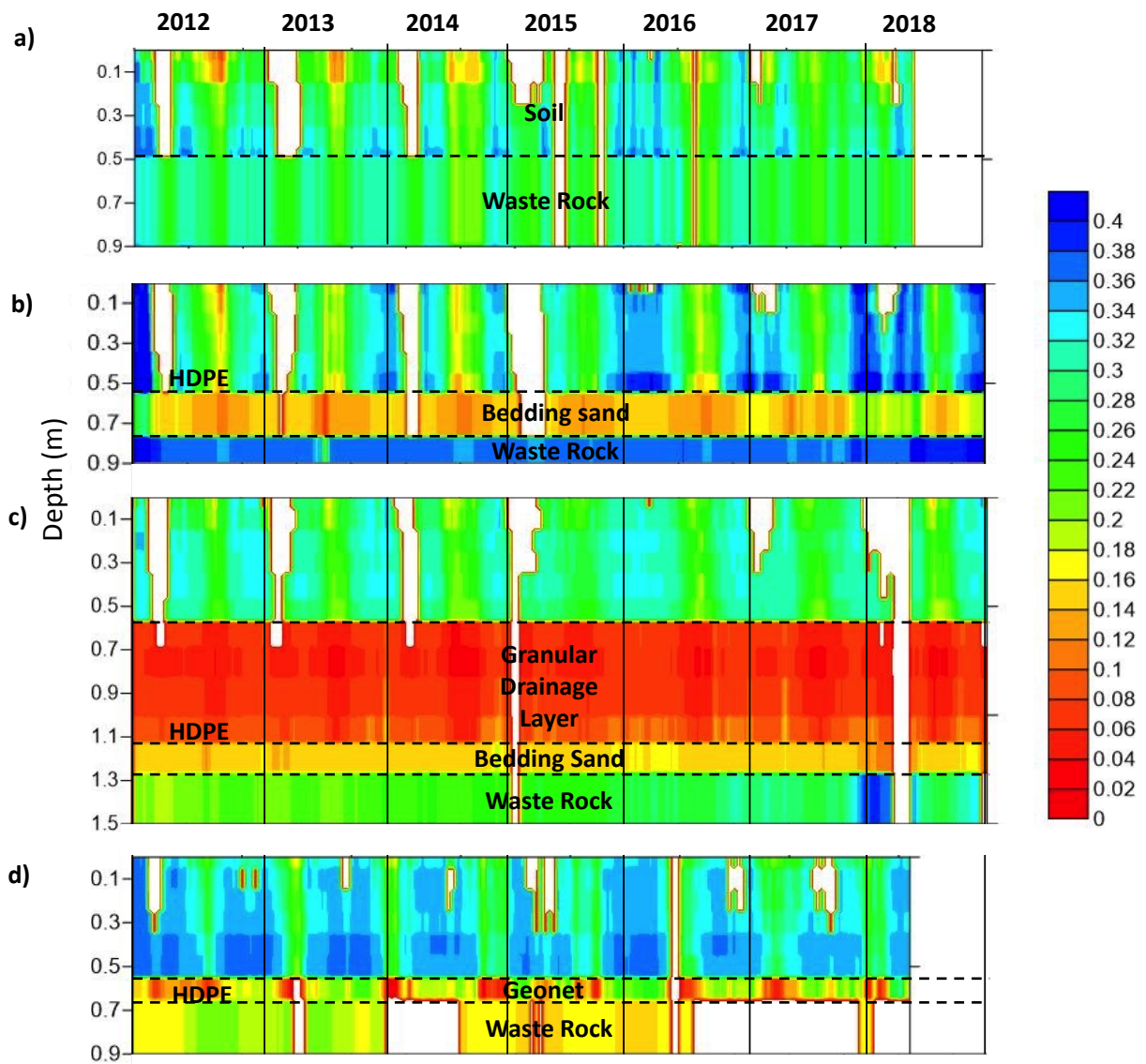


Figure 4-11: 2D contour plots of moisture content within the cover system and shallow waste rock at (a) Lingan, (b) Summit, (c) Victoria Junction, and (d) Franklin.

#### 4.4.1.5 Changes in Snow Storage

Figures 4-9 and 4-10 present the cumulative change in snow storage (light grey line) for each year. As expected, the largest changes occur between December and March each year, with changes evident between April and November where no snowfall occurs.

#### 4.4.1.6 Interflow

The cumulative interflow (brown line) is shown in Figures 4-9 and 4-10 at just the Summit and Victoria Junction WRPs. It is evident that the interflow at Victoria Junction is significantly larger than that at Summit. This is due to the granular drainage layer at Victoria Junction, which promotes lateral percolation of water above the HDPE liner, and the lack of a drainage layer at Summit, which severely limits the lateral movement of water towards the interflow collection system. This lack of lateral interflow at Summit corresponds to the high moisture contents observed, and the large head of water measured by the OTT-PLS and HOBO loggers shown in Chapter 3.

#### 4.4.1.7 Net Percolation

NP was calculated as the residual from the water balance equation in Equation (4-1), and is plotted in Figures 4-9 and 4-10. The NP (red line) has the largest increases during spring and fall at each WRP. Lingan exhibits significant NP each year, while the NP at Summit, Victoria Junction and Franklin is barely visible.

To improve interpretation of the NP at each site, Figure 4-12 presents a comparative bar chart of annual NP at each site between 2012 and 2018. NP is the lowest at Franklin, closely followed by Victoria Junction, which matches the water influx estimates in Chapter 3. This further confirms the effectiveness of drainage layers above HDPE liners, which enables a larger amount of water to be expelled from the cover through runoff and interflow. In contrast, the lack of drainage layer at Summit WRP, resulted in high moisture contents, water build-up on top of the HDPE liner, and limited lateral interflow, especially during high periods of PPT. This lack of a drainage layer is further compounded by the low pile slopes existing at Summit. In combination with the topography of the site resulted in poor performance at limiting water build up.

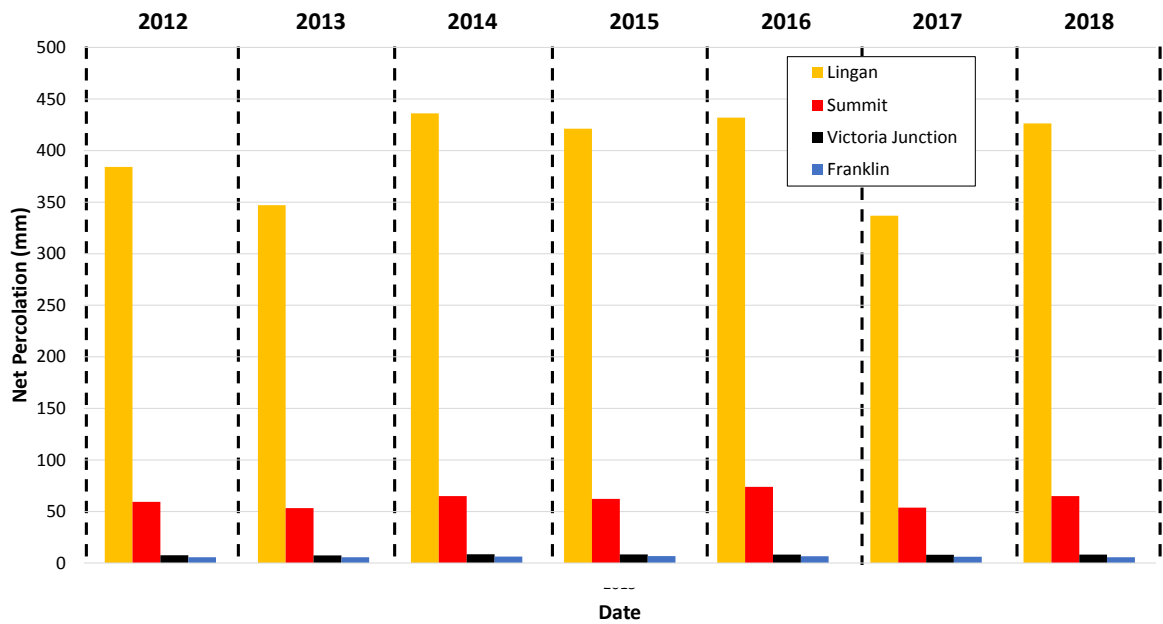


Figure 4-12: Net percolation at each WRP site over the 7 year monitoring period

A summary of the water balance breakdown is presented in Figure 4-13, where the annual PPT at each site is broken down into the respective parameters, and displayed in a stacked bar graph to visually see the performance of each cover system every year.



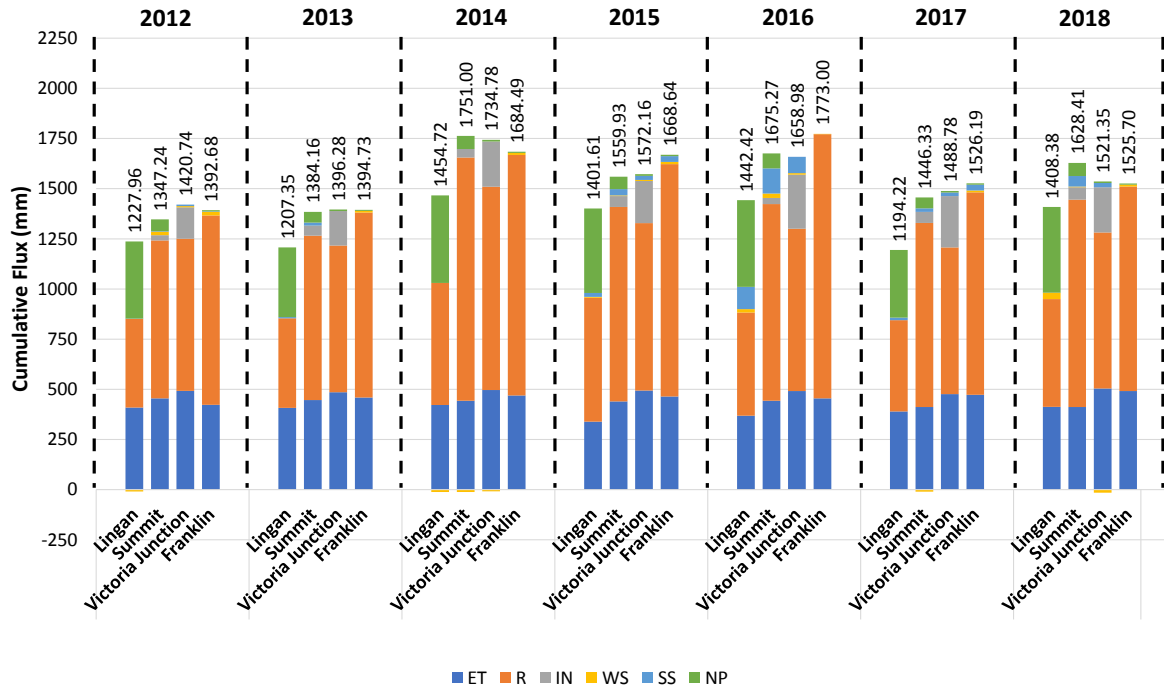


Figure 4-13: Comparative cumulative flux of each water balance parameter at each WRP, with the total precipitation (PPT) value placed on top of each bar

Table 4-4: Water influx in terms of precipitation (PPT)

Year	Lingan			Summit			Victoria Junction			Franklin		
	PPT (mm)	Flux (mm)	% PPT	PPT (mm)	Flux (mm)	% PPT	PPT (mm)	Flux (mm)	% PPT	PPT (mm)	Flux (mm)	% PPT
2012	1227.96	384.18	31.29	1347.24	59.43	4.41	1420.74	7.60	0.53	1392.68	5.60	0.40
2013	1207.35	347.14	28.75	1384.16	53.27	3.85	1396.28	7.48	0.54	1394.73	5.61	0.40
2014	1454.72	436.21	29.99	1751.00	65.03	3.71	1734.78	8.61	0.50	1684.49	6.27	0.37
2015	1401.61	421.26	30.06	1559.93	62.27	3.99	1572.16	8.43	0.54	1668.64	6.71	0.40
2016	1442.42	431.93	29.94	1675.27	73.90	4.41	1658.98	8.24	0.50	1773.00	6.60	0.37
2017	1194.22	336.87	28.21	1446.33	53.72	3.71	1488.78	7.98	0.54	1526.19	6.14	0.40
2018	1408.38	426.32	30.27	1628.41	65.01	3.99	1521.35	8.22	0.54	1525.70	5.68	0.37

#### 4.4.2 Oxygen Flux

Figure 4-14 presents the average oxygen and carbon dioxide concentrations that were reliably measured at each WRP. As shown, the HDPE-lined cover systems were effective at diminishing oxygen concentrations (and corresponding increases in carbon dioxide) within the waste rock below the cover. In contrast, the soil cover at Lingan was not effective for limiting oxygen influx, as noted by the similar oxygen concentrations with the cover material and waste rock.

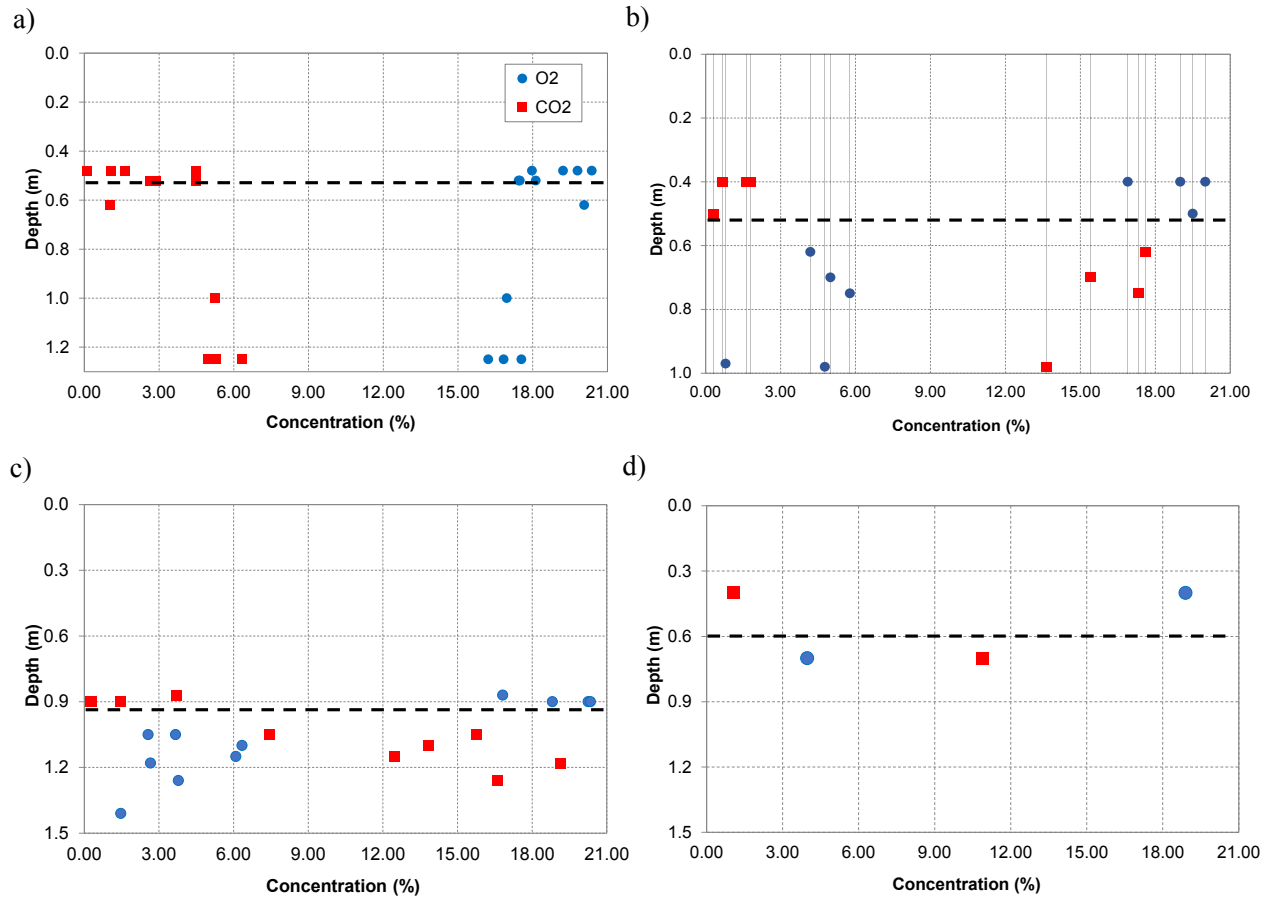


Figure 4-14: Average oxygen and carbon dioxide concentrations measured within the cover material and shallow waste rock at (a) Lingan, (b) Summit, (c) Victoria Junction, and (d) Franklin, where the dashed line defines the soil and waste rock interface in (a), and the HDPE liner in (b), (c), and (d).

#### 4.4.3 Costs

Table 4-4 presents a breakdown of the cost of each material (per m<sup>2</sup>) that was installed in each WRP cover system. While it performs poorly for limiting atmospheric flux, the simple soil cover at Lingan is inexpensive relative to the other sites. Victoria Junction performed very well, but it

was the most expensive due to the cost of the granular drainage layer in terms of both material and transportation costs. In contrast, the cover installed at Franklin was less expensive than the cover implemented at Victoria Junction due to the reduced cost of the geonet drainage layer used.

Table 4-4: Breakdown of the cost of materials for total cover system cost

<b>WRP</b>	<b>Item</b>	<b>Unit price/m<sup>3</sup> * m<sup>2</sup> for HDPE</b>
Lingan	<i>Soil</i>	\$8
Summit	Soil	\$10
	Geofabric	\$4
	HDPE	\$15
	Bedding Sand	\$15
	<i>Total Cost</i>	<i>\$44</i>
Victoria Junction	Soil	\$13
	Granular Drainage Layer	\$20
	HDPE	\$19
	Bedding Sand	\$22
	<i>Total Cost</i>	<i>\$74</i>
Franklin	Soil	\$10
	Geonet	\$1
	HDPE	\$15
	Bedding Sand	\$15
	<i>Total Cost</i>	<i>\$41</i>

## 4.5 Conclusion

Engineered cover systems have proven to be an effective solution at limiting atmospheric ingress to mine waste rock piles, and thereby prevent and/or control the generation of toxic acid mine drainage (AMD) and its contamination of the surrounding environment. This study assessed the performance of different cover systems at four reclaimed coal mine WRPs in the Sydney Coalfield in Nova Scotia, Canada. All cover systems were unique and can be defined by their characteristics as follows: (i) Lingan: simple, single-layer soil-only cover, (ii) Summit: multi-layer HDPE-lined cover with no specific drainage layer, (iii) Victoria Junction: multi-layer HDPE-lined cover with a thick gravel drainage layer, and (iv) Franklin: multi-layer HDPE-lined cover with a geocomposite drainage layer. A comprehensive field monitoring program was conducted between January 2012 and December 2018 to monitor the daily moisture and oxygen dynamics within each cover system over these seven years.

HDPE inclusive covers have proven to be an effective material to utilize in cover systems when limiting water and oxygen ingress. However, the frequent occurrence of defects within HDPE liners poses a threat to its impermeable functionality. To determine the water flux, and the resulting potential AMD generation, defect leakage through the liner imperfections can be calculated using analytical equations and empirical models. These calculations include assumptions about the size and shape of defect, contact quality, etc. Therefore, further analysis through a detailed monitoring program to determine the water flux using the water balance method was necessary to confirm the findings of Chapter 3.

A comprehensive water balance was developed to estimate the daily net percolation into the underlying waste rock at each site. All parameters within the water balance were calculated, including precipitation (PPT), actual evapotranspiration (AET), runoff (R), interflow (IF), changes in water storage (WS), and changes in snow storage (SS). The residual from this water balance was then inferred to be net percolation (NP). A comparative analysis of each cover system confirmed that all three HDPE-lined cover systems dramatically reduce water influx compared to the natural soil cover at Lingan. Furthermore, the composition of the drainage layer

above the HDPE liner influences the net percolation, as both granular drainage and geocomposite drainage exhibiting reduced NP compared to the HDPE-lined cover with no drainage layer at Summit. These findings are reinforced with the findings from defect leakage calculations in Chapter 3. The HDPE-lined cover systems also diminished oxygen concentrations within the waste rock, again demonstrating the effectiveness of HDPE-lined cover systems as barriers to atmospheric flux to mine waste rock.

## 4.6 References

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## 5 Summary and Conclusions

### 5.1 Summary

Canada ranks within the world's top 5 countries for mining 17 of the most important metals and minerals (Marshall, 2019). With the wealth of mining occurring in Canada, large amounts of waste are produced alongside the extracted resources. The Sydney Coalfield in Nova Scotia, Canada, represented one of the largest sources of coal in Canadian history, with over 500 million tonnes of coal mined across its ~200 years of operation (Meiers et al., 2014). These mining activities left behind a legacy of solid waste rock deposited into large, partially water-saturated porous piles on the ground surface. Trace sulphides in the waste rock have the potential to become toxic acid mine drainage (AMD) upon reaction with atmospheric components. A common solution is the installation of engineered cover systems to isolate the reactive waste rock from the atmosphere. A number of cover systems exist, from a single layer of native soil to multiple layers of soils, geosynthetics and geomembranes. The inclusion of geomembrane liners, such as high density polyethylene (HDPE), within multi-layer covers exhibit significant potential, as pristine geomembrane liners are expected to be 100% effective at limiting water and oxygen flux. However, it is accepted that these liners become diminished in the presence of deformations such as thermal expansion wrinkling, ageing, and defects (Rowe, 2012; Rowe et al., 2012). As these deformations occur during and after field installation, their performance needs to be evaluated over time at in-service WRPs. However, little research has been done on the *in situ* performance of geomembrane-lined cover systems at reclaimed WRPs (Power et al., 2017).

The goal of this thesis was to assess the long-term performance of different geomembrane-lined cover systems following installation at large WRPs. For coal mine WRPs in the Sydney Coalfield in Nova Scotia, Canada, were reclaimed with different cover systems, with three covers containing HDPE liners (but with different drainage layer compositions) and one cover comprising a single layer of native soil. Following installation, all cover systems were monitored over seven years with state-of-the-art field instrumentation to evaluate their performance and determine whether site closure objectives were being achieved. The thesis goal was then broken down into two distinct research objectives. The first was to evaluate the effect of drainage layer composition on defect leakage rates within the three HDPE-lined cover systems, while the second

was to compare the water influx and oxygen levels of the three HDPE-lined covers to a simple soil cover. Both research topics have the same goal which is to determine the cover systems performance at limiting AMD contamination of nearby environmental receptors.

The *first* research objective was to assess the effect that drainage layers have on HDPE-inclusive cover systems. Three WRPs at the Sydney Coalfield in Nova Scotia, containing HDPE liners, were monitored for seven years, in which the precipitation, moisture content, and head of water on top of the HDPE liner were recorded. As HDPE liners can contain a number of defects which permit water influx and potential generation of AMD, established defect leakage equations were used. The three cover systems had unique drainage layers: (1) no specific drainage layer at Summit, (2) granular drainage layer at Victoria Junction, and (3) man-made geonet drainage layer at Franklin. The various field parameters were compiled and analyzed to eventually estimate the defect leakage rate (or water influx) occurring every day at each WRP over seven years. Considering the proximity of the WRPs to each other, each site experienced relatively similar precipitation. The measured moisture content indicated that Summit, with no drainage layer, exhibited the highest moisture content above the HDPE liner, along with the largest head of water. In contrast, Franklin, with a geonet drainage layer, exhibited the lowest levels of moisture and head of water directly above the HDPE liner. The calculated defect leakage rate at each WRP confirmed that Summit had the highest leakage rates, while Franklin experienced the least amount of leakage, closely followed by Victoria Junction. This study demonstrated the importance of drainage layer composition on water influx. The drainage layers at Franklin and Victoria Junction were so effective at reducing the build-up of water above the HDPE liner, that even if defects did exist, the water influx would be limited.

The *second* research objective was to evaluate the performance of HDPE-lined cover systems for limiting water and oxygen influx in comparison to a single layer cover system. The same three HDPE-lined cover systems in first objective were studied here, in addition to an adjacent WRP at Lingan that was remediated with a single layer of native soil. A seven-year monitoring program with state-of-the-art field instrumentation was conducted, with parameters such as rainfall, snow water equivalent, air temperature, runoff, interflow, evapotranspiration, moisture content, soil temperature, and pore-gas concentrations being measured. A comprehensive water balance was



generated for each WRP to determine the respective rates of net percolation to the underlying waste rock. Results demonstrated that Franklin permitted the least amount of net percolation (<1% of total precipitation), while Lingan produced the largest amount of net percolation (28% of precipitation). Oxygen and carbon dioxide concentrations measured both within the cover system and below the cover system, confirmed that the HDPE-lined cover systems dramatically reduced oxygen levels within the waste rock.

## 5.2 Recommendations

Chapter 3 determined the amount of defect leakage experienced at the HDPE-lined cover systems, while also highlighting mechanics of fluid movement surrounding a defect, and the key parameters of concern when designing a cover system to limit water influx. The following recommendations are suggested when utilizing an impermeable layer within an engineered cover system:

- A drainage system above the impermeable membrane (in this case, HDPE) within the cover system is key to limiting the build-up of water above the HDPE liner and divert the flow out of the cover.
- An anthropogenically created drainage layer, such as a geocomposite drainage net (i.e., geonet) provides a greater amount of drainage than natural granular material. This is possibly due to the repetitive and consistent netted structure of the geonet, which provides the most optimal pathway for flow compared to the random assortment of pore space within a granular drainage layer.
- The most important parameter when attempting to limit leakage through defects is the height of water above HDPE liner followed by the saturated hydraulic conductivity of the underlying layer while the least sensitive is the size of the defect based on the range used in this study.

Chapter 4 evaluated the amount of net percolation and oxygen entering the waste rock at the four covered WRPs in The Sydney Coalfield over seven years. The following recommendations are suggested for future engineered cover system design and application to optimize the limitation of AMD generation:

- A complex multi-layer cover system is the most effective at limiting atmospheric ingress compared to a simple soil cover. Specifically, Franklin, which used a HDPE and geonet cover allowed a net percolation of 0.4% of precipitation, compared to Langan which allowed 28% of PPT as NP.
- The HDPE-lined cover with a geonet drainage layer at Franklin had the lowest net percolation amongst all HDPE-lined cover systems, again highlighting the benefit of the geonet for effectively draining water above the HDPE liner.
- All HDPE-lined covers effectively diminished the oxygen concentrations within the waste rock compared to the single layer soil cover at Langan. In this case, the drainage layer does not strongly influence oxygen flux, with all three HDPE-lined covers equally effective at diminishing oxygen influx to the waste rock.

### 5.3 Future Work

- Supportive work on the groundwater and surface water chemistry could be conducted to further ascertain the efficacy of the cover systems.
- Further study into possible preferential pathways within the cover material could be analyzed. These results could be important to determine water influx.
- Future work into the aging process could be monitored, including the cover system materials performance as well as the WRP settlement, shape and stability.
- Testing into the use of various underlying bedding materials beneath the HDPE liner and how that could impact defect leakage.

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# Curriculum Vitae

**Name:** Deanna Hersey

**Post-secondary Education and Degrees:** University of Western Ontario  
London, Ontario, Canada  
2014-2019 H.B.Sc

The University of Western Ontario  
London, Ontario, Canada  
2019-2021 M.E.Sc

**Awards and Honours:** Most Implementable Project Solution; How to Change the World Program (2021)

CIM Student Poster Award (3<sup>rd</sup>) (2021)

**Related Work Experience** Teaching Assistant  
The University of Western Ontario  
2019-2020