Hydrology of a Constructed Fen Watershed in a Post-mined Landscape in the Athabasca Oil Sands Region, Alberta, Canada

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis.

This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This thesis has been structured in accordance with the manuscript option. Chapters two, three and four have been submitted to peer-review journals and are currently under review. Accordingly, these chapters will be subjected to the requests of the reviewers and may differ from the respective chapters presented here.

Dr. J. Price was the advisor for this thesis. Accordingly, he played a critical role in the research presented herein. Dr. Price and S. Ketcheson collectively developed the conceptual approach to the field instrumentation design. Through numerous discussions, both in the field and during the writing of the thesis, Dr. Price contributed important ideas and suggestions with respect to data analyses and interpretation. S. Ketcheson was the first author on all of the chapters within this thesis. Accordingly, S. Ketcheson did the majority of the writing. As the thesis advisor, Dr. Price reviewed all of the chapters within this thesis and provided comments and suggestions where needed. The comments from Dr. Price often helped to strengthen conceptual ideas and interpretation, and they occasionally identified new data analysis ideas. Dr. Price also provided typically minor editorial revisions where appropriate.

Chapter two is submitted as:

Ketcheson, S.J., Price, J.S., Carey, S.K., Petrone, R.M., Mendoza, C.A. and Devito, K.J. Can fen peatlands be successfully constructed in post-mining oil sands landscapes? Submitted to: *Earth-Science Reviews*. MS# EARTH2800.

S. Ketcheson wrote the majority of this paper and provided the original conceptual ideas, which were subsequently advanced and adapted through contributions from the co-authors. Co-authors also provided interpretation and editorial suggestions, which were incorporated into the chapter. Note that the title of this chapter has been updated within this thesis.

Chapter three is accepted for publication as:

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S. Ketcheson completed the data analysis and writing for this manuscript. As advisor and second author, Dr. Price provided important comments and suggestions with respect to data analyses and interpretation, as well as typically minor editorial revisions, as outlined above. Comments from industrial partners (J. Martin and C. Hansen) and two anonymous peer reviewers and were also incorporated into this chapter during the peer-review process.

Chapter four is submitted as:

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The data analysis and writing for this manuscript was completed entirely by S. Ketcheson. As advisor and second author, Dr. Price provided important comments and suggestions with respect to data analyses and interpretation, as well as typically minor editorial revisions, as outlined above. Some minor comments received from industrial partners (J. Martin and C. Hansen) have been incorporated where appropriate (mostly with respect to the reclamation material descriptions and operational procedures).

Chapter five has been prepared (but not yet submitted) as:

Ketcheson, S.J., Price, J.S., Petrone, R.M. and Sutherland, G. An initial assessment of the hydrological functioning of a constructed fen wetland watershed in the Athabasca Oil Sands Area, Alberta, Canada.

The majority of the data analysis and all of the writing for this manuscript was completed by S. Ketcheson. G. Sutherland and Dr. R. Petrone collected and analyzed the energy budget and evapotranspiration (eddy covariance) data and provided the associated detailed methodological write up. As advisor and second author, Dr. Price provided important comments and suggestions with respect to data analyses and interpretation. All co-authors provided comments, suggestions and typically minor editorial revisions on the completed manuscript draft, where appropriate.

By signing below, I indicate that I am in agreement with the evaluation of the roles and contributions of the various authors expressed above.

J. Price	R. Petrone	S. Carey
K. Devito	C. Mendoza	G. Sutherland

Abstract

Peatlands (i.e., wetlands with organic soil) cover approximately 12% of Canada's total land area, 18% of Alberta's land base and nearly half of the landscape in Canada's Western Boreal Plain. Some of these peatlands overlay vast fossil fuel resources. Mounting pressure from resource extraction industries is impacting an increasing proportion of peatland ecosystems in Canada. In Alberta, approximately 4800 km^2 of the Athabasca Oil Sands Region near Fort McMurray has been deemed suitable for surface mining, which involves the removal of large expanses of undisturbed peatlands to access the oil sands beneath. The concept of peatland creation has been adapted into the Canadian regulatory framework and fen peatlands have now been constructed in post-mined oil sands landscapes. However, there is little information with respect to the nature of the hydrological processes that operate within constructed fen ecosystems and their associated watersheds and this concept is only now being tested in the field.

Oil sands reclamation requires the reconstruction of entire landforms and drainage systems. The hydrological regime of reclaimed landscapes will be a manifestation of the processes operating within the individual landforms that comprise it. Hydrology is the most important process regulating wetland function and development, as it exhibits a strong control on the chemical and biotic processes operating in peatlands. Accordingly, this research aims to tackle the growing and immediate need to understand the hydrological processes that operate within reconstructed landscapes. The approach is to couple the controls on water distribution, storage and release within several reclaimed landforms (reclaimed slopes, tailings sand upland aquifer and fen peatland) to the function of a constructed fen watershed (the Nikanotee Fen watershed).

A comparison of two constructed fen ecosystems with fundamentally different conceptual approaches provides the framework for examination of the key challenges and opportunities associated with fen creation in an oil sands reclamation setting. Although the focus of this work is on the hydrological processes, issues related to both water quantity and quality are identified as major challenges for fen creation. An adaptive approach to fen creation is recommended, in which the knowledge developed in

concurrent research should be assimilated with the available longer-term information. The multi-faceted complexities associated with the ability to deem fen creation projects a success within the context of oil sands reclamation are also explored. The suggestion from this discourse was that success should be measured by the ability to design and construct systems that exhibit predictable and desirable characteristics.

The distribution, ablation and fate of snowmelt waters were quantified for the constructed watershed, which addresses a lack of understanding of snowmelt dynamics within reclaimed landscapes. Results indicated that the snowmelt period hydrology within recently constructed landscapes is fundamentally different from that reported for natural settings. Reclaimed slopes represented large stores of over-winter precipitation and generated substantial surface runoff during the snowmelt period. This research demonstrates that snow dynamics must be incorporated into the design of landscape-scale constructed ecosystems.

The dominant controls on the soil water regimes and runoff generation mechanisms on two reclaimed slopes (reclaimed five years apart) within the Nikanotee Fen watershed were also investigated during the snow-free period. The contrasting hydrological regime exhibited by these slopes suggests that changes in the hydrophysical properties of reclamation materials following construction could result in a shift in the hydrological role of reclaimed slopes at the watershed scale. It appears that, over time, recently reclaimed slopes should produce less overland flow and shift from water conveyors to water storage features in constructed watershed systems.

Finally, the water fluxes within the Nikanotee Fen – upland system were evaluated for the first two years following construction (2013 - 2014). The hydrological performance of the constructed system was assessed and discussed within the context of the construction-level design. It was determined that the system design was capable of sustaining wet conditions within the Nikanotee Fen during the snow-free period in 2013 and 2014, with persistent ponded water in some areas. Evapotranspiration dominated the water fluxes from the system. These losses were partially offset by groundwater discharge from the upland aquifer, which demonstrated strong hydrologic connectivity with the fen in spite of most construction materials having lower than targeted saturated hydraulic conductivities. However, the variable surface infiltration rates and thick placement of a soil-capping layer constrained recharge to the upland aquifer, which remained below designed water contents in much of the upland.

These studies comprise one of the most comprehensive hydrological evaluations of a constructed fen peatland watershed to date. The findings of this research indicate that it is possible to engineer the post-mining landscape to accommodate the hydrological functions of a fen peatland. Several recommendations are made to help guide the construction of future fen peatlands, which should be done at the commercial-scale. Research priorities include understanding the storage and release of water within coarse-grained reclaimed landforms as well as evaluating the relative importance of external water sources and internal water conservation mechanisms for the viability of fen ecosystems over the longer-term. The novel, catchment-scale approach to reclamation research presented within this thesis provides an integrated understanding of the hydrological functioning of constructed watersheds, and a similar approach is recommended for future research in reclaimed landscapes.

Acknowledgements

I have received an immeasurable amount of support from many people during the long journey to the completion of this thesis. First of all, I would like to express my deep gratitude to my advisor and friend, Dr. Jonathan Price. Your contributions to this research and commitment to my academic development have been instrumental and have made this a truly enjoyable experience. The lessons that I have learned from you, both in science and in life, will always be remembered. I also would like to express my appreciation to my thesis committee members, Dr. Richard Petrone, Dr. Sean Carey and Dr. David Rudolph, for their guidance along the way. An extra 'thank you' is in order for the additional career advice and support from Dr. Petrone – it has been much appreciated.

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Dedication

To my greatest accomplishment: our sweet little lady Olivia.

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1 INTRODUCTION

Peatland development occurs naturally over long periods of time in response to climate, geology, hydrology and vegetation. Approximately 4800 km^2 of the Athabasca Oil Sands Region (AOSR) in Northern Alberta, Canada, has been deemed suitable for surface mining (Government of Alberta, 2015). These mining activities involve the large-scale removal of the surficial landscape. For example, by the start of 2014, open-pit oil sands mining activities in the AOSR had disturbed an area in excess of 800 km^2 (Government of Alberta, 2015). Wetlands comprise approximately half of the pre-disturbance landscape in the AOSR, the majority of which (~90%) are fen peatlands (Vitt *et al.*, 1996). Consequently, oil sands extraction activities are removing large quantities of peatlands from the landscape (Daly *et al.*, 2012; Rooney *et al.*, 2012).

Mine closure and reclamation designs aim to return landscapes to functioning ecosystems following surface mining of oil sands deposits. In 2007, the concept of peatland creation was adapted into the regulatory framework (AEPEA approval 94-02-00). Oil sands companies were required to undertake, or participate in, a study on reclamation techniques that examined the feasibility of incorporating constructed bog and/or fen peatlands into a portion of the final reclaimed landscape. Prior to this, the concept of peatland creation was largely untested. Due to the lack of prior experience, the development and refinement of the conceptual approaches suitable for peatland creation relied upon application of the current understanding of peatland and hydrological processes within natural and disturbed ecosystems into a mine reclamation context.

Natural fen peatlands typically receive a portion of their water inputs from ground and surface water inflows (Ingram, 1983). Thus, fens were considered to be an attractive option for peatland creation, since groundwater fluxes could be relied upon to supplement periods of limited atmospheric water availability (Price *et al.*, 2010), which are common in the Western Boreal Plain (WBP; Bothe and Abraham, 1993; Marshall *et al.*, 1999). Thus, the creation of a fen peatland was considered possible in highly engineered reclaimed landscapes by constructing a suitable hydrogeologic setting capable of providing a sufficient water supply under regional climatic conditions to sustain fen peatland functions (Price *et al.*, 2010; Devito *et al.*, 2012). Accordingly, a conceptual model was developed (Price *et al.*, 2010) which, combined with revegetation strategies, formed the basis for a fen construction plan (Daly *et al.*, 2012) that was initiated by Suncor Energy in August 2010 and was completed in the winter of 2013.

The design consisted of a constructed upland-fen system, which formed part of a larger catchment that includes additional reclaimed and natural slopes. This watershed, named the Nikanotee Fen watershed, was constructed on an overburden dump within the Millennium mine lease at the Suncor Energy Inc. oil sands mining operations ~40 km north of Fort McMurray, Alberta. In an attempt to artificially accelerate peatland succession, which can take thousands of years (Clymo, 1983), the fen portion of the watershed (named the Nikanotee Fen) was constructed using peat substrate extracted from newly developed lease areas. The peat was placed at the toe of an upland aquifer constructed using tailings sand materials and contoured to slope towards the fen. The tailings sand materials were placed over a basal geosynthetic clay liner to minimize water losses via deep drainage and direct water flow towards the low-lying fen peatland. The upland aquifer was capped with a thin (30 – 50 cm thick) reclamation material to provide a suitable substrate for revegetation and to promote percolation of precipitation water. Ultimately, the goal was to create a self-sustaining ecosystem that is carbon-accumulating, capable of supporting a representative assemblage of vegetation species and resilient to normal periodic stresses.

The creation and development of fen peatlands in a post-mined oil sands setting in the AOSR faces several challenges. For example, the regional climate is sub-humid (Bothe and Abraham, 1993; Marshall *et al.*, 1999) and, thus, water availability to satisfy soil water storage and recharge to constructed aquifers is limited. In this setting, climate controls the relative importance of the components of regional water budgets (Devito *et al.*, 2005a), which are typically dominated by soil water storage and evapotranspiration (Smerdon *et al.*, 2005). On average, ~25% of annual precipitation falls as snow (Environment Canada, 2011). Although the spring freshet can represent an important recharge event on some natural landforms in the WBP (Smerdon *et al.*, 2008), little is known about the distribution of snow and the availability of snowmelt water for recharge in reclaimed oil sands landscapes. Since water availability is of profound importance for the design and development of constructed fen peatland ecosystems, an understanding of snow dynamics should be a requisite for their design. However, this aspect of reclamation has yet to be characterized.

Another challenge exists with respect to reinstating interconnectivity between individual landforms within the reclaimed landscape. On a landscape-scale, establishing hydrological connectivity, and understanding how this connectivity evolves over time, is critical for the development of effective water management strategies after oil sands extraction. The reclaimed slopes within the Nikanotee Fen watershed could provide a source of water for the designed upland-fen system that they encompass, although this was not an explicit aspect of the original design. Further, the hydrophysical properties of reclamation materials can change following placement (Guebert and Gardner, 2001; Kelln *et al.*, 2007; Meiers *et al.*, 2011), which means that the hydrologic role of reclaimed slopes could change over time. Accordingly, understanding the hydrological significance and evolution of these reclaimed slopes is critical for the evaluation of the hydrology of the designed upland-fen system as well as for understanding the hydrological regime of the entire watershed, and how this evolves in the first few years following construction. Furthermore, issues related to water quality also represent a substantial challenge for the creation of viable fen peatlands in post-mined settings. Although not quantified empirically in this thesis, some of the major challenges associated with water quality are discussed to provide a balanced assessment of the feasibility of fen creation in the AOSR.

The concept of fen creation in a post-mined oil sands landscape is largely untested. A fundamental requirement of the design of constructed fen ecosystems is the ability to provide a sufficient water supply under local climate conditions to sustain a carbon-accumulating ecosystem. As such, characterization of the hydrological parameters within both the upland watershed and fen ecosystem, and the quantification of water fluxes between these systems, is essential for understanding the hydrological performance of the constructed system as well as the vegetation establishment and carbon exchanges within the constructed peatland.

1.1 Objectives

The overall goal of this research is to provide a watershed-scale evaluation of the dominant hydrological processes operating within the constructed Nikanotee Fen watershed. The specific objectives, outlined below, each address a separate component of the constructed system that is essential for the comprehensive assessment of the system design and hydrological performance of the Nikanotee Fen watershed. Thus, the main objectives of this research are to:

1) Synthesize the pertinent literature regarding the fundamental issues, challenges and opportunities associated with the construction of fen peatland ecosystems in a post-mining oil sands landscape, from a predominantly hydrological perspective;
2) Quantify the distribution, ablation and fate of snowmelt waters within the landforms that comprise the constructed watershed to assess the importance and role of spring snowmelt on the hydrology of reclaimed watersheds;
3) Examine the dominant controls on the soil water regimes of the reclaimed slopes in the Nikanotee Fen watershed to evaluate the hydrological role of reclaimed slopes on watershed-scale landscape reclamation; and
4) Characterize the distribution, storage and movement of water within the designed upland-fen system over the range of conditions encountered in the field.

1.2 Organization of thesis

This thesis consists of six chapters that have been structured in accordance with the manuscript option at the University of Waterloo. The introduction presented in the first chapter contextualizes the thesis topic and outlines the overall goal and specific objectives of the research. The subsequent four chapters each address one of the specific objectives and research themes outlined in chapter one.

Chapter two is a literature review-style chapter that provides an overview of the conceptual approach, underlying principles and numerical modelling used to guide the construction of the upland-fen portion of the Nikanotee Fen watershed. In doing so, this chapter also addresses the first objective of the thesis. While the focus of this thesis is on evaluating the hydrological processes operating within the Nikanotee Fen watershed, this chapter includes an evaluation of the conceptual design of a second fen watershed that was also constructed in the AOSR. Since the underlying conceptual models used to guide the design of these two fen ecosystems are quite different, the concurrent comparison presented in chapter two provides a valuable and balanced perspective of the contrasting approaches to fen creation that have been undertaken in the AOSR. This chapter also includes a review of the relevant literature necessary to fully introduce this thesis and provides the context for the subsequent chapters, which are research articles.

Chapters three to five are based on empirical data collected for this thesis. Chapter three addresses a deficient knowledge of snow hydrological processes in recently constructed systems and, thus, addresses the second objective of this thesis. Chapter four addresses the third objective of this thesis by comparing the hydrological role of two of the reclaimed slopes within the Nikanotee Fen watershed. Chapter five provides an evaluation of the hydrological performance of both the designed upland-fen system as well as the Nikanotee Fen itself, which addresses thesis objective four.

A summary of the conclusions from each of the four manuscripts is presented in chapter six. This chapter highlights the main contributions of the thesis and provides a synthesis of the recommendations for future fen creation and wetland reclamation projects.

Two appendices are located at the end of the thesis: A.1 contains a comparison of the water table dynamics at the Nikanotee Fen to three relatively undisturbed natural fen ecosystems that were selected as regional reference systems for the Nikanotee Fen; and A.2 presents the particle size distribution and organic matter content of many of the soils used to construct the various landforms within the Nikanotee Fen watershed.

2 CONSTRUCTING FEN PEATLANDS IN POST-MINED OIL SANDS LANDSCAPES: CHALLENGES AND OPPORTUNITIES FROM A HYDROLOGICAL PERSPECTIVE

2.1 Introduction

Peatland creation is a new concept, not attempted prior to the construction of the two fundamentally different fens, and their associated watersheds, on post-mined oil sands leases that are discussed in this paper. These systems were guided by different conceptual approaches. The Nikanotee Fen and watershed was based on landscape optimization through numerical modelling of an isolated upland-fen system. It was constructed within the Millennium mine lease at Suncor Energy Inc. oil sands mining operations site. The Sandhill Fen and watershed was designed to mimic the landscape position of regional, connected natural fen systems with the design being tested with numerical modelling of interactions of groundwater from adjacent landscapes. It was constructed on Syncrude Canada Limited's Mildred Lake lease. Both systems are located approximately 40 km north of Fort McMurray, Alberta. The Nikanotee Fen was constructed on an overburden dump (Daly *et al.*, 2012), whereas the Sandhill Fen was constructed on a sand-capped composite tailings deposit (Pollard *et al.*, 2012). Both system designs attempt to accelerate succession by adding peat substrate and revegetating, with the belief that the system will stabilize within decades as opposed to millennia. The unique features of each system and the implications for ecosystem function are described within this paper.

Although natural peatlands form over thousands of years (Clymo, 1983), creation of a fen peatland was considered possible if the landscape was configured to provide a hydrogeological setting that can deliver a supply of water necessary to sustain fen peatland functions (Price *et al.*, 2010; Devito *et al.*, 2012). Because it exhibits a strong control on the chemical and biotic processes operating in peatlands, hydrology is the most important process regulating wetland function and development (Mitsch and Gosselink, 2000). Generally, a basic understanding of the hydrogeological setting is required prior to developing a conceptual model and applying it to a system (Reeve *et al.*, 2000), since both the local landscape and regional topographic position can influence system function. Similarly, an understanding of the hydrologic function, both within individual systems as well as their connectivity within the surrounding constructed system, is required for constructed landscapes. However, within these landscapes, the hydrogeological setting can be designed, modified and constructed to meet the requirements of a conceptual model. The most important aspect to consider during the development of watershed designs with fen peatlands is the influence of climate (Devito *et al.*, 2005a; Devito *et al.*, 2012) and water availability to satisfy soil water storage and recharge groundwater, which is driven by the difference between precipitation (*P*) and actual evapotranspiration (*AET*) (Smerdon *et al.*, 2008). Indeed *AET* rates can be controlled to an extent through soil texture, water availability, vegetation cover and microclimatic manipulations (e.g., mulch surface cover) in constructed landscapes. However, manipulation of precipitation dynamics is unrealistic. Accordingly, fen creation must be guided by the ability to design and contour the reconstructed landscape to provide a suitable hydrogeological setting for a fen peatland under regional climatic conditions at the time of construction.

One of the major challenges facing fen creation and development in this setting is that of limited water availability in the sub-humid climate of the Canadian Western Boreal Plain (WBP), where *P* is often less than potential evapotranspiration (*PET*), and wet periods occur with a 10 to 15 year frequency. Additional challenges exist with regards to water quality in a post-mining landscape comprising a substantial proportion of oil sands tailings and saline-sodic overburden materials. In an effort to surmount these challenges, multidisciplinary teams of research scientists and engineers have developed strategies to create fen peatlands and integrate them into constructed watershed designs (Pollard *et al.*, 2012). Despite the incorporation of water and solute management strategies designed to mitigate anticipated challenges, the performance of these constructed systems is difficult to predict due to the lack of precedent.

Analysis of the initial field-based measurements of constructed fen systems is now underway. The purpose of this commentary is to present and discuss the main issues that are central to the subject of fen creation, from a hydrological perspective, in open pit post-mined oil sands environments. A brief overview of the challenges associated with water quality is included in this paper, since it is an important aspect to consider when discussing the feasibility of integrating constructed fen ecosystems into reclaimed landscapes. Further, peatland creation requires consideration of external climatic forcings and coupled internal hydrological, ecological and biogeochemical processes. However, the focus here will be on the hydrological processes and their controlling factors. The general approach is to: 1) assess the feasibility of peatland creation in a regional (WBP) context; 2) identify the underlying principles that are incorporated into the fen creation conceptual approaches; 3) discuss the suitability of the conceptual models for implementation in an oil sands environment; and 4) address the complexity of determining if these fen creation projects can be classified as a success or failure.

2.2 Suitability of regional climate

The oil sands region of Northern Alberta is within Canada's Boreal Plain ecozone (Soil Classification Working Group, 1998) where deep (20-200 m) heterogeneous glacial deposits result in a complex subsurface hydrology (Devito *et al.*, 2005a; Smerdon *et al.*, 2005; Devito *et al.*, 2012) that underlies a surficial landscape mosaic of forestlands and wetlands (predominately fen peatlands; Vitt *et al.*, 1996). In most years, *PET* exceeds *P* in the sub-humid climate of the WBP region (Bothe and Abraham, 1993; Marshall *et al.*, 1999). Regional water budgets are generally dominated by soil water storage and *AET* (Smerdon *et al.*, 2005), with runoff being strongly controlled by the combination of *P* volume and timing, in relation to available storage capacity (Devito *et al.*, 2005b; Redding and Devito, 2008). A large proportion (>70%) of annual precipitation occurs in the summer, usually as short-duration, convective-cell storms that rarely exceed 10 mm (Smerdon *et al.*, 2005). The synchronization of summer rainfall and peak evapotranspiration demand greatly reduces the potential for runoff generation (Devito *et al.*, 2005b), and often the available soil water storage capacity is sufficient to hold most of the mid-summer precipitation inputs (Redding and Devito, 2008). However, soil water storage deficits are reduced or eliminated during wet periods that occur approximately every 10 to 15 years (Devito *et al.*, 2005b; Mwale *et al.*, 2009).

Consequently, one of the major challenges of creating and establishing fens in this setting is that of limited water availability. Many fen peatlands in the WBP are isolated from hillslope and groundwater inputs in topographically high positions (Riddell, 2008). These hydrologically isolated fens function mostly with internal control of soil moisture and water conservation mechanisms, such as decreased *AET* rates and seasonally persistent ground frost, that limit water lost from storage (Devito and Mendoza, 2007; Petrone *et al.*, 2007; Kettridge and Waddington, 2014; Waddington *et al.*, 2015). In addition to these internal mechanisms, fen peatlands at lower topographic positions may rely upon a combination of ground and surface water inflows to sustain water levels necessary for peatland function (Ingram, 1983). This characteristic makes fens an attractive candidate for peatland creation since the construction of a suitable local geomorphic setting can help mitigate regional climatic factors (i.e., dry conditions) by providing the requisite topographic setting, surface and groundwater flow to sustain hydrological, biogeochemical and ecological processes and functions within the constructed fen peatland. However, water requirements of natural fen ecosystems vary across a broad range that depend upon a combination of fen type (e.g., poor versus rich fen), prevalent climatic conditions (e.g., cool/moist versus warm/dry), dominant vegetation cover (e.g., vascular versus non-vascular) and internal water storage and retention dynamics (including ground frost). As such, the requisite natural (i.e., not artificially supplemented) water input for constructed fen ecosystems has yet to be determined (Price *et al.*, 2010). Furthermore, the timing of construction in relation to the 10 to 15 year climatic cycle may impact the critical successional period in the first few years post-construction. For instance, a system constructed within a dry period would face greater challenges in sustaining a sufficient level of moisture to support peatland processes than a system constructed at the start of a wet period.

Accordingly, a suitable water balance within the numerical modelling-based Nikanotee Fen design was based on vegetation-related threshold moisture conditions established within peatland restoration research literature (Price and Whitehead, 2001). In contrast, the conceptual design of the Sandhill Fen was initially more strongly guided by an empirically based understanding that attempted to mimic the conditions observed in natural ecosystems. The rationale was that this natural landscape design had proven suitable for long-term fen existence in the sub-humid WBP in a range of hydrogeologic conditions representative of the AOSR (Devito *et al.*, 2012). After the initial design for the Sandhill Fen watershed had been characterized, numerical modelling was performed to (a) confirm that adequate water from precipitation would be available for the fen over future years and (b) analyze the movement of salts from neighboring tailings deposits (Wytrykush *et al.*, 2012). Nevertheless, the climatic conditions (i.e., surplus or deficit) during the first few years after construction will have a substantial impact on the performance of each of the fen systems.

2.3 General approach to fen creation

The Sandhill Fen conceptual design is based on research on the function and maintenance of WBP fen peatlands (e.g., Ferone and Devito, 2004; Devito *et al.*, 2005b; Smerdon *et al.*, 2005; Petrone *et al.*, 2007; Petrone *et al.*, 2008; Redding and Devito, 2008; Smerdon *et al.*, 2008; Brown *et al.*, 2010; Petrone *et al.*, 2011; Devito *et al.*, 2012; Brown *et al.*, 2014; Petrone *et al.*, 2015) where local wetland systems and adjacent forestlands exchange water symbiotically in accordance with the prevailing moisture conditions (i.e., wetlands supply the forestlands with water under dry conditions, and vice versa during wet cycles), both in the absence and presence of large scale groundwater flows. As such, the construction design of the Sandhill Fen incorporates a series of local topographic upland areas (referred to as hummocks), ephemeral draws and perched fens that border a low-lying fen system (Figure 2-1). This design was guided by evidence that local to regional groundwater flows represent important contributions to the water budget in natural wetlands situated in topographically low portions of flow systems within coarse-grained deposits (Smerdon *et al.*, 2005).

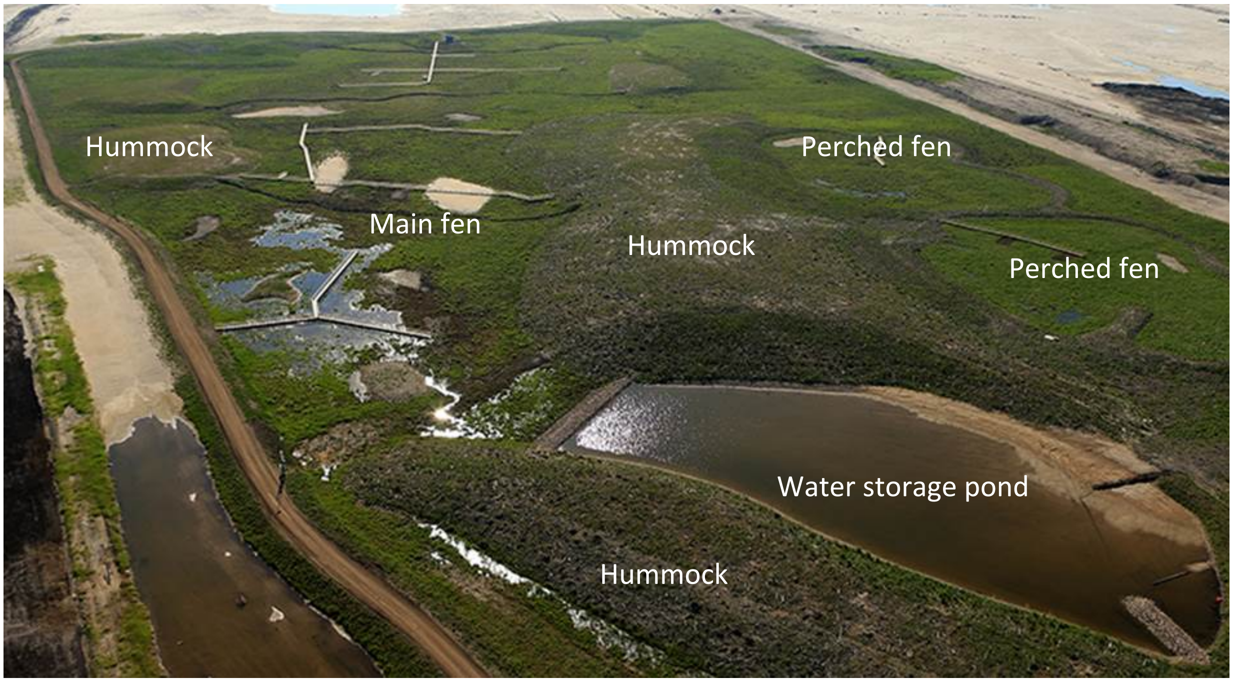

Figure 2-1 - Aerial view of the Sandhill Fen. Image provided by Syncrude Canada Ltd.

An adjustable weir was installed at the outflow of the constructed system to accommodate surface discharge from the fen. The hummocks and ephemeral draws are designed to provide storage and periodic local groundwater recharge and surface flow, respectively, to the adjacent fen system. However, two hummocks were removed from the original design of the Sandhill Fen during the construction phase due to limited availability of suitable materials for construction. Similarly, the hummocks that remained in the system were smaller (lower material volume) than originally intended and designed. Nevertheless, a water storage pond located at the headwater portion of the watershed was included to provide an initial experimental control on the surficial inflows. Underdrains were also included in the design as an experimental water (and solute) management strategy. Both the water storage pond and underdrains were designed for experimental manipulation and were never intended to be a part of a true reclamation scenario (Pollard *et al.*, 2012). The Sandhill Fen is described in greater detail in Wytrykush *et al.* (2012) and Pollard *et al.* (2012).

The conceptual approach adapted in the Sandhill Fen attempts to mitigate the water deficit of the sub-humid climate through the application of natural landscape design analogues (Devito *et al.*, 2012) with basic water balance and regional groundwater modelling. In the absence of reliable runoff from adjacent uplands in natural systems (Devito *et al.*, 2005b), larger scale groundwater flows are the likely mechanism that supplies water for the maintenance of natural wetlands on coarse permeable deposits during periods of drought (Smerdon *et al.*, 2005; Devito and Mendoza, 2007; Devito *et al.*, 2012). In the constructed system, hummocks were designed to recharge local aquifers and supply groundwater to the low-lying fen system, as well as to support forests that obtain water from these low lying wetlands. Local groundwater systems fluctuate on timescales much longer than surficial systems, which rapidly respond to climatic conditions (Smerdon *et al.*, 2008). Thus, incorporating localized groundwater flow systems into the conceptual design (via hummocks) reduces the susceptibility of the forestlands and wetlands to drought. Furthermore, the hummocks represent water storage mechanisms analogous to the enhanced water storage of geological materials observed in natural settings (Redding and Devito, 2010). Additionally, natural peatland systems within the WBP possess storage mechanisms that contribute to their ability to survive during periods of water deficit (Devito and Mendoza, 2007; Devito *et al.*, 2012) and three-dimensional structures that limit evapotranspiration losses (i.e., canopy architecture and sheltering by adjacent forests; Petrone *et al.*, 2007; Brown *et al.*, 2010). The presence of thick and seasonally persistent ground frost into late summer contributes to constrained water losses from the natural peatland systems by restricting *AET* rates (Petrone *et al.*, 2008; Brown *et al.*, 2010). However, ground frost dynamics will likely differ in constructed fen systems, owing to the increased bulk density of peat soils following transportation and placement (Nwaishi *et al.*, 2015b) as well as the thermodynamic interaction with the underlying tailings materials. Regardless, the water conservation mechanisms caused by persistent ground frost, although not necessarily by design, will increase the ability of the constructed system to constrain water losses.

Unlike the approach of the Sandhill Fen system that was initially based on natural analogues and later supported by modelling, the design of the Nikanotee Fen was guided largely by numerical modelling and supported by experience in natural WBP systems. The design approach (described in greater detail by Daly *et al.*, 2012) was to provide an upland aquifer system constructed from materials with suitable hydraulic properties to conduct groundwater flow under an imposed hydraulic gradient (via sloping topography) to a fen peatland located at the base of the upland slope (Figures 2-2 and 2-3). Price et al. (2010) applied a numerical model to the conceptual design to examine the hydrological conditions and system geometries required to sustain hydrologic conditions in the fen system within a range deemed suitable for survival of fen vegetation, specifically non-vascular mosses (Price and Whitehead, 2001). This modelling work was based on the regional historical climate record (1940 to 2004) and incorporated several drought cycles of differing degrees of severity (Price *et al.*, 2010). The optimized system from the modelling formed the specifications of the Nikanotee Fen construction plan (Daly *et al.*, 2012), which has been implemented in a field setting. The Nikanotee Fen design is also described in Pollard *et al.* (2012). The designed fen-upland system is situated within a larger watershed that includes additional reclaimed and natural slopes (Daly *et al.*, 2012). Although these previously reclaimed slopes are not explicitly relied upon for the contribution of water to the designed fen-upland system, downslope movement of water from similar reclaimed slopes has been observed (Kelln *et al.*, 2006; Meiers *et al.*, 2006; Kelln *et al.*, 2007). This could provide a supplementary contribution of water to the constructed fen system, at least in early stages of forest succession. During the spring freshet, most snowmelt water typically flows off reclaimed slopes as surface runoff (Kelln *et al.*, 2009). There is potential for this to represent an important source of water for constructed wetlands, provided that it is properly managed (i.e., excess water stored appropriately within the landscape). However, snowmelt dynamics remain poorly understood in these landscapes.

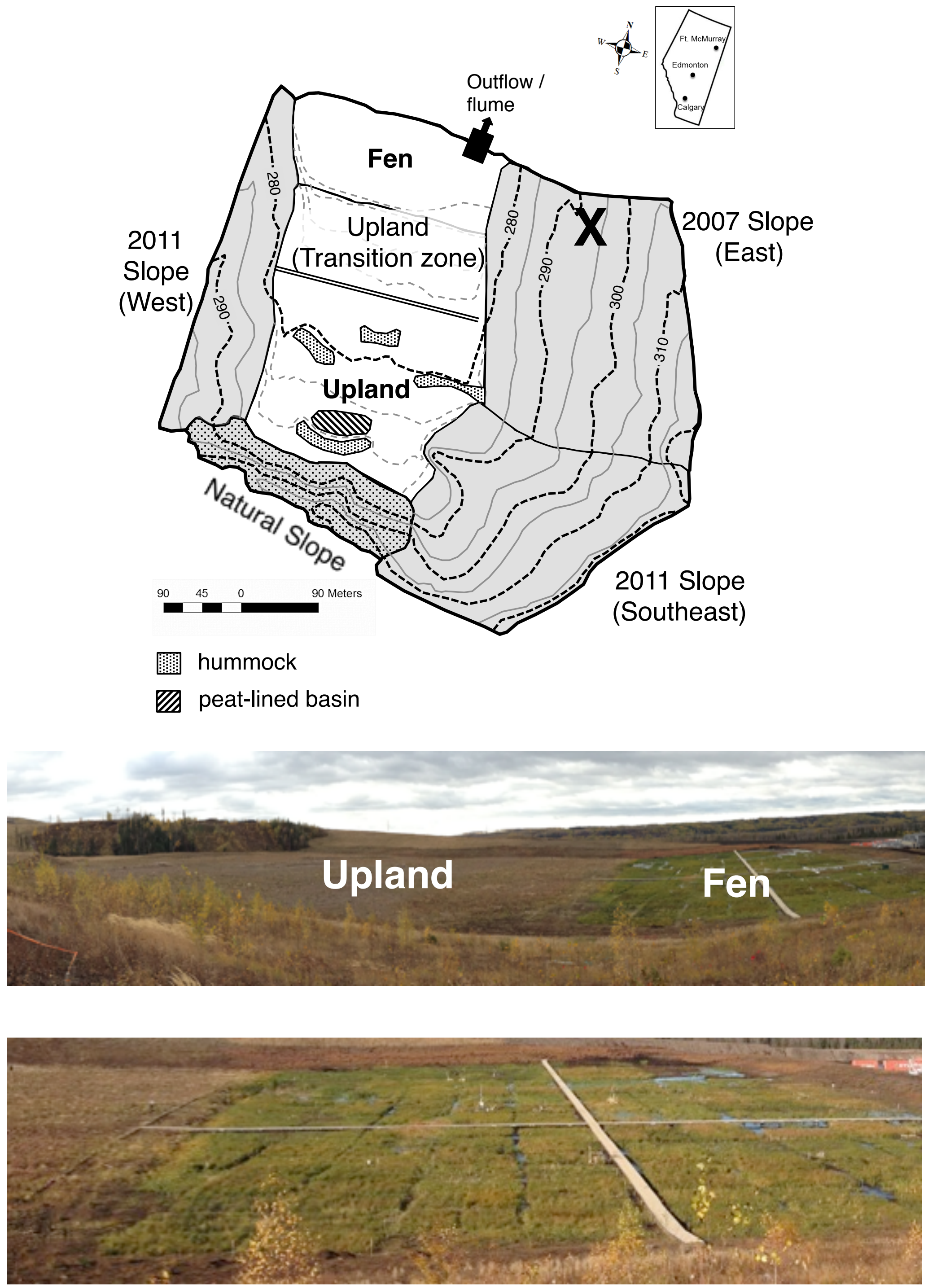

Figure 2-2 - Map and view of the Nikanotee Fen. The photographs were taken facing west from the “X” on the map.

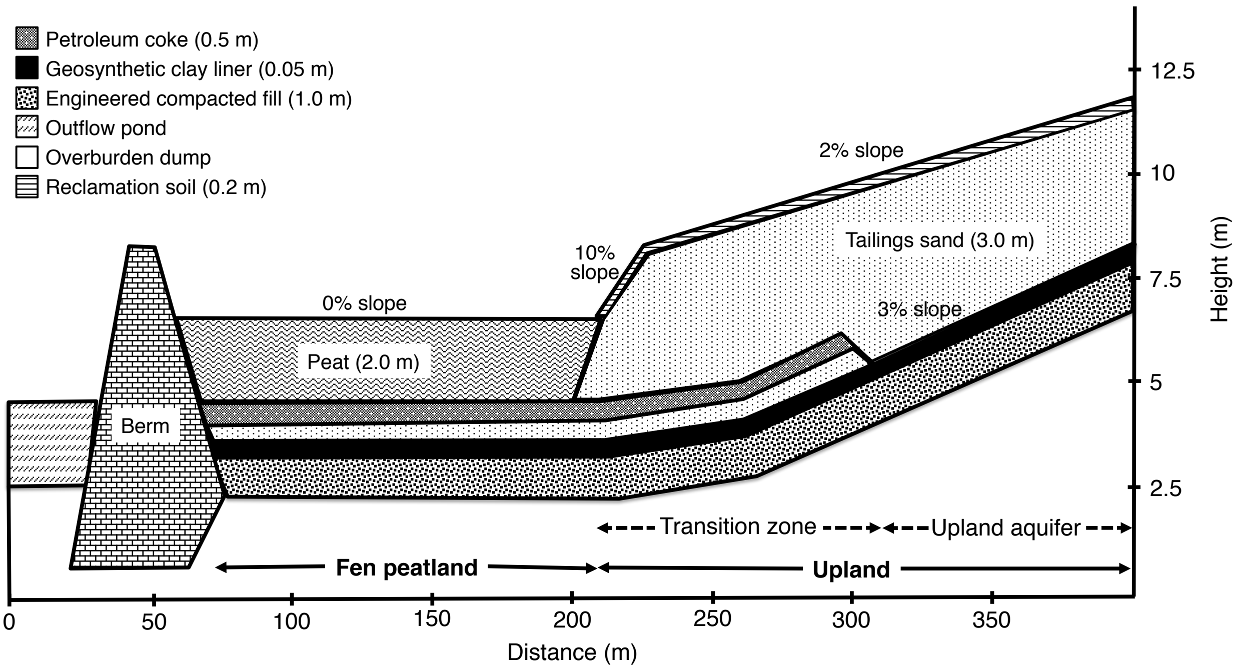

Figure 2-3 - Cross-section of the Nikanotee Fen watershed. The thickness of each layer is indicated in parentheses. Note that the thickness of the liner in the diagram is not to scale (shown thicker than the ~0.05 m actual thickness)

The underlying principle incorporated into the Nikanotee Fen conceptual design is that of hillslope runoff generation. In humid and steep environments, this typically comprises vertical flow to a confining layer (usually relatively impermeable bedrock) followed by lateral flow along the confining layer (Buttle and McDonald, 2002; Tromp-van Meerveld and McDonnell, 2006). Similarly, percolating water (i.e., vertical flow) will recharge the saturated zone within the upland aquifer material situated atop a basal geosynthetic clay liner in the constructed system (Daly *et al.*, 2012).

The moisture conditions within the Nikanotee Fen system are directly related to the ability of the upland aquifer to provide suitable discharge to the fen. However, the entire constructed system was situated within a much larger watershed as an important strategy to mitigate the possible impact of years with water deficits. Such an approach needs to be considered in mine closure landscape designs (Ayres *et al.*, 2006). Furthermore, considering the importance of water availability on the processes operating within these systems, more research is needed to determine the significance and partitioning (e.g., between surface runoff and groundwater recharge) of water stored within the over-winter snowpack in constructed landscapes.

2.4 Issues related to water quality

In addition to the issues regarding water quantity in a sub-humid climate, another major challenge facing fen creation is that of water quality. Oil sands process-affected tailings materials contain chemicals including naphthenic acids (NAs), hydrocarbons, salts (specifically, the cation sodium (Na^+)), heavy metals and organic acids (Scott *et al.*, 2005; Rezanezhad *et al.*, 2012a). Of particular concern are elevated salinity levels (Purdy *et al.*, 2005) because of the toxic effect on non-halophilic wetland vegetation (Renault *et al.*, 1998; Renault *et al.*, 1999; Trites and Bayley, 2005). Preliminary modelling in the Nikanotee Fen (unpublished) indicates that solute transport from the uplands (comprising tailings sand) into the fen peat is expected to increase the salinity of near-surface porewater in the fen. Conversely, the Sandhill Fen watershed was constructed from both tailings and clean-fill sand; however, the entire system is situated atop saline composite tailings. The concern in the Sandhill Fen system is the upwards transport of high salinity waters from the underlying tailings materials into the fen system, similar to the upward flux of saline sodic waters observed on reclaimed soil covers capping overburden materials (Kelln *et al.*, 2006; Kelln *et al.*, 2009; Kessler *et al.*, 2010). Daly *et al.* (2012) outline several important modifications that were made to the original Nikanotee Fen watershed design to meet site-specific conditions. Several of these were added to mitigate the susceptibility of the system to salinization. For example, the thickness of the upland sand aquifer was altered to limit ET to the atmosphere. Also, a new layer was added under the fen that extends partway upslope to preclude groundwater (and salts) from discharging at the upland-fen interface (constructed using petroleum coke and referred to as the 'underdrain' layer).

Na^+ and NAs are readily transported through sand/gravel aquifers, with only slight attenuation beyond dispersive dilution (Gervais and Barker, 2005). Within peat soils, solute transport processes are largely governed by the influence of groundwater flow on the rate of solute dispersion and removal by chemical, physical and microbial processes (Hill and Siegel, 1991; Hoag and Price, 1995; Todorova *et al.*, 2005). Recently, Rezanezhad *et al.* (2012b) documented substantial delays in the transport of Na^+ and NAs through peat columns due to sorption and diffusion into immobile water within dead-end pores (i.e., pores that do not contribute to water flow) within the peat matrix. Nonetheless, the negative effect that elevated salinity levels have on the survival of fen vegetation (Trites and Bayley, 2009) remains a concern. However, vegetation present in salt marshes is able to tolerate both saline and waterlogged conditions (National Wetlands Working Group, 1997) and typical fen gramminoid (vascular) vegetation can tolerate concentrations of ~385 mg l^{-1} of Na^+ and ~40 mg l^{-1} of NAs when exposed to oil sands process affected water (Rezanezhad *et al.*, 2012a). Mosses, however, are more susceptible to the presence of solutes, especially when they acquire water via capillarity from the underlying peat soil (Rezanezhad *et al.*, 2012a). The vegetation strategy for the Nikanotee Fen included targeting more salt-tolerant species (see Daly *et al.*, 2012), which should help to further mitigate the negative impact of potentially elevated salinity on vegetation survival.

Vegetation cover can also influence the distribution of Na^+ and NAs in constructed peat profiles via controls on ET. For example, increased ET rates and root water uptake from peat soils dominated by vascular vegetation cover resulted in an increased upward migration of both Na^+ and NAs in comparison to a moss-dominated vegetation cover in a recent greenhouse mesocosm experiment (Rezanezhad *et al.*, 2012a). The lower evaporation rate from the moss vegetation and lack of root water uptake resulted in a sequentially delayed increase in solute concentration at higher elevations in the peat profile. *Sphagnum* moss has been shown to reduce evaporative water losses from the surface of an underlying (cutover) peat soil (Price and Whitehead, 2004), as *Sphagnum* that is not saturated is an inefficient evaporating surface (Price, 1991). Similarly, reduced evapotranspiration rates from moss-covered surfaces could decrease vertical solute transport rates in the constructed fen. However, mosses showed a considerable decline in health with increasing surface solute concentrations (Rezanezhad *et al.*, 2012a), indicating a lowered probability of moss survival in the constructed fen systems.

2.5 Connectivity in natural and constructed landscapes

The topography of the WBP region is relatively flat but can be locally variable (Fenton *et al.*, 1994). On the regional scale, the surface of the underlying sedimentary bedrock (the pre-Quaternary unconformity) is complex, as it is an erosional setting that consists of relicts of paleo-river systems and isolated upland remnants that have been modified by glacial and fluvial processes (Andriashek, 2003) that produced deep (20-200 m) surficial deposits (Devito *et al.*, 2005a). The majority of the dominant hydrological processes occurring within the WBP on a relevant time scale are constrained to these highly heterogeneous glacial deposits and landforms with differing water storage and transmission properties. Different conceptual and numerical modelling approaches may be required on different landforms. Thus, the traditional concept of topographic control on watershed hydrology does not necessarily apply across the landscape (Devito *et al.*, 2005a; Smerdon *et al.*, 2005). The design of the Sandhill Fen was based on replicating the hydrology typical of coarse textured glacial-fluvial landscapes. Thus, it appears to be well-suited for the hummock and swale topography that is designed for most tailings-sand storage areas within the post-mining landscape (BGC Engineering Inc., 2010), since changes in slope or heterogeneities in the subsurface geology (tailings materials) should favour the formation of localized discharge areas (cf. Ferone and Devito, 2004). Further, the texture of materials used to reconstruct these landscapes will be of similar texture to those found in natural WBP systems (Devito *et al.*, 2012; CEMA, 2014). Nonetheless, the efficacy in which these materials are manipulated and placed will improve with an increased understanding of these systems.

The Nikanotee Fen watershed was constructed on, and is hydrologically isolated from, a fine textured overburden dump (Daly *et al.*, 2012; Pollard *et al.*, 2012). However, many constructed wetlands will be located on seepage discharge zones on tailings sand beaches (BGC Engineering Inc., 2012) with stronger landscape connectivity than the current (pilot-scale) Nikanotee Fen. Nonetheless, since future wetlands could receive water discharging from tailings sand materials, the upland aquifer within the Nikanotee Fen watershed design was constructed from tailings sand materials. Since the current Nikanotee Fen design relies heavily upon sufficient recharge from the upland aquifer, it is intended to be less reliant on the broader landscape connectivity that was an integral part of the Sandhill Fen design. Given the larger scale of future reclamation, integration and connectivity of landscape units should be incorporated into designs.

Johnson and Miyanishi (2008) and Devito *et al.* (2012) suggest an integrated landscape scale reconstruction of the post-mining oil sands landscape is essential, since recompiling isolated and fragmented systems is not likely to restore ecosystem function (Choi *et al.*, 2008). Although the simple concept of catchment area as a first-order control on discharge does not always apply in the WBP region (Devito *et al.*, 2005a; 2005b), the reconstructed watersheds will have more distinct catchment areas than most natural WBP settings. Nevertheless, some similarities will exist between the reconstructed geological substrata and the thick glacial deposits of the undisturbed WBP landscape, with respect to soil textures and the presence of layered materials with distinct hydrophysical properties.

In constructed systems, connectivity of individual landscape components would complement the incorporation of fen systems into closure plans. This should create areas more prone to consistently saturated conditions by increasing the cumulative upslope area contributing to depressional areas situated in the lower portion of the larger (i.e., regional) watershed. If properly integrated into the catchment design, wetlands and ephemeral draws could play an important landscape connectivity role whereby they could serve as important storage mechanisms during large, convective storms common to the WBP, while representing sources of water for the adjacent landscapes during dry periods. From this perspective, peatlands could be used to conserve water within the landscape through their inherent water storage mechanisms rather than solely be the recipient of water. Research in natural WBP landscapes has demonstrated that fen peatlands can function as a source of water to adjacent forestlands, even if these fen systems are isolated from groundwater inputs (Riddell, 2008; Thompson *et al.*, 2015). Accordingly, future landscape construction design plans would benefit from integrating fen peatlands within the catchment as mechanisms of landscape connectivity and potential water sources instead of designing catchments solely to supply water for the fens (see Devito *et al.*, 2012). The formation of several 'opportunistic' (i.e., unplanned) marsh and shallow open water wetlands in both low-lying and topographic high, flat fine textured areas within reclaimed landscapes (CEMA, 2014) demonstrates that incorporating fen peatlands into closure plans is possible. Gross drainage area may act as a reasonable metric to predict the probability of wet conditions within reconstructed landscapes at an ecosystem scale, although the establishment of more mature upland forest trees will reduce water availability. Nonetheless, this metric (gross drainage area) could assist planners and engineers in identifying portions of a landscape that are well-suited for the maintenance of targeted constructed wetland forms, including fen peatlands.

2.6 Fen proportions

Another challenge facing fen peatland construction are constraints imposed by the post-mining landscape (Rooney *et al.*, 2012). The inclusion of end-pit lakes in many closure plans results in a materials surplus, where the volume of tailings sand and overburden materials exceeds the size of mine pits. Consequently, the closure landscape will have a complex hilly topography instead of the relatively flat pre-mining landscape, which could restrict wetland habitats to the low-lying areas. Rooney *et al.* (2012) also contend that, if the suggested minimum ~2:1 (3:1 is optimal) upslope to fen peatland ratio determined in the numerical modelling simulations for the Nikanotee Fen design (Price *et al.*, 2010) proves to be accurate, then recreating a landscape with the same pre-disturbance proportion of wetland ecosystems (~50%; Vitt *et al.*, 1996) is not possible. However, the actual upslope: fen ratio is influenced by the hydraulic conductivity of the basal liner and upland aquifer materials, not solely the proportion of upland and fen (Price *et al.*, 2010). In addition, the presence of healthy fen peatlands in the sub-humid climate of the WBP, often in the absence of water contributions from groundwater and adjacent hillsopes (Riddell, 2008; Smerdon *et al.*, 2008), suggests that upland water contribution is not the sole determinant responsible for the maintenance of fen peatlands in this setting (Devito and Mendoza, 2007). Enhanced water storage mechanisms and constrained *AET* rates outlined earlier also contribute to the maintenance of fen peatlands during periodic water deficits (Petrone *et al.*, 2007; Brown *et al.*, 2010). These factors contribute to the dominance of wetland ecosystems in natural WBP landscapes where wetlands can cover more than 50% of the landscape (Vitt *et al.*, 1996; Devito, unpublished data). Integrating fen peatlands throughout the catchment should increase landscape connectivity and alleviate the constraint of the post-mining landscape. Thus, it stands to reason that the minimum upland: fen ratio requirement for fen creation in the WBP setting is much less than 2:1 and ratios of less than 1:1 should be sustainable. Targeted placement of fens in areas prone to wet conditions (indicated by gross drainage area) should help to alleviate concerns associated with upland: fen ratios in closure landscape designs.

2.7 Success or failure?

Often times, defining success requires that criteria be established *a priori*, preferably as quantifiable values; however, the Nikanotee and Sandhill fen systems represent the first attempts to create fen peatlands in a post-mining oil sands setting, which eliminates the possibility of using information from past projects to establish goals. The development of the conceptual models was based in part on an understanding of the function of regional fen peatlands as well as the influence of the landscape setting on groundwater interactions under regional climatic controls. As such, functional equivalence may be determined by comparison with regional reference systems, and success defined by this comparison (Lewis, 1990). In the constructed fen system, components integral to the function of the system (i.e., hydrology, water quality, micrometeorology, carbon cycling, microbial processes and ecology) will be characterized using independent metrics that must ultimately be combined into an integrated functional framework to facilitate this comparison (Carey and Petrone, 2014). Nwaishi *et al.* (2015a) have proposed use of a functional-based approach to guide the evaluation of constructed peatlands that includes an evaluation of quantifiable variables (e.g., peat hydraulic properties, vegetation diversity, microbial activity, greenhouse gas fluxes) as functional indicators of ecosystem condition. This type of approach should be adapted into a standard framework for evaluating these constructed ecosystems.

Mitsch and Wilson (1996) identify three fundamental requirements for achieving success of wetland creation: understanding wetland function; giving the system time; and allowing for the self-designing capacity of nature. To properly determine the success of ecosystem creation, an understanding of the fundamental processes responsible for the desired ecosystem characteristics is required. In peatlands, the hydrology and water use efficiency largely determines the type of vegetation present and controls the rates of photosynthesis and decomposition, which consequently modifies the system hydrology as the accumulation of plant materials forms the matrix within which water flows (Waddington *et al.*, 2009). Accordingly, ecological, biogeochemical and hydrological processes are inextricably linked in peatland ecosystems. As such, a holistic, integrated ecosystem approach is a requisite for the ability to declare "success" or "failure" of the constructed fen peatlands and to understand their potential resilience in a larger framework (Waddington *et al.*, 2015).

There are, however, several additional facets of success to consider within the context of oil sands reclamation. For example, government approval and certification of reclaimed land could be viewed as a success. From an industry perspective, in addition to certification of the constructed landscape, success could broadly include logistical and financial feasibility of constructing fen systems at an operational scale, satisfying mine closure planning goals and regulatory commitments and effective transfer of technology for future fen creation (BGC Engineering Inc., 2012). Clearly, the perception of "successful" peatland creation varies greatly across the range of involved parties. Accordingly, it is necessary to maintain realistic goals and consider probable outcomes as well as the logic for deeming them successes or failures.

The intention of the fen watershed designs was to reduce the length of time required to establish wetland process and function by providing the suitable hydrogeological setting and the fen peat substrate upon which a vegetation community could be established (Price *et al.*, 2010). Based on experience from peatland restoration in Eastern Canada, an optimistic estimate to achieve a vegetation cover that possess natural functions (i.e., acrotelm) is nearly two decades (Lucchese *et al.*, 2010); however, these restored peatland sites are able to return to a net carbon sink within 6 to 10 years post-restoration (Waddington *et al.*, 2010). At this point, there is much uncertainty associated with predicting the amount of time it will take to develop an understanding of the function and trajectory of constructed ecosystems. Since peatland restoration and creation/reclamation are different (Daly *et al.*, 2012), and wet periods occur approximately every 10 to 15 years in the WBP, it is difficult to provide an accurate assessment of the system trajectory on time periods of less than 10 to 20 years. The system design attempts to accelerate succession by adding the peat substrate and revegetating, with the belief that the system will stabilize within decades as opposed to millennia. The short timeframes that often constrain research projects (e.g., five years) is sufficient to characterize a range of processes operating on the system. However, relatively rapid changes in the soil properties (Meiers *et al.*, 2011), biogeochemical conditions and vegetation development and succession (CEMA, 2014) on a timescale less than regional climate cycles, leaves considerable uncertainty as to the system's trajectory. Monitoring on a longer timescale is needed to indicate if the system is on the right successional pathway. Nevertheless, the detailed understanding of our ability to recreate fundamental conditions and control processes, in a relatively short time-frame, can provide insights that are immediately transferable to ongoing reclamation designs.

The declaration of success, from an ecosystem creation perspective, should be shifted away from an attempt to replicate natural systems identically and towards assessing our ability to design a system that exhibits a hydrologic regime (i.e., maintain water levels/wetness) within a range of expected values that are deemed as suitable for the survival of a select community of vegetation while operating at a sufficient efficiency to leave enough water for other landscape types at the catchment scale. This is because peatlands may take millennia to form and, as such, the hydrology of the constructed system is the key to understanding if the system will be viable over the longer term. Furthermore, design modifications are possible as projects progress from concept to design to operational construction (Daly *et al.*, 2012). For example, availability and proximity of suitable construction materials (volume and properties) could result in alterations to the original design. Under these circumstances, expectations for system function may need to be adjusted relative to the original goals based on the operational design modifications.

Natural analogues appear as a compelling choice to provide a standard range in ecohydrological conditions upon which the fen construction success and trajectory can be assessed. Although natural analogues are required to guide fen creation design, realism is required for their use in evaluating newly created systems. The post-mining landscape provides a clean slate for scientists and engineers to apply our cumulative fundamental knowledge of ecosystem behaviour through combining engineering and ecosystem design approaches into practice, in an effort to create an ecosystem that otherwise would take decades to millennia to develop under the self-design of nature alone (Gorham, 1957; Clymo, 1983; Beven *et al.*, 1988). The design of the two fen systems was inherently and intentionally experimental (Pollard *et al.*, 2012) to maximize the advancement of fen creation proficiencies by constructing systems that were conducive to characterization of the dominant processes within these ecosystems. The science produced from these projects will be invaluable in informing future fen creation efforts. In practice, success should include a quantitative assessment of our ability to replicate what we developed conceptually. The consequences of deviations from design must be quantified to facilitate the integration of this new knowledge into future designs.

2.8 Conclusions

Fen peatlands have now been constructed in post-mined oil sands landscapes. Although their long-term viability remains unknown, the experience and knowledge gained will provide the solid foundation required to guide and improve the design and construction of future fen peatlands. For both the Nikanotee and Sandhill fens, lack of prior experience required that conceptual design development be based on the culmination of peatland and hydrologic science. Issues related to water quality and quantity represent major challenges, and will be defined by the interactions between the components of the water budget, the storage properties of the watershed and the hydrogeological setting within which the fen is situated. Mitigation structures have been incorporated into the constructed systems in an effort to alleviate some of these challenges; however we are only now learning the efficacy of these measures. Climate is a strong control on the health and trajectory of the constructed system, as it governs the availability of water and broadly defines limits on the relative roles of frost, water storage and vegetation water demand, the culmination of which will determine water relations in the constructed system. Hence, the design and construction of a fen watershed must provide conditions suitable for the maintenance of a fen ecosystem within variable climactic conditions. Ongoing, long-term monitoring and research within these constructed systems is necessary to understand how the systems evolve over time and to guide any necessary interventions in the future. An adaptive approach should be employed when designing future constructed fen peatlands that assimilates the knowledge developed in the current research and the information attained over the longer-term to guide the design of future fen systems. From an ecosystem creation perspective, discernment of successes should focus on our ability to design and construct systems that exhibit predictable and desirable characteristics of a healthy fen ecosystem. Then, we wait.

2.9 Acknowledgements

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3 SNOW HYDROLOGY OF A CONSTRUCTED WATERSHED IN THE ATHABASCA OIL SANDS REGION, ALBERTA, CANADA

3.1 Introduction

Oil sands extraction in the Athabasca Oil Sands Region (AOSR) requires landscape reclamation on an unprecedented scale. The amount of water available to recharge constructed aquifers within the post-mined landscape is largely controlled by the regional climate (Devito *et al.*, 2005a; Devito *et al.*, 2012). The AOSR is located within the Western Boreal Plain (WBP) region of Canada, where the climate is sub-humid (Bothe and Abraham, 1993; Marshall *et al.*, 1999) and, thus, groundwater recharge is often constrained by limited water availability. Based on the 30-year climate normal (1981 - 2010), approximately 25% of the average annual precipitation (*P*; ~419 mm) falls as snow (Environment Canada, 2011). Snowmelt and early spring rainfall are important contributions to annual groundwater recharge on some WBP landforms (Smerdon *et al.*, 2008); though, the probability of rainfall in the late summer and fall is low, which results in low soil water content (i.e., high soil water storage capacity) prior to freezing and limited spring snowmelt runoff response in natural settings (Devito *et al.*, 2005b). However, reclaimed landscapes have a distinctly different hydrological regime than the former natural landscape (Elshorbagy *et al.*, 2005). Hence, the development of effective water management strategies within reclaimed landscapes must explicitly address the influence of the regional climate and the impact of the timing and magnitude of water fluxes on an annual basis. Yet few studies have characterized the distribution of snow and, thus, the storage of winter precipitation in reclaimed oil sands landscapes and constructed ecosystems.

In addition to the regional climate, the storage properties of the reclamation soil materials also influence the availability of water for aquifer recharge. Many reclamation soil covers are designed to maximize available water holding capacity for vegetation growth and to minimize seepage into deeper soil layers (Meier and Barbour, 2002; Shurniak and Barbour, 2002; Meiers *et al.*, 2006; Carrera-Hernández *et al.*, 2012). Consequently, downslope interflow from surface mine waste deposits reclaimed using typical soil cover prescriptions occurs infrequently during the summer months (Kelln *et al.*, 2006) and reclaimed slope landforms are largely considered water storage features in the reconstructed landscape. Furthermore, the importance and magnitude of snowmelt period recharge to constructed aquifers remains unclear. Kelln *et al.* (2009) observed a time-lag of approximately one month between the completion of snowmelt and the onset of interflow on a reclaimed slope. However, a rapid response in reclamation soil cover volumetric water content (*VWC*) to snowmelt water has also been documented (Meier and Barbour, 2002) and snowmelt recharge can be considered an important source of water for sustained plant growth throughout the summer period (Carey, 2008). In natural settings in the WBP, the partitioning of snowmelt water between infiltration and runoff is a complex process owing to several dynamic controls, such as the timing of snow cover and rate of snowmelt (Ireson *et al.*, 2015). However, during the snowmelt period in constructed landscapes, the majority of water stored within the snowpack on reclaimed slopes is conveyed downslope as surface runoff (Kelln *et al.*, 2009). Thus, low-lying landforms within constructed landscapes could receive large influxes of water from adjacent reclaimed slopes during the spring freshet. Despite these observations, there has yet to be a comprehensive assessment of the snow distribution and snowmelt period hydrology in constructed systems and, thus, little is known about snowmelt dynamics in reclaimed landscapes.

In reclaimed landscapes, soil characteristics and vegetation cover evolve with time since the completion of reclamation. The accumulation and ablation of the snowpack could be influenced by the presence (or absence) and structure of a vegetation cover (Pomeroy *et al.*, 1998a; Storck *et al.*, 2002; Pomeroy *et al.*, 2006; Boon, 2009; 2011; Ketcheson *et al.*, 2012), as well as surface topography within the reclaimed landscape (Carey and Woo, 1999; Redding and Devito, 2011). Considering the importance of water availability in the planning and design of reclaimed mine closure landscapes in the sub-humid climate of the WBP, it is critical to quantify the partitioning of snowmelt water between surface runoff, soil water storage and groundwater recharge in constructed landscapes during the snowmelt period. The current deficiency of information on these processes in reclaimed landscapes must be addressed. As such, the goal of this study is to quantify the distribution, ablation and fate of snowmelt waters within constructed ecosystems to assess the importance and role of spring snowmelt on the hydrology of constructed watersheds. Specifically, this research aims to identify the controls on snow distribution and ablation and to quantify the partitioning of snowmelt water (to surface runoff, soil storage and/or groundwater recharge) within a constructed watershed comprising a valley-bottom wetland and a variety of upland reclamation slopes of different age and character.

3.2 Study site

This study was conducted in a constructed watershed (the Nikanotee Fen watershed) within the Millennium mine lease at Suncor Energy Inc. oil sands mining operations approximately 40 km north of Fort McMurray, Alberta (56°55.944'N 111°25.035'W; average watershed elevation ~288 masl; Figure 3-1). In the constructed system, fen peat from newly developed lease areas was placed at the toe of an upland aquifer (~3% grade towards the fen) designed to supply the requisite groundwater flow to sustain fen processes and functions. The numerical modelling and final watershed design are described in detail by Price *et al.* (2010) and Daly *et al.* (2012). The designed fen (2.9 ha) and upland (7.7 ha) system is situated within a larger watershed (total watershed area = 32.1 ha) that includes three previously reclaimed (hence also constructed) slopes of varying age and a natural remnant slope (Figure 3-1). Thus, the upland-fen system is positioned within a gently sloping valley bottom surrounded by the relatively steep reclaimed slopes. The east slope (8.1 ha) was reclaimed in 2007 (soils placed) and has a well-established vegetation cover (vegetated in 2008) relative to the southeast (8.2 ha) and west (2.4 ha) slopes, which were both reclaimed in 2011 (soils placed) and vegetated in 2012. Planting on the slopes was guided by the Cumulative Environmental Management Association (CEMA) Revegetation Manual (Alberta Environment, 2010). Dominant tree species included white spruce (*Picea glauca*), aspen (*Populus tremuloides*), white birch (*Betula papyrifera*), green alder (*Alnus viridis*), and planting schemes also included an assortment of shrubs (e.g., Saskatoon berry (*Amelanchier alnifolia*), pincherry (*Prunus pensylvanica*) and chokecherry (*Prunus virginiana*)). The average height of the vegetation canopy on the east slope was ~1.5 m (range = 0.3 to > 4.0 m height), while it was only 0.8 (range = 0.2 to 1.4 m height) on the west and southeast slopes. The fen and upland landforms had no vegetation at the time of this study. The stratigraphy of the reclaimed slopes comprises a ~40 - 50 cm thick ‘peat/mineral mix’ cover soil underlain by a ~100 cm secondary capping layer (low sodic soil) above reclaimed Clearwater overburden substrate. The south slope (2.8 ha) is a natural remnant of the pre-mining landscape and, hence is composed of natural soils characteristic of the WBP. The snow dynamics on this slope are not explicitly addressed in this study; however, no water contributions from this slope were observed.

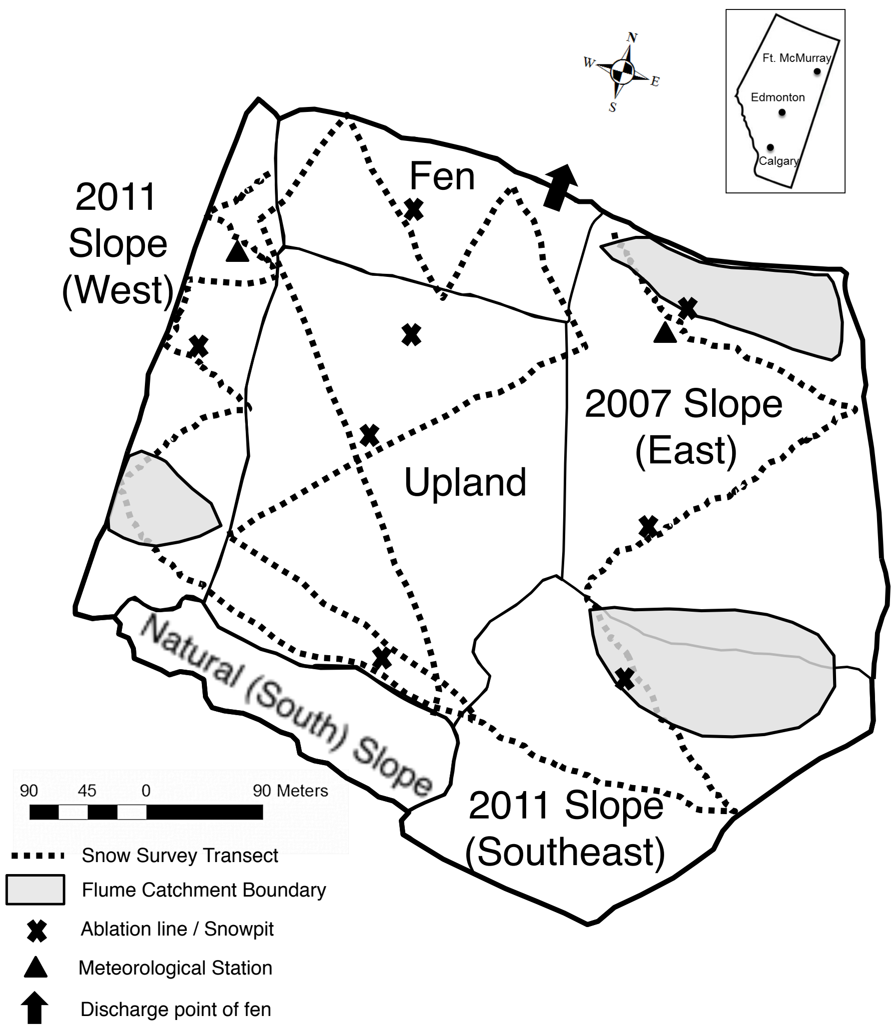

Figure 3-1 - Map of the Nikanotee Fen watershed, design of snow survey transects and location of slope flumes and respective sub-watersheds.

3.3 Methods

3.3.1 Field methods

Field measurements made during March/April 2013 included snow surveys (conducted approximately every second day) along transects through three previously reclaimed slopes (the east, south-east and west slopes) and the constructed upland-fen system (Figure 3-1). Depth measurements were made approximately every 10 m and multiplied by density measurements (collected every 30 m using a standard Meteorological Service of Canada snow tube sampler) to calculate snow water equivalent (*SWE*). Frost table (i.e., depth to frozen ground) measurements were recorded using an incremented metal rod every 30 m along the same snow survey transects once the snowpack thinned enough to facilitate this measurement. Daily ablation was estimated by measuring the lowering of the snow surface across several ablation lines (each ~10 m long; measurements made every 50 cm) and multiplying the surface lowering rate by the average snowpack density (measured with the snow tube sampler) within each reclaimed slope and the upland-fen system (c.f. Woo and Heron, 1987). Snow pits were completed near each ablation line (where possible) to quantify snowpack structure and density using standard methods (Adams and Barr, 1974) and to characterize within-pack variability and verify measurements made with the snow tube sampler. Over-winter dust accumulation rates were estimated from 65 full-depth snow samples taken at locations throughout the watershed. These snow samples were transported back to the laboratory where they were melted, filtered and the sediments dried in an oven (80°C). Over-winter accumulation rates were estimated by expressing the total mass of dust (g) in each sample normalized for the sample surface area.

A meteorological station was deployed on both the west and east slopes in the summer of 2012 for measurement of net radiation (NR-LITE2 net radiometer; 2.5 m height), ground heat flux (REBS HFT-3; 0.01 m depth) wind speed and direction (R.M. Young Wind Monitor; 2.75 m height), relative humidity and air temperature (Hobo U23 Pro v2 dataloggers; 1.0 and 2.3 m heights) and continuous soil moisture (*VWC*) and ground temperature measurements (Campbell Scientific CS 650 probe arrays). *VWC* probes were installed into the peat/mineral reclamation surface soil layer (~50 cm thick) at depths of 2.5, 10 and 32.5 cm, as well as within the underlying secondary capping material at depths of 75 and 60 cm on the east and west slopes, respectively. Two discrete probe arrays were installed on each slope, with ~20 m downslope separation (2 m elevation difference) between arrays. However, due to equipment malfunction of the downslope probe array on the east slope, there are only data for both probe array locations on the west slope. An additional meteorological station, installed on the east slope in the fall of 2013 as a part of Suncor's reclamation weather monitoring program, included a logging snow depth sensor (Campbell Scientific SR50A Sonic Ranging Sensor; 2.7 m height). Snow depth data from this station during the 2014 snowmelt period are included in this study to demonstrate the timing of the snowmelt period in 2014 when field-based measurements were not available.

Soil samples were extracted carefully to minimize disturbance and transported back to the laboratory where independent *VWC* calibration curve functions were derived for each the east and west slope soils following standard procedures (e.g., Jacobsen and Schjønning, 1993). Seven wells and three piezometers were installed in the latter portion of the melt period in the upland-fen system to facilitate water sampling from the constructed aquifers for water chemistry analyses as outlined below. Wells in the upland were installed to a targeted depth of ~2.75 m below ground surface (bgs) using a Stihl BT121 power auger. Stainless steel drive-point piezometers (Solinst Canada Ltd. model 615) were installed in the upland and the transition (near-fen) zone of the upland using a Pionjar 120 percussion rock hammer (screen centered at either 2.25 or 2.75 m bgs). The steel drive pipe that extended the piezometer screen to the surface was lined with low-density polyethylene (LDPE) tubing (1.2 cm I.D.) attached directly to the piezometer screen. All measurements were made within, and water samples extracted from, the LDPE tube. Installation of wells and piezometers did not begin until most of the snow in the watershed had melted (hence melt had nearly finished), and installation progressed very slowly thereafter due to the presence of ground frost. Accordingly, the use of these wells and piezometers is limited to collecting samples for water chemistry and not melt-period water table dynamics, since the first measurement was made long after snowmelt was initiated.

Surface runoff collectors and bucket weirs were installed near the toe of the east, southeast and west slopes to characterize surface runoff from each landform (positioned at the outlet of each of the sub-watersheds in Figure 3-1). These flow collectors, herein referred to as 'flumes' were constructed from plastic resin landscape edging set and sealed (with hydraulic cement) approximately 5-10 cm into the ground that directed flow through a trough and into a bucket containing a v-notch and a logging pressure transducer (Schlumberger Mini-Diver). Manual measurements of discharge (made once or twice daily when flow was present) were used to develop independent rating curves for each flume. A YSI Model 63 handheld probe was used to periodically measure the electrical conductivity (*EC*) of the water flowing through the slope flumes. Water was also sampled from the flumes for laboratory analysis of major ions and oxygen ($\delta^{18}O$) and hydrogen (δD) isotopes (see laboratory analyses details below). Rainwater samples were also collected at least monthly from May to September 2013 and 2014 (as a part of an ongoing research program) using a rain gauge specially designed for isotopic sampling of precipitation (constructed following the design developed by the International Atomic Energy Agency - Global Network of Isotopes in Precipitation; IAEA/GNIP). This information, along with the snow samples from this study, allowed for determination of a local meteoric water line (LMWL). A heated flume and spillbox were installed at the discharge point of the fen to quantify runoff from the entire catchment. Detailed topographic surveys on the reclaimed slopes using a Topcon (Tokyo, Japan) HiPER GL RTK GPS system permitted delineation of the sub-catchment gross drainage area for each of the slope flumes.

3.3.2 Data and laboratory analysis

Vegetation and topographical controls on snow accumulation were assessed graphically with notched boxplots of peak snow depth for each of the reclaimed slopes as well as for lower, mid and upper slope positions. Common slope positions for each slope were grouped together for the topographic analyses. Notched boxplots provide an approximate 95% test of the null hypothesis that the two medians are equal, where notches between boxes that overlap suggest that the medians are not statistically different at $p = 0.05$ (Chambers *et al.*, 1983). Digital elevation models were derived from the topographic survey data using SAGA (System for Automated Geoscientific Analysis) GIS (Olaya and Conrad, 2009) and an inverse distance weighted interpolation module for contour generation. Catchment boundaries were manually delineated based on the topographic contours within the SAGA environment.

Water samples from the field were filtered within 24 hours using 0.45 µm nitrocellulose membrane filters and stored in tightly sealed 10 mL scintillation vials with no head space at 4°C for isotope analyses or frozen in 60 mL high density polyethylene bottles for major ion analyses. All laboratory analyses were completed at the Biotron Experimental Climate Change Research Centre at Western University. Isotopic analyses for $\delta^{18}O$ and δD were performed using a Picarro L2120-i Cavity Ring-Down Spectroscopy analyzer. This technique yields an analytical precision of ±0.5‰ for δD and ±0.1‰ for $\delta^{18}O$. Major ion analyses (fluoride, chloride, nitrite, bromide, nitrate, phosphate, sulfate, lithium, sodium, ammonium, potassium, magnesium, calcium) were completed using a Dionex ICS-1600 Ion Chromatograph.

3.4 Results

3.4.1 Regional snow accumulation trends

Canadian climate normals (1981 – 2010) for Fort McMurray indicate that the snow depth at the start of March is typically close to 29 cm. Based on an assumed snow density the same as measured in the current study (0.23 g cm^{-3}; n = 125), this represents an early-March *SWE* of approximately 67 mm. Basin-averaged *SWE* in the current study (fen excluded due to the over-winter construction of the system; see explanation below) was 106 mm, which indicates that 2013 was a high snowpack year (161% of the climate normal). However, the Environment Canada snow data become sparse in 1999 (2003 is the only year with snowpack data between 2000 – 2013), and thus may not be representative of more recent regional snow accumulation patterns. Information on over-winter snow accumulation at different locations (n = 16-33 locations, depending on the year) throughout the AOSR collected as a part of the Regional Aquatics Monitoring Program (RAMP) between 1997 - 2013 indicates mid-March *SWE* between 39 and 122 mm, with an average of 76 mm (RAMP, 2014). Similarly, the average *SWE* of the annual snowpack at the nearby Syncrude Canada Ltd. Mildred Lake mine site has been reported as about 80 mm (Kelln *et al.*, 2008). Furthermore, the Utikuma Region Study Area (URSA) is located approximately 250 km southwest of Fort McMurray and has a climate with similar precipitation patterns and magnitudes to those in Fort McMurray (Devito et al., 2012). The average annual maximum *SWE* measured at URSA (2000 – 2011) is 91 mm, with a maximum of 174 mm (Devito, unpublished data). Since 2005 there have been five years with a peak *SWE* within the RAMP and URSA datasets that exceeds the *SWE* reported in the current study of 106 mm (Figure 3-2). Accordingly, 2013 can be considered a high snow year, but does not represent an outlier year with an atypically high snow accumulation.

A second year of field-based data collection in 2014 was not possible due to a large mid-winter melt period (early January 2014; snowpack depth reduced from 37 to 27 cm) followed by an atypically early and rapid spring snowmelt period (early March 2014). Automated snow depth measurements revealed a reduction in snowpack depth from ~25 cm to ~1 cm over a one week period starting 10-March-2014 (Figure 3-3). During this period, the average daily air temperature was greater than 0°C, with daily maximum temperatures in excess of 10°C on three separate days during the same time period. In contrast, snowmelt was initiated more than two weeks later in 2013 (~26-March) when daily average air temperature exceeded 0°C.

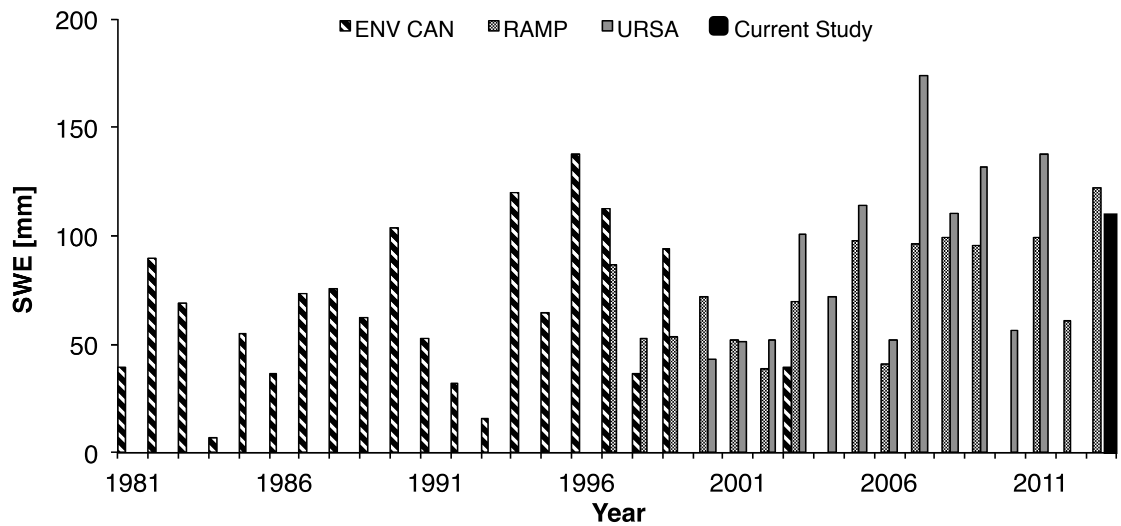

Figure 3-2 - Regional historic *SWE* data. Environment Canada (ENV CAN) data based on snowpack depth at the start of March (converted to *SWE* based on the snow density measured in the current study). RAMP data is an average of snow surveys conducted at 16 – 33 regional locations in mid-March each year. URSA data represents the maximum *SWE* observed during mid-winter snow surveys (Devito, personal communication).

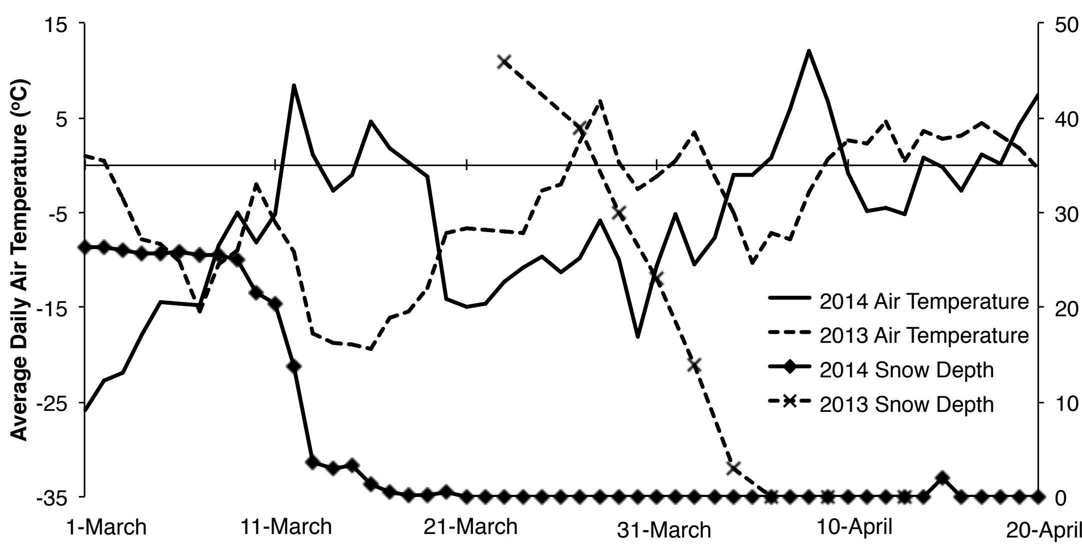

Figure 3-3 - Average daily air temperature and catchment snow depth during the snowmelt periods in 2013 and 2014. 2013 snow depths are daily median values based on manual snow surveys, while 2014 snow depths are daily average values based on the automated snow depth sensor measurements. Horizontal axis represents 0°C.

3.4.2 Snow distribution and ablation

The watershed average peak snow depth (23-March-13) was 43 cm and ranged from 10 – 86 cm (standard deviation = 15 cm; n = 246). A fairly uniform snow cover was observed throughout the different landscape components that comprise the constructed watershed, regardless of the stage of vegetation development; established (east slope; average vegetation height = ~1.5 m), sparse (west and southeast slopes; average vegetation height = ~0.8 m) or nonexistent (upland; not vegetated) (Figure 3-4). The constructed upland, situated within the gently sloping valley bottom and surrounded by reclaimed slopes (Figure 3-1), had the deepest average snow pack, whereas the snowpack was shallowest on the fen. The shallow snowpack on the fen was an artifact of the construction of the system, as peat was being placed in the fen (i.e., fen construction was ongoing) throughout the first half of the winter of 2013. Accordingly, the snow depth observed in March only represents snow accumulation during approximately half of the winter season. The shallowest snowpack (fen excluded) was observed on the west slope, which was the smallest and steepest slope. The trend for peak *SWE* was similar to snow depth (Figure 3-4) and differences in *SWE* between landscape components of comparable snow depths were attributed to slight differences in snowpack density (Table 3-1). Due to differing number of measurement points in each landform, it is most representative to derive an aerially weighted estimate of the watershed *SWE* based on the summation of the *SWE* in each individual landform multiplied by the proportional area of the watershed that each landform comprises. This approach yielded an estimated watershed peak *SWE* of 106 mm (fen excluded).

Landscape components were grouped together to investigate the influence of topography (slope position) on snow accumulation patterns using the measurements of peak snow depth. Snow depth was greatest at the lowest slope position (i.e., near the toe of the slope) and became progressively shallower towards the upper (i.e., crest) slope positions (Figure 3-5). The notches of the lower and upper slope positions do not overlap, which suggests that their medians are statistically different at $p = 0.05$ (Chambers *et al.*, 1983). Consequently, slope position was the strongest control on snow distribution within the constructed watershed. Greater spread across the median of the notched boxplots at lower slope positions indicates more variability in snowpack depth compared to farther upslope.

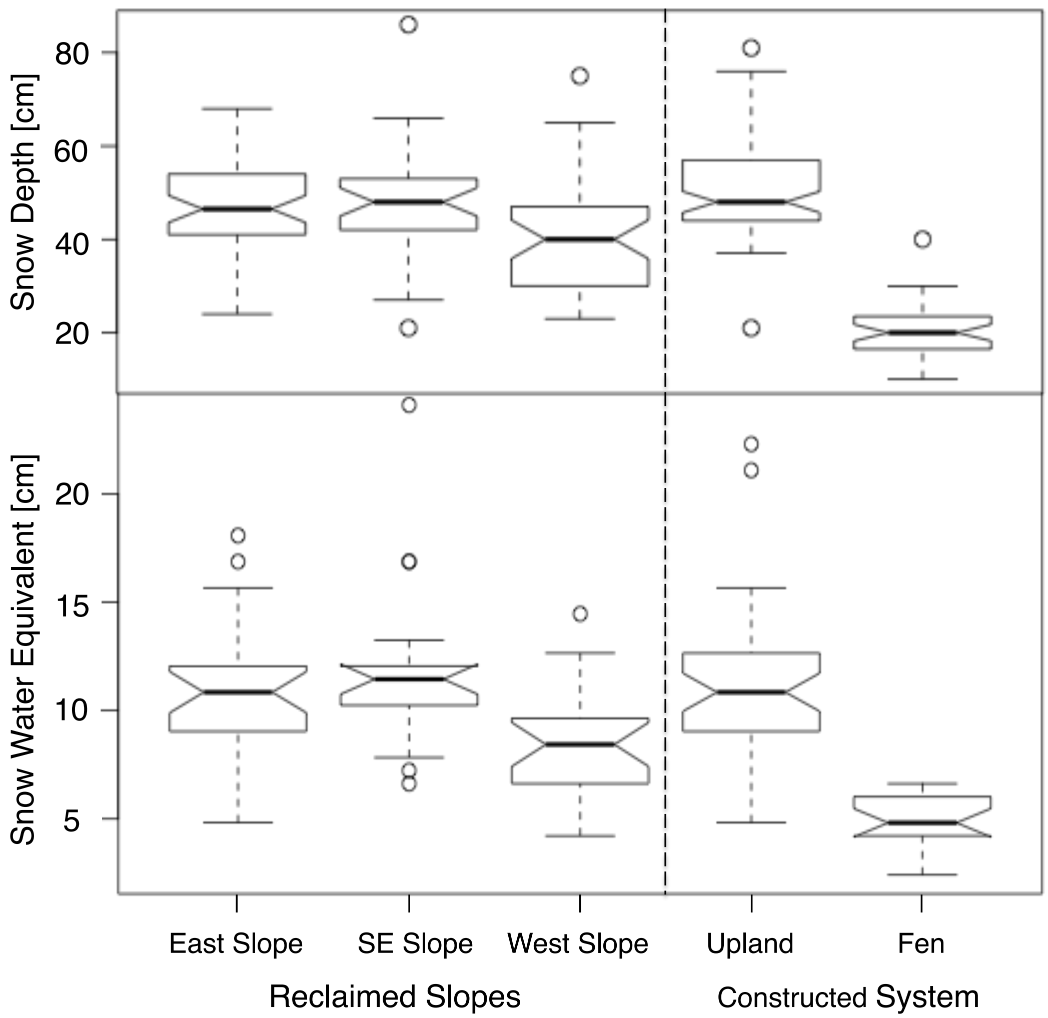

Figure 3-4 – Notched boxplots of peak snow depth (top) and *SWE* (bottom) in the individual landforms within the constructed watershed (23-March-13). In this plot, the lower and upper limits of the box represent the first and third quartiles (25th and 75th percentiles), respectively, with the maximum and minimum values denoted by the ends of the vertical lines. The line inside the box is the median and outliers, defined as data points exceeding 1.5 times the interquartile range, appear as points. The notches approximate a 95% confidence interval for the median (Krzywinski and Altman, 2014).

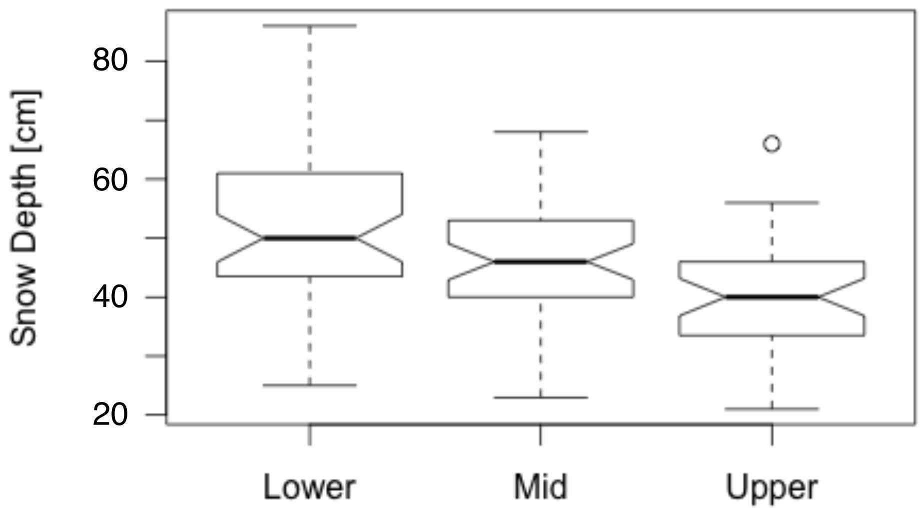

Figure 3-5 - Notched boxplots of peak snow depth with slope position for the reclaimed slopes.

Initiation of snowmelt throughout the watershed between 26-March and 27-March coincided with an isothermal 0°C snowpack, as indicated by snow pit measurements (not shown) and reflected in the *SWE* depletion curves (Figure 3-6). The highest average daily ablation rates were observed on the vegetated east slope (14 mm *SWE* d^{-1}), which resulted in a melt period that was several days shorter as compared to the other landscape types (Table 3-1) and contributed to the steeper *SWE* depletion curve slope early in the snowmelt period. During this early snowmelt period, peak net radiation was consistently higher on the east slope than the west slope, with a cumulative net radiation flux 20 MJ m^{-2} higher on the vegetated east slope than on the sparsely vegetated west slope by the end of the melt period (8-April; Figure 3-7). Consequently, the ablation rates on the west slope were lowest (average = 8 mm *SWE* d^{-1}) and were the last to peak on 4-April. Substantial dust layering was present within the snowpack, often corresponding with layers of ice. Over-winter total dust accumulation rates of 6 – 230 g dust m^{-2} (average 48 g m^{-2}; n = 65) were observed.

Table 3-1 - Landscape properties and melt period characteristics. Snow depth, density and *SWE* represent average values measured at peak snow depth (23-March-13), unless otherwise indicated. n represents the number of snow depth measurement locations. Note that density and *SWE* measurements were conducted at every other measurement of snow depth. Thus, n for snow density and *SWE* is approximately half of the number of snow depth measurement locations.

Landscape	Size (ha)	Aspect	Grade (%)	Snow Depth (cm)			Snow Density (g cm^{-3})	*SWE* (mm)	Average melt rate (mm *SWE* day^{-1})	>75% snow-free	Duration of melt period (days)
				Average	Max	n					
East Slope (vegetated)	8.1	West	13%	48	68	50	0.23	109	14	4-April	10
Southeast Slope	8.2	West-northwest	13%	48	86	33	0.25	120	11	9-April	15
West Slope	2.4	East	19%	40	75	42	0.21	85	8	8-April	14
Upland	7.7	NA	3%	50	81	82	0.22	114	10	12-April	18
Fen	2.7	NA	0%	20	40	39	0.24	49	NA	31-March	6

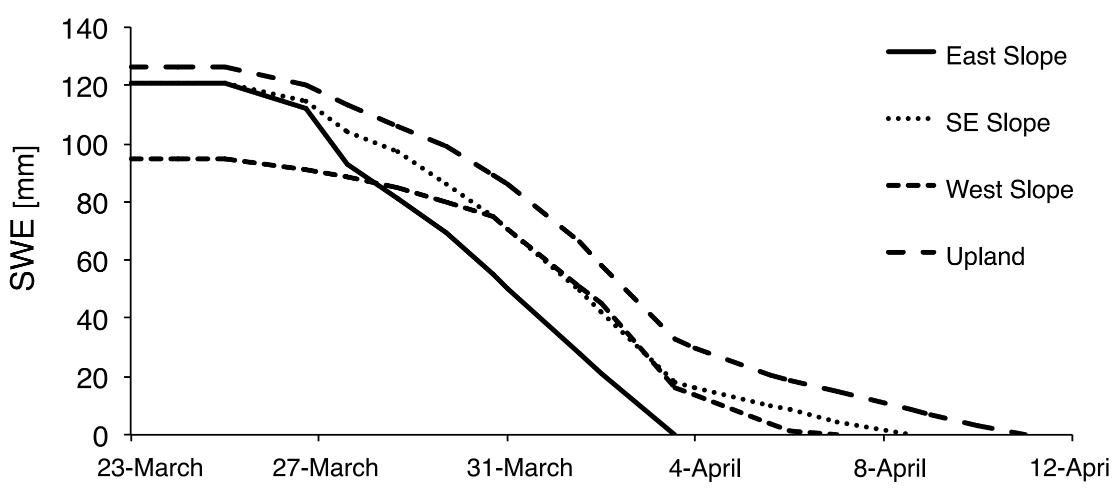

Figure 3-6 - *SWE* depletion curves for each landscape type in the constructed watershed during the melt period in 2013.

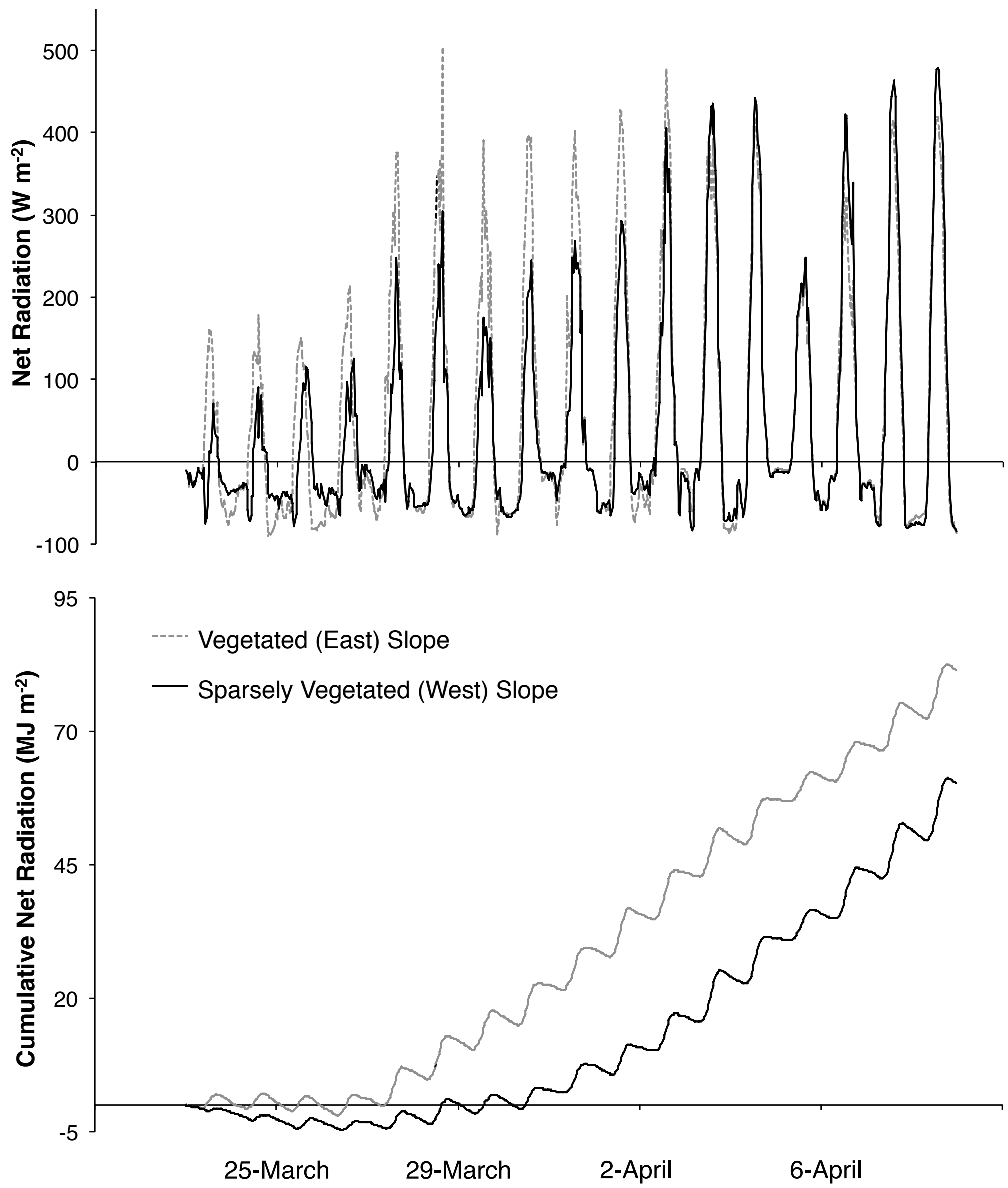

Figure 3-7 - Daily (top graph) and cumulative (bottom graph) net radiation fluxes on the east and west slopes.

3.4.3 Soil moisture and runoff from reclaimed slopes

A time lag of one and two days between the onset of snowmelt on ~27-March and the response in near-surface (2.5 cm depth) soil moisture was observed on the east and west slopes, respectively (Figure 3-8). Following this lag, the shallow *VWC* on the east slope responded strongly to diurnal fluctuations in snow ablation during the early melt period, followed by a notable, albeit muted, diurnal response in *VWC* deeper in the soil profile. Some melt water percolated downwards and recharged deeper soil layers on the east slope as snowmelt progressed, with *VWC* increasing by approximately 10% at 32.5 cm depth over the melt period (Figure 3-8). On the west slope, following an initial gentle increase in near-surface (2.5 cm) *VWC* from 15 to 20% in the early melt period, a strong diurnal response in the shallow *VWC* was observed later in the melt period. However, this response to snow melt did not propagate as strongly into the deeper soil layers on the west slope as it did on the east slope, with an increase in *VWC* at 32.5 cm depth of only ~2% (Figure 3-8). Peak soil moisture occurred two and five days prior to the disappearance of the snowpack (considered to be true when the landscape is > 75% snow-free) on the east and west slopes, respectively. Only very subtle responses of < 2% *VWC* were observed in the top of the secondary capping material at depth on both slopes.

Soils on the reclaimed slopes remained frozen during the early melt period when they were covered by snow. Accordingly, a shallow ground frost layer was observed within the upper ~0-5 cm of the soil surface (average = 1.5 cm). The near-surface soil temperatures became more strongly influenced by air temperature on both the east and west slopes as the snowpack thinned during the melt period (Figure 3-9). This thermal phenomenon propagated downwards into the deeper soil layers towards the end of the melt period. Nonetheless, the presence of ground frost in the near-surface soil constrained percolation of snowmelt water into the ice-rich mineral soils during most of the melt period (until after the slopes were effectively snow-free). Consequently, substantial surface runoff was observed from all reclaimed slopes (Figure 3-10). The surface runoff flumes were installed after snowmelt had begun and surface runoff had been observed. Thus, the runoff measurements only represent a portion of the melt period (Table 3-2). However, snow surveys were conducted within the catchment of each flume to facilitate estimation of runoff ratios (the ratio of runoff to *SWE*) for each slope. High runoff ratios suggest limited storage of meltwater in reclaimed slopes (Table 3-2). Snowmelt runoff peaked in early April, with strong diurnal trends in flow caused by overnight re-freezing of the snowpack and cessation of runoff. Rills and diffuse sheetflow were the dominant modes of surface flow on the reclaimed slopes. Surface erosion was constrained on the east slope by a well-established vegetation community relative to the recently placed southeast and west slopes. Thus, sheetflow dominated water fluxes on the east slope while soils on the southeast and west slope were rapidly eroded and the majority of meltwater was conveyed downslope through rills and gullies. Consequently, the high flow rates observed (up to ~2000 ml s^{-1}) transported large amounts of sediment downslope, much of which was eventually deposited on the surface of the fen (field observation). Although not directly measured, it is likely that the natural slope at the south end of the system yielded little, if any, lateral flow during the study period (none observed). In the upland, measurements taken after the watershed was snow-free (mid-April) indicated that the water table remained approximately 1 to 2 m below the ground surface, with the highest water table levels (i.e., nearest to the surface) in the near-fen (transition) zone of the upland (data not shown).

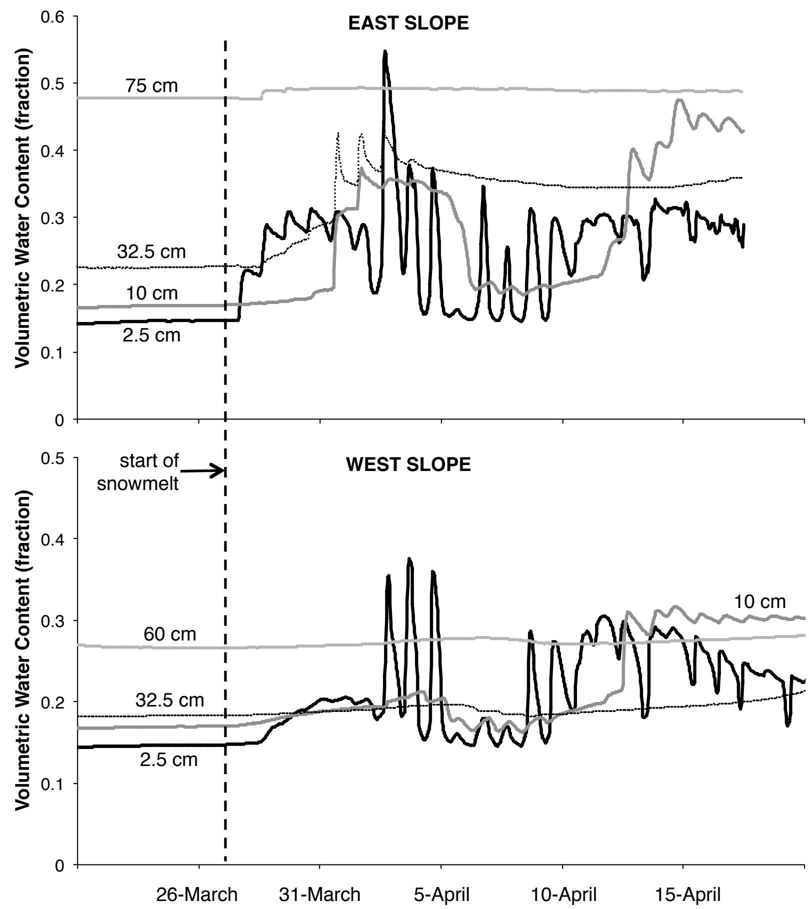

Figure 3-8 - Volumetric water content profiles during the snowmelt period for the east (top) and west (bottom) slopes.

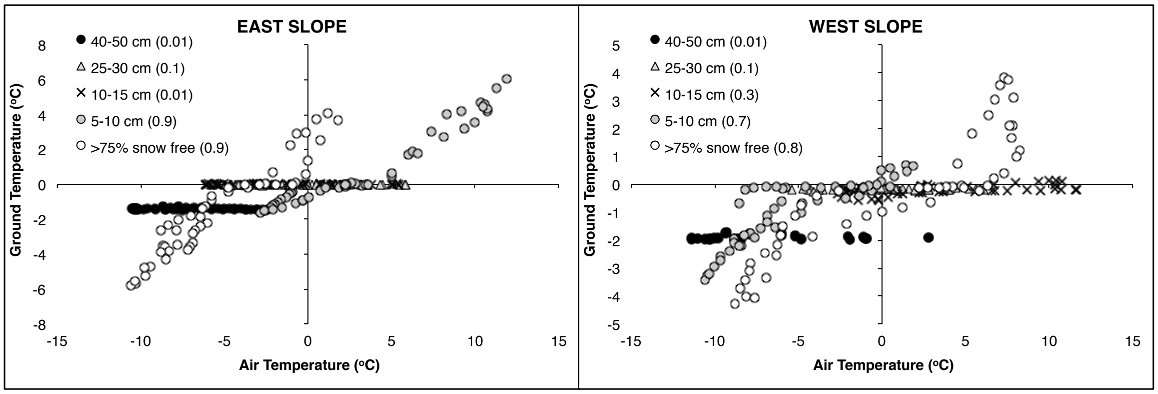

Figure 3-9 - Half hourly measurements of ground temperature (2.5 cm depth) versus air temperature with varying snow cover depths during the melt period. The snow depth range that each different symbol represents is expressed in the legend, with the coefficient of determination of the relationship between ground and air temperature for each depth range expressed in parentheses.

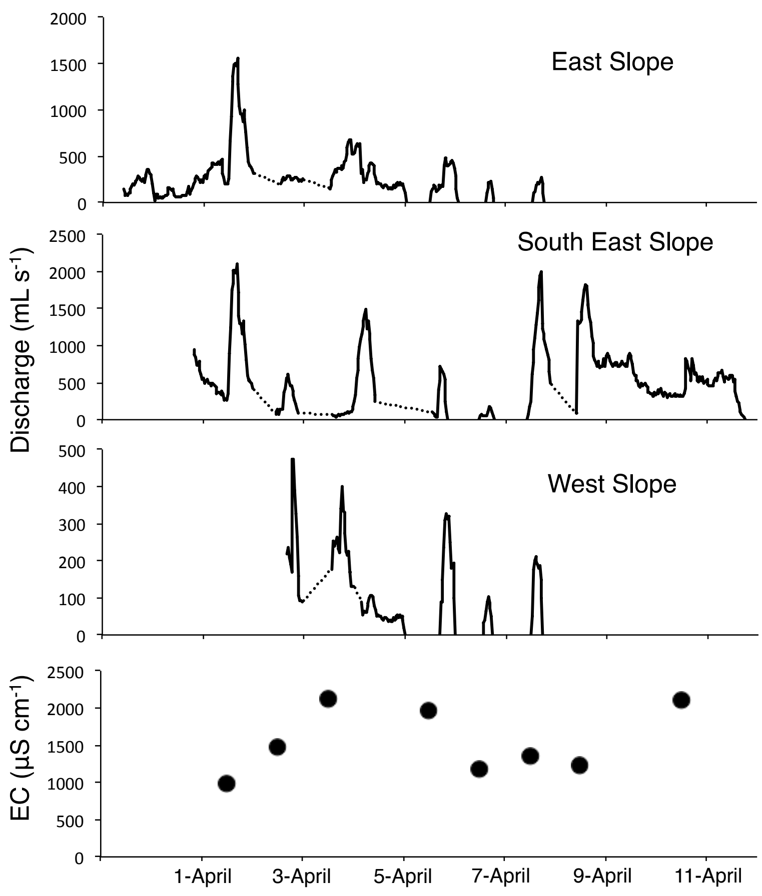

Figure 3-10 - Discharge hydrographs for the reclaimed slopes (upper three graphs) and average electrical conductivity (*EC*) of the slope runoff water (each point represents an average of the *EC* measured in the flumes that had flow at the time of measurement).

Table 3-2 - Slope flume details and runoff measurement. *SWE* represents the average slope *SWE* on date of flume installation.

Slope (date of install)	Catchment size (ha)	Runoff (mm)	*SWE* (mm)	Runoff Ratio
East (31-March)	1.1	19	27	0.7
Southeast (2-April)	1.2	35	39	0.9
West (3-April)	0.2	17	23	0.7

In addition to conveying large amounts of sediment and water to low-lying landforms within the constructed watershed, the reclaimed slopes also transported substantial amounts of dissolved constituents downslope during the snowmelt period, as indicated by elevated *EC* values in flume runoff water (Figure 3-10) relative to the *EC* of snow (average snow *EC* = 87 µS cm^{-1}; n = 83). Surface runoff from the east slope demonstrated the maximum measured *EC* during the melt period of 3970 µS cm^{-1} (4-April), with an average *EC* of all reclaimed slope runoff during the snowmelt period of 1529 µS cm^{-1} (n = 32). *EC* from the west slope (average of 478 µS cm^{-1}; n = 8) was consistently lower than the east and southeast (average of 1879 µS cm^{-1}; n = 24) slopes. Laboratory analyses of water samples from reclaimed slope runoff for ion composition (n = 7) revealed a predominance of several major ions: sulfate (average = 604.3 mg l^{-1}), potassium (average = 10.9 mg l^{-1}), chloride (average = 3.8 mg l^{-1}), sodium (average = 61.9 mg l^{-1}) and nitrate (0.62 mg l^{-1}). All ions were comparably low in snow samples (n = 7), with only detectable concentrations of chloride (0.6 mg l^{-1}), nitrate (0.4 mg l^{-1}) and sulfate (1.3 mg l^{-1}).

Isotopic analysis of water sampled during the snowmelt period indicated that snow had a distinctly depleted signature (Figure 3-11). Conversely, water sampled from wells installed within the upland tailing sand aquifer immediately following the snowmelt period (sampled between 13-April to 17-April) had an enriched signature. The reclaimed slope runoff flumes and standing water ponded on the surface of the fen had an isotopic signature that was slightly enriched relative to the snow. The LMWL determined in this study was similar to that of Baer (2014), which was determined for a study site ~20 km northwest of the Nikanotee Fen.

3.5 Discussion

Vegetation canopies typically play a significant role in snow hydrology due to their impact on snow accumulation patterns (Pomeroy *et al.*, 1998a; Storck *et al.*, 2002; Buttle *et al.*, 2005; Pomeroy *et al.*, 2006; Boon, 2011) and snow ablation rates (Pomeroy and Granger, 1997; Boon, 2009; Ketcheson *et al.*, 2012). Accordingly, it is important to understand the effect of the presence and development of vegetation covers on snow dynamics in constructed ecosystems, where vegetation could be selected to optimize different functions on a landform. In the current study, similar snow depths were observed throughout landscape components with contrasting vegetation covers. This indicates that vegetation was not a dominant control on snow distribution, likely due to the immature vegetation stands relative to those in a natural ecosystem. Instead, surface topography was the dominant control. Although fairly uniform snow distributions have been observed across reclaimed slopes (Kelln *et al.*, 2008), substantial differences in snowpack depth were observed between upper/crest (deepest, greatest variability) and lower/toe (thinner snow pack) slope positions in this study. A graphical assessment of the notched boxplots of snow depth with slope position (Figure 3-5) suggests statistical differences ($p = 0.05$; Chambers *et al.*, 1983) between the median snowpack depth at lower and upper slope positions. These differences were likely driven by enhanced wind erosion of the snowpack near the crest of the slopes where wind speeds are accelerated due to the vertical constriction of air flow paths over moderate topographical features (Oke, 1987). Higher wind speeds can also cause sublimation of wind-blown snow particles, which contributes to reduced snowpack depths (Pomeroy and Essery, 1999; Liston and Sturm, 2002).

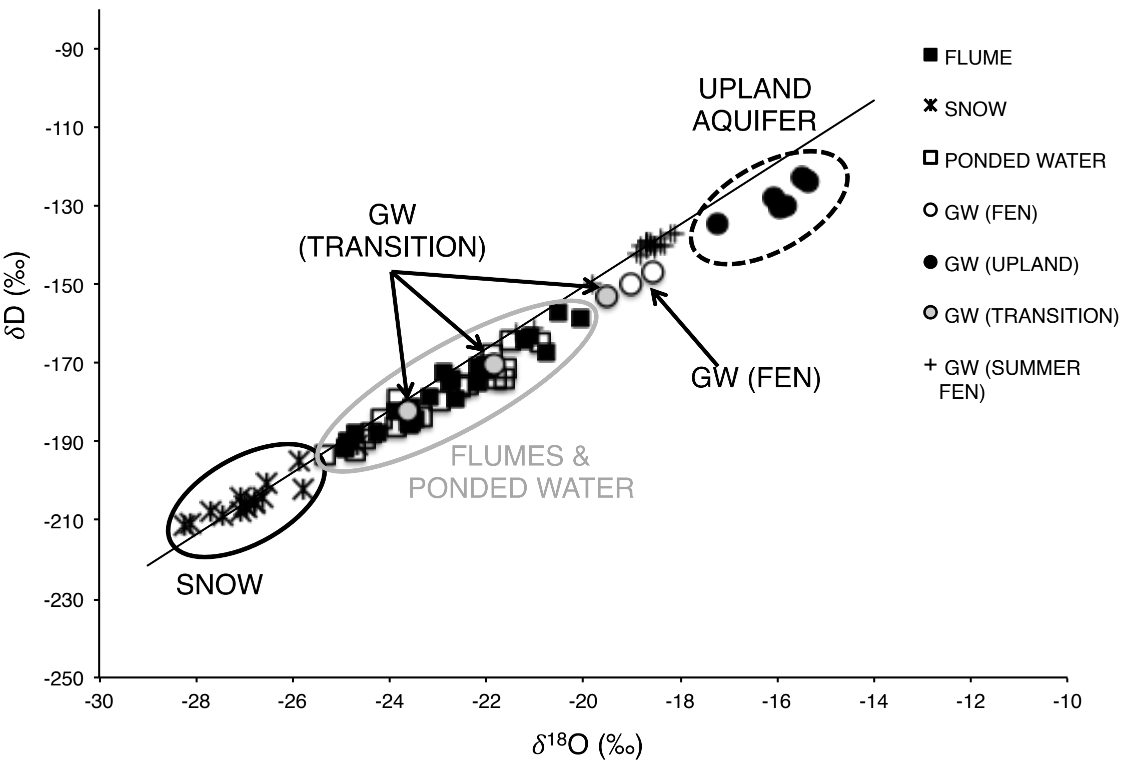

Figure 3-11 - Isotopic signatures of various water samples from the snowmelt period. Groundwater (GW) samples extracted from the fen during the summer of 2013 are also included to supplement the small sample size (n = 2) of groundwater samples from the fen during the snowmelt period (constraints due to well installation during the snowmelt period). The solid line represents the local meteoric water line.

Although vegetation was not observed to influence snow accumulation, it did exhibit an appreciable effect on the snow ablation rate, whereby the earliest and most rapid progression of snowmelt occurred on the vegetated slope. During snowmelt, shrub branches can decrease the reflectance of shortwave radiation and enhance snowmelt rates relative to more sparsely vegetated areas (Pomeroy *et al.*, 2006). This effect was evident in the net radiation data, which were consistently higher on the east slope than on the west slope in the early snowmelt period (Figure 3-7) as a consequence of the increased absorption of shortwave radiation by vegetation emerging from the snowpack. The effect of the increased shortwave radiation has been shown to overwhelm the increased outgoing longwave radiation from the relatively warm vegetation, generally resulting in higher melt rates in the presence of shrubs (Pomeroy *et al.*, 2006). Accordingly, the steep slope of the *SWE* depletion curve in the early melt period observed on the vegetated east slope can be attributed to the presence of vegetation branches and stems during the snowmelt period. The similar slopes of the *SWE* depletion curves for vegetated and non-vegetated landscapes from ~31-March onwards (Figure 3-6) indicate that this vegetative influence on ablation was minimized in the latter portions of the melt period when atmospheric conditions began to dominate. This is also supported by the similar net radiation measured on the east and west slopes during the late melt period (Figure 3-7).

Slope aspect is not explicitly considered in this study; hence, it cannot be completely ruled out as a contributing factor in the rates and timing of snow ablation observed on the reclaimed slopes. Although sharp contrasts exist on north and south-facing slopes (e.g., Carey and Woo, 1998; Carey and Woo, 1999; Redding and Devito, 2011), similar snowmelt timing has been observed on slopes with eastern and western aspects (Carey and Woo, 2001). The aspect of the reclaimed slopes in the current study are west, west-northwest and east, which are unlikely to result in discernable differences in snowmelt dynamics between slopes as a consequence of aspect. Further, the vegetated east slope demonstrated a higher ablation rate and an earlier melt than the portion of the southeast slope that is directly adjacent to, and has a similar aspect (west-facing) as, the east slope. Thus, the influence of slope aspect on snowmelt was likely minimal between the reclaimed slopes in this study.

The emergence of dust layers within the snowpack also appeared to influence snow ablation rates. The presence of dust in layers within the snowpack is a reflection of the dust deposition between snowfall events over the winter. This dust likely originated from a road associated with mining operations located within close proximity to the watershed. However, the presence and extent of these dust layers during the melt period were not anticipated and confounded the planned approach for quantification of the snow surface energy budget. Nonetheless, visual field observations indicated a two-stage effect of the presence of dust on the observed ablation rate: 1) increased ablation rate initially upon emergence of some dust at the surface of the snow, which transitioned eventually to; 2) decreased ablation caused by insulation of a thick dust and ice layer. More research is required to suitably address and quantify the impact of dust layer development on the snow surface energy budget in environments where over-winter accumulation of dust is substantial.

Although deposition of aerial particulates within the snowpack has been observed in the AOSR (e.g., Kelly *et al.*, 2009; Kelly *et al.*, 2010), the concentration of ions measured within the snowpack in the Nikanotee Fen watershed were much lower than those measured in the water discharging through the slope runoff flumes. Salts can migrate into, and accumulate within, reclamation soil covers by diffusion from the underlying overburden material (Kessler *et al.*, 2010). Kessler *et al.* (2010) found that sulfate and sodium were the dominant anion and cation, respectively, within a reclamation soil cover layer. Similarly, sulfate and sodium represented the highest two ion concentrations measured in the snowmelt runoff through the flumes in the current study, with average concentrations of 604.3 and 61.9 mg l^{-1}, respectively. Comparatively, snow samples had concentrations of only 1.3 and 0.6 mg l^{-1} for sulfate and sodium, respectively. The higher concentrations measured in the water flowing through the flumes suggests that snowmelt water accumulated dissolved constituents along the flowpath near the surface of the reclaimed slopes. Thus, the spring freshet could represent both a flushing mechanism for reclaimed soil covers as well as an important time to monitor the water quality of downstream landforms and ecosystems, considering the large quantity of water that these slopes can produce. However, the concentrations reported here are much lower than sulfate and sodium concentrations measured in interflow from reclaimed slopes during the summer months, which can exceed 3000 mg l^{-1} (Kelln *et al.*, 2007) and 1000 mg l^{-1} (Kelln *et al.*, 2008), respectively.

Many reclaimed ecosystems in the AOSR have been constructed within the past decade and comprise individual vegetation stands of varying maturity, as well as bare (unvegetated) landforms. Accordingly, the manner in which vegetation influences snow accumulation and ablation is expected to evolve over time as vegetation communities mature into forestlands. For example, as a consequence of the high ablation rate caused by the presence of vegetation, the east slope became effectively snow-free four days before any other slope (Table 3-1). Thus, over the first several years following reclamation, the snowmelt period could tend to occur earlier in the season than it otherwise would, based on the control of weather patterns, as the vegetation cover becomes better established and contributes to enhanced ablation rates during the early snowmelt period. This process is comparable to the evolution of snow dynamics observed during the hydrologic recovery of harvested forest sites (the return of the hydrologic characteristics to preharvest conditions), where snow ablation rates were the highest in stands undergoing initial regeneration after harvest (Buttle *et al.*, 2005). The snow surface energy budget and ablation rates will continue to evolve as vegetation stands mature, since incoming radiation will be reduced as the vegetation canopy develops. For example, peak solar irradiance measured above a tree canopy can be more than twice that received below the canopy (Hardy *et al.*, 1997). Furthermore, branches in the canopy absorb shortwave radiation and contribute to decreased net radiation at the snow surface in spite of the irradiance of long wave radiation from the branches (Pomeroy and Dion, 1996). This increased attenuation of shortwave and enhanced long wave emission as tree canopies develop have offsetting effects (Sicart *et al.*, 2004), although the effect of the reduction in shortwave radiation at the snow surface generally dominates and results in decreased snowmelt rates under canopies (Link and Marks, 1999). While no differences in snow accumulation were observed between vegetated and unvegetated landforms in the current study, snow accumulation can be greater in the presence of shrubs than in sparsely vegetated areas in a shrub tundra setting (Pomeroy *et al.*, 2006). In contrast, snow accumulation in areas beneath tree canopies in forests is typically much less than forest clearings (Hardy *et al.*, 1997; Storck *et al.*, 2002; Buttle *et al.*, 2005) and sublimation of snow intercepted by the canopy of mature tree stands can represent a significant loss of water from forests (Pomeroy *et al.*, 1998b; Gelfan *et al.*, 2004).

The findings of the current study represent a point in time along an evolving vegetation system. Reclaimed landscapes are, however, composed of a mosaic of landforms with differing construction and revegetation timeframes. The current study presents findings from reclaimed landforms that range from five years following revegetation to landforms that had yet to be revegetated. Thus, the vegetation cover maturity ranges from well-established to nonexistent. This only represents a portion of the wide range of vegetation covers present in reclaimed landscapes. So, although the findings of the current study will be applicable somewhere in the post-mining landscape for the foreseeable future, additional research is required in more mature reclaimed vegetation stands to better understand the long-term snow dynamics within these constructed landscapes. Based on research in natural ecosystems with contrasting vegetation covers outlined above, large shifts in snow dynamics can be expected as reclaimed vegetation stands mature in these constructed ecosystems. This represents an emerging and important aspect of oil sands reclamation research that requires consideration in the development of mine closure design plans. While the findings of this study are directly relevant to, and applicable in, recently reclaimed landscapes in the AOSR, they could also have applicability in other reclaimed / post-mining landscapes that have similar characteristics to the reclaimed watershed presented in this study (e.g., immature vegetation communities, highly disturbed sloping soil covers) that are located within a regional climate that receives snow.

Since reclamation soil covers are designed to promote water storage, they are generally a combination of organic peat and mineral soils (termed ‘peat/mineral mix’) obtained by over-stripping of natural peat deposits on glacial soils (Meiers *et al.*, 2006). These soil covers typically exhibit strong soil-water retention characteristics (Shurniak and Barbour, 2002) that are influenced by the proportion of clay, sand and organic matter (Leatherdale *et al.*, 2012). Greater water retention at freeze-up results in more ground ice that can cause delayed ground thaw in the spring (Carey and Woo, 1998), although natural landscapes in the WBP often have low soil water content prior to freezing (Devito *et al.*, 2005b). In the current study, the insulating nature of the overlying snowpack delayed the ground frost thaw until after the majority of the snowpack had melted (Figure 3-9). It is noteworthy, however, that the fall of 2012 was very wet. The total precipitation received during September and October 2012 at the constructed system was 164 mm, which is 98 mm more than the long-term climate normal of 66 mm for the same months (Environment Canada, 2011). This could have contributed to the extent of the ground frost and the minimal infiltration into the reclaimed slopes, since the wet conditions in the fall of 2012 would have resulted in ice-rich soils that have lower infiltration rates than drier frozen soils (Kane and Stein, 1983). Although *VWC* measurements indicated that a portion of snowmelt water did percolate into the soils on the reclaimed slopes, this was largely constrained by the presence of shallow ground frost during the time when most of the snowpack melted and likely only comprised a small amount of the total snowpack *SWE*. Thus, most of the snowpack *SWE* was conveyed downslope as surface runoff. Similarly, Kelln *et al.* (2009) reported that the majority of *SWE* on reclaimed slopes ended up as surface runoff during the snowmelt period. Snowmelt infiltration water has been shown to bypass the near-surface soil matrix on reclaimed slopes (Kelln *et al.*, 2008), with snowmelt water rapidly percolating to the base of reclamation cover capping soil layers via preferential flow paths (Kelln *et al.*, 2007). This mechanism of snowmelt infiltration would not be sufficiently represented by the *VWC* measurements in the current study. However, preferential flow paths were likely unimportant on the recently reclaimed west and southeast slopes (soils placed in 2011), since macropore development can take several years (Guebert and Gardner, 2001; Kelln *et al.*, 2006) and these slopes are only sparsely vegetated. Infiltration of snowmelt water via preferential flow paths was likely more predominant on the older vegetated east slope (soils placed in 2007). Regardless, runoff ratios of < 1 (Table 3-2) indicate that some percolation of snowmelt water occurred on all reclaimed slopes in this study, in addition to water losses via sublimation.

Topographic position on the reclaimed slope also demonstrated a dynamic control on soil water distribution; although, due to equipment failure, this could only be evaluated on the west slope. Responses in near-surface *VWC* observed at the two discrete probe arrays at slightly different slope positions (i.e., with ~20 m downslope separation (2 m elevation difference) between measurement locations) illustrated similar trends but distinct magnitudes in the mid-melt period. For example, measurements recorded in the lower slope location on the west slope responded strongly to daily melt patterns, with the upper few centimeters of soil nearly reaching saturation (Figure 3-8). In contrast, soils directly upslope of this position (~20 m towards the crest at ~2 m higher elevation) demonstrated subdued responses (data not shown). Similarly, Kelln *et al.* (2008) suggested that lower antecedent moisture conditions in upper/crest slope positions reduce the occurrence of saturated conditions during the snowmelt period. Although increased soil moisture conditions have been observed in lower relative to upper slope positions (Kelln *et al.*, 2008), this effect is often inconsistent (Leatherdale *et al.*, 2012). The strong response observed in the downslope *VWC* coincided with the maximum melt rate measured on the west slope, which suggests that topography represents a stronger control on soil water dynamics at peak melt than later on in the melt period when similar patterns were observed at both slope positions.

3.5.1 Fate of snowmelt water

Frozen soils on the reclaimed slopes restricted the amount of snowmelt water that went into soil water storage. Estimates of recharge to soil water storage on the reclaimed slopes from *VWC* measurements are complicated by the freezing and thawing of the soils, since the CS-650 probes are only able to detect liquid water content. Thus, the melting of ice within pores caused an apparent increase in *VWC*, although this is in part an artifact of the increase in the proportion of the *VWC* that was unfrozen, not necessarily a change in the total *VWC* within the soil. This increase would also reflect water recharging the soils. However, the estimated runoff ratios of 0.7 for the east and west slopes and 0.9 for the southeast slope suggests that the slopes were each able to store between ~10 to 30% of the *SWE* (sublimation excluded). Although *VWC* measurements were not made on the constructed upland aquifer due to the timing of the construction of the system, the presence of shallow ground frost likely also constrained infiltration and recharge into this landform. Soon after the onset of melt, surface runoff from the reclaimed slopes and upland began to pond on the surface of the fen peatland, since this is the lowest lying landform within the constructed watershed. The crest-height for the discharge point for the watershed was initially set (i.e., during the construction phase) at a higher elevation than that of the surface of the fen, which prevented the fen from draining and resulted in ponded water ~30 cm deep on over 80% of the fen by 6-April (Figure 3-12). When the fen surface was flooded in early April, a localized recharge pipe developed through the frozen peat (likely by thermal erosion) that resulted in rapid percolation of ponded melt water into the unsaturated underlying peat (the peat was unsaturated when placed). This recharge mechanism substantially contributed to the initial saturation of the deep peat layer, as well as 0.5 m thick petroleum coke and tailings sand layers beneath the fen that were included in the modified construction design (see Daly *et al.*, 2012).

The enriched isotopic signature of groundwater from the upland tailing sand aquifer relative to the depleted signature of snow samples implies that the upland aquifer received little (if any) recharge from the snowmelt water during the 2013 melt period (Figure 3-11). Approximately 5000 m^3 (~65 mm) of water was applied to the upland aquifer during the construction phase to facilitate compaction (summer of 2012), which simultaneously supplemented the groundwater storage. This probably contributed to the enriched signature of the upland groundwater and would help to explain the slight offset from the LMWL. Isotopic signatures of the reclaimed slope runoff flumes plotted along the local meteoric water line and demonstrated a slightly enriched signature relative to the snow. This can be attributed in part to the continuous enrichment that occurs as snow melts (Stichler *et al.*, 1981; Taylor *et al.*, 2001; Lee *et al.*, 2010), sublimation (which can also enrich the isotopic signature of a snowpack (Stichler *et al.*, 2001)), and the potential enrichment caused by mixing of snowmelt water with antecedent rainwater stored within the upper soil layer from the previous year. However, frozen soils and high runoff ratios imply that this mixing was minimal. Standing water ponded on the surface of the fen demonstrated an isotopic signature similar to that measured from the runoff flumes. Groundwater samples from the fen (sampled 6-April) plotted between the enriched upland aquifer water and the relatively depleted water flowing off of the reclaimed slopes (flume samples). This implies that the fen received groundwater recharge from snowmelt water, predominantly via the observed recharge pipe, in addition to overwinter groundwater input from the upland aquifer (which received water inputs from both summer precipitation and the artificial irrigation during construction in 2012). Fen groundwater samples from throughout the summer of 2013 are included in Figure 3-11 to bolster the small sample size from the snowmelt period (n = 2) and demonstrate that there was little variation in the signature of fen groundwater over the season. Groundwater samples collected from wells installed at the transition zone (near-fen zone of upland) showed a signature more similar to snow than in the fen, which suggests the movement of some snowmelt water from the ponded water in the fen into the transition zone aquifer at the toe of the upland.

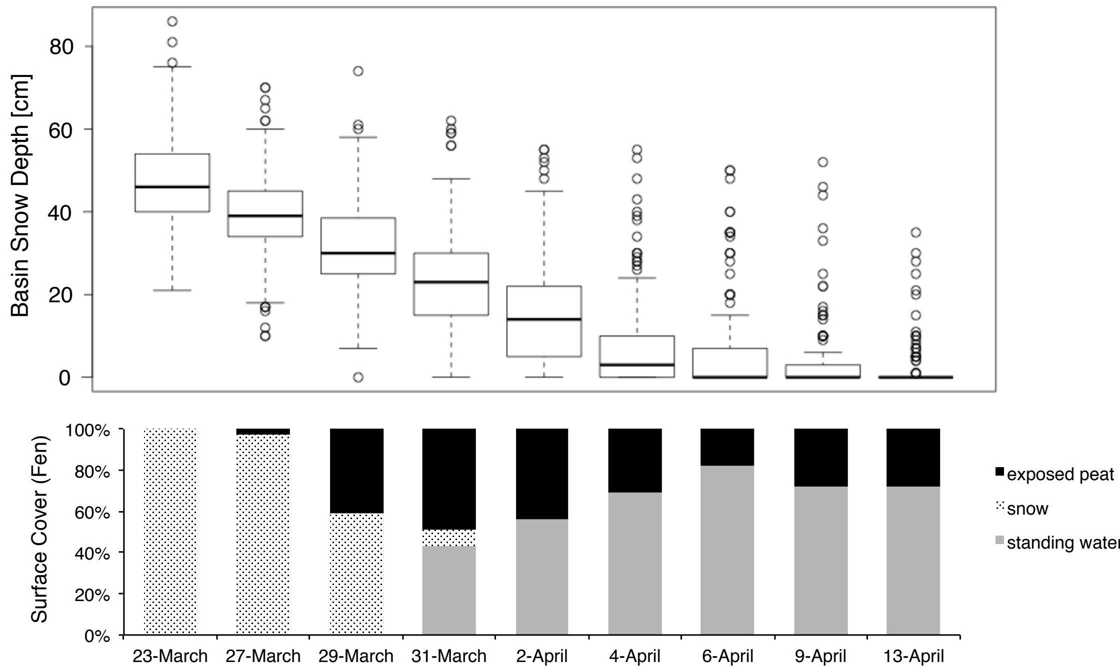

Figure 3-12 – Boxplots of snow depths within the watershed (top graph) and the proportion of the fen peatland covered by snow, standing water and exposed peat/bare ground surface (bottom graph) during the snowmelt period.

3.5.2 Water management in reclaimed landscapes during melt

Surface runoff is rarely observed in the majority of natural landscapes in the WBP (Devito *et al.*, 2005b), even during the snowmelt period (Redding and Devito, 2011). The south (natural) slope within the constructed watershed represents the most similar landform to the pre-disturbance landscape, since this small area is a relatively undisturbed remnant of the pre-mining landscape that was not artificially constructed. No surface runoff was observed from this landform, which is a sharp contrast to the large volumes of water and sediment yielded by the reclaimed slopes within the watershed. These observations are supported by literature on runoff from natural landscapes in the AOSR (Western Boreal Plain). For example, Redding and Devito (2011) found that infiltration was far greater than near-surface runoff, representing 87% and 7% of snow water equivalent, respectively (median drainage and runoff coefficients stated, respectively). Further, runoff due to snowmelt from undisturbed catchments in the AOSR is typically small due to the high soil storage in hillslopes (Devito *et al.*, 2005b).

Devito *et al.* (2005b) also observed that runoff in the WBP has a wide range of interyear variability, with variations in runoff exceeding 250 mm year^{-1}. Since this variability was not determined to be related to precipitation on an annual basis, regional runoff ratios varied from 20 to 60%, with subcatchment runoff ratios as low as < 1% in some years (Devito *et al.*, 2005b). This was explained by a combination of the moisture conditions during the autumn of the previous year and the accumulation of snow over the winter, where the highest runoff (hence highest runoff ratio) was observed in the year that followed a wet autumn and atypically high snowpack. These conditions are similar to those of the current study, since ~2.5 times the long-term normal precipitation was received during the autumn preceding the year of the study (September and October 2012) and the 2013 snowpack represented 161% of the long-term climate normal. Thus, the snowmelt period hydrology within reclaimed landscapes is fundamentally different than that reported for natural WBP settings where the primary role of snowmelt is to satisfy soil storage (Devito *et al.*, 2005b). In constructed ecosystems, surface runoff supersedes soil water storage during the spring freshet. The large slopes that dominate post-mining landscapes could result in increased flashiness of downstream watercourses, as well as increased sedimentation caused by high rates of surface erosion of newly placed reclaimed soils via rill and gully development, especially during the spring freshet. Consequently, water management during the snowmelt period is very important in constructed landscapes.

The topographic control on snow distribution observed in the current study suggests that including more complex surface topography into closure landscape designs might help to distribute snow more evenly throughout the landscape during the winter months. For example, integrating more breaks in slope would lessen the disparity between toe and crest snow depths. Due to the insulating nature of the overlying snowpack on the soil thermal regime (Goodrich, 1982), the soil temperature profile is more strongly coupled to air temperature under thin snow packs (Figure 3-9). Thus a more evenly distributed snow cover could help to reduce the depth of ground frost in upper slope positions where the snow pack was thin (Figure 3-5), which should result in increased infiltration during the snowmelt period due to the reduction in the amount of ice present in the soil (Kane, 1980) and an earlier ground thaw. Since the delivery of interflow can lag behind the completion of snowmelt by up to a month (Kelln *et al.*, 2009), greater infiltration during the snowmelt period would help to prolong the delivery of melt water and slightly alleviate the high surface runoff rates observed from reclaimed slopes. Likewise, the use of snow fencing could be a simple option to help address non-uniform snow distribution. Also, integrating macrotopographic features such as swales and hummocks could serve to help detain water during the rapid melt period. Several hummocks were included on the upland of the constructed watershed of the current study to intercept and enhance recharge from the reclaimed slopes (Daly *et al.*, 2012). Field observations of water ponded behind (i.e., upslope of) these structures support their function as water detention structures. Site-specific design modifications should serve to optimize this function. Similarly, microtopographic management of the surface of reclaimed soils, such as surface tilling perpendicular to the topographic slope, could also contribute to increased detention of snowmelt water as well as assist in promoting infiltration and recharge to constructed aquifers.

Effective water management strategies need to utilize the new surface runoff-dominated hydrological processes operating within post-mining landscapes during the snowmelt period. The original design and modelling of the constructed watershed (Price *et al.*, 2010) was done to test a concept and optimize an upland-fen configuration. Consequently, the reclaimed slopes that surround the upland-fen system were not considered. In the model, the annual input to the system from snowfall was represented as precipitation that occurred when the daily average temperature was less than or equal to 0°C (Price *et al.*, 2010). Based on the climate normals, this is ~25% of annual *P* (Environment Canada, 2011). However, due to the large volume of water produced by the adjacent reclaimed slopes, the upland-fen system received far more water input during the spring freshet than indicated solely based on measurements of over-winter snow accumulation or landscape *SWE*. For example, the total volume of water stored in the snowpack on the reclaimed slopes represented an area-normalized (i.e., the total volume of water on the reclaimed slopes expressed relative to the area of the upland-fen system) flux of nearly 200 mm of water in addition to the *SWE* solely on the upland and fen. Therefore, if efficient water management strategies are implemented, snow can represent a more important contribution to the annual water budget of constructed watersheds than suggested when considering its generalized input of ~25% of annual precipitation alone. Although integrated landscape design incorporates the water fluxes from all of the individual landforms, these findings have identified an opportunity to design landscapes in an advantageous manner to maximize the detention and redistribution of water during the spring freshet.

3.6 Conclusions

Snowmelt in reclaimed landscapes is a process of fairly high intensity and short duration, with high runoff ratios and small storage of snowmelt water on reclaimed slopes. The establishment of a vegetation cover, which appears to cause an earlier and more rapid snowmelt, further exacerbates this. Patterns of snow accumulation in the constructed Nikanotee Fen watershed indicated that surface topography was the dominant control on snow distribution in this reclaimed landscape. Surface runoff was rapidly conveyed down reclaimed slopes via sheetflow on the older, vegetated east slope (reclaimed six years prior to study) while rills and gullies quickly developed on the recently reclaimed southeast and west slopes (reclaimed two years prior to study). The runoff from these slopes was likely enhanced by the wet conditions during freeze-up in the previous fall. The development and implementation of effective water management strategies designed to handle the large volume of water produced in constructed landscapes during the spring freshet will help to offset the challenges associated with limited water availability imposed by the regional sub-humid climate. Snowmelt can contribute a substantial amount of water to the annual water budget of low-lying landforms within constructed watersheds if fluxes from adjacent (upland) landforms are also considered. Using excess water availability during the spring freshet is especially relevant when designing wetland ecosystems into reclamation closure design plans. Over time, the role of vegetation on snow hydrology will likely evolve as the vegetation cover becomes well established and a denser canopy develops. The vegetation covers in the landforms of the current study are immature compared to those in natural systems and, thus, the results should be interpreted with this in mind. Increased interception and subsequent sublimation of intercepted snow will reduce the amount of *SWE* on reclaimed slopes. However, research in older reclaimed areas, conducted in parallel with longer-term monitoring of recently reclaimed landscapes, is required to validate these processes and incorporate interannual climatic variations. Reduced ablation rates can also be expected as vegetation covers develop and constrain incident shortwave radiation at the surface of the snow. These changes could eventually help to alleviate the challenge of managing large volumes of water within constructed landscapes during the spring freshet.

3.7 Acknowledgements

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4 A COMPARISON OF THE HYDROLOGICAL ROLE OF TWO RECLAIMED SLOPES OF DIFFERENT AGE IN THE ATHABASCA OIL SANDS REGION, ALBERTA, CANADA

4.1 Introduction

Large-scale disturbances caused by oil sands extraction activities in the Athabasca Oil Sands Region (AOSR) in Canada require the reconstruction of individual ecosystems and landforms at the scale of whole landscapes (Johnson and Miyanishi, 2008). Understanding the connectivity between individual landforms within the reclaimed landscape is fundamental in re-establishing ecosystem functioning. Soil covers used during land reclamation and mine decommissioning at oil sands mining operations are often designed to mitigate percolation into stockpiled overburden or waste (Elshorbagy *et al.*, 2005; Kelln *et al.*, 2007; Meiers *et al.*, 2011) and to provide an adequate water supply for vegetation over dry summer periods (Carey, 2008; Meiers *et al.*, 2011). Accordingly, the majority of reclamation soil cover research has focused on assessing the performance of these soil covers at the hillslope (i.e., individual landform) scale and do not explicitly consider their hydrologic function within the context of a larger-scale landscape (i.e., watershed-scale). Although some studies (e.g., Shurniak and Barbour, 2002; Kelln *et al.*, 2007) quantify downslope movement of water (interflow) and other studies have documented soil water distribution and temporal variability within reclaimed upland slopes (e.g., Kelln *et al.*, 2008; Leatherdale *et al.*, 2012), there is a need to couple the controls on soil water distribution to the storage and transmission of water through reclaimed slopes to their hydrologic role (i.e., storage or conveyor) within the larger-scale watershed.

In natural landscapes within the AOSR, deep glaciated substrates result in extremely complex surface and groundwater interactions and topography does not always control watershed hydrology (Devito *et al.*, 2005a; Smerdon *et al.*, 2005). However, the hydrologic regime of the reclaimed landscape has been highly altered relative to natural areas (Elshorbagy *et al.*, 2005). Consequently, the hydrologic response of reclaimed landscapes is quite different than the responses of undisturbed areas (Negley and

Eshleman, 2006); though the dominant controls on soil water distribution within reclamation soil covers are not fully understood. For example, the influence of topography (i.e., slope position) on soil water distribution in reclaimed slopes is unclear. Kelln *et al.* (2008) found that soil moisture conditions were wetter at lower slope positions on a reclaimed slope landform in the AOSR during the wet spring season as well as throughout the comparably dry summer and fall seasons. Conversely, Leatherdale *et al.* (2012) determined that lower slope positions did not have higher soil moisture contents than upper slope positions and concluded that soil water distribution was not consistently influenced by slope position on any of four reclaimed slopes (also in the AOSR). Understanding the controls on water distribution within reclaimed slopes is a necessary step in evaluating the hydrological importance of these slopes on the performance and behaviour of the larger watershed-scale reconstructed landscape. Accordingly, there is an ongoing need to discern the dominant controls on water storage and distribution within reclaimed slopes.

Since the hydrophysical properties of reclaimed slopes can undergo substantial changes in the first few years following their construction (e.g., Guebert and Gardner, 2001; Kelln *et al.*, 2007; Meiers *et al.*, 2011), the soil water regime and, thus, the hydrologic role of reclaimed slopes will change over time. The development of a secondary soil structure (i.e., macropores) contributes to the evolution of the hydraulic properties of reclaimed soils. For example, preferential flowpaths can develop around large rock fragments in reconstructed soils (Guebert and Gardner, 2001). Also, freeze/thaw cycling can contribute to the observed changes in the properties of reclaimed soils. Meiers *et al.* (2011) observed an increase in the saturated hydraulic conductivity of reclamation cover soils of one to two orders of magnitude over the first two years following soil placement and attributed these changes to the occurrence of an annual freeze/thaw cycle in the AOSR. Further, reclaimed slopes are typically vegetated with pioneer plant communities that transition through several successive vegetation communities in the years following reclamation (Carey, 2008). The growth of vegetation and the establishment of root infrastructure in the shallow subsurface can contribute to the evolution of the hydrophysical properties of reclaimed soils as well (Loch and

Orange, 1997); although this effect is constrained to within the rooting zone and, thus, is not considered to be a primary control on the evolution of soil properties (Meiers *et al.*, 2011). Nonetheless, insufficient consideration has been given to evaluating the importance of these changes and how they relate to hydrological regime shifts on reclaimed slopes over time. Accordingly, an understanding of how the evolution of the hydrophysical properties of reclamation soil materials relates to the hydrological role of reclaimed slopes in the reconstructed landscape is required. In addition, soil materials used in the construction of these landscapes (e.g., peat/mineral mix soils) have demonstrated some hydrophobic tendencies. For example, Leatherdale *et al.* (2012) noted difficulty saturating samples of oil sands reclamation soils (peat/mineral mix and tailing sands) in the laboratory and suggested that this was caused by the hydrophobic properties of the materials. Hydrophobic soils tend to have lower surface infiltration rates and are often associated with enhanced overland flow (Doerr *et al.*, 2000). Consequently, the soil water regime of reclaimed slopes could be influenced by the presence and extent of soil hydrophobicity. However, quantification of the extent of the hydrophobicity and its impact on the hydrologic function of reclamation soil covers has not been documented.

This research examines the dominant controls on the soil water regimes of two reclaimed slopes in the AOSR. The approach is to compare the soil hydrophysical properties, soil water dynamics and runoff generation mechanisms on two reclaimed slopes that were reclaimed five years apart using the same prescribed soil-placement and revegetation approach. The discussion includes an evaluation of the role that existing slopes can play in watershed-scale landscape reclamation. Accordingly, the specific objectives of this research are to: 1) validate existing and identify new controls on soil water dynamics within two reclaimed slopes with differing reclamation timelines; 2) quantify the downslope movement of water; and 3) examine the function of reclaimed slopes in the context of landscape-scale design.

4.2 Site Description

4.2.1 Constructed watershed

This study was conducted in a constructed watershed (the Nikanotee Fen watershed) within the Millennium mine lease at Suncor Energy Inc. oil sands mining operations approximately 40 km north of Fort McMurray, Alberta (56°55.944'N 111°25.035'W; average watershed elevation ~288 masl; Figure 4-1). The individual landforms within the constructed watershed (total watershed area = 32.1 ha) include: an upland aquifer (7.7 ha) constructed from tailings sand materials; a fen peatland (2.9 ha) built using fen peat from newly developed lease areas; a sloping natural remnant of the pre-mining landscape (2.8 ha; the "natural slope"); and three reclaimed slopes of varying age and character (combined area = 18.7 ha). The upland aquifer and fen peatland are situated in a gently sloping valley bottom (constructed upland grade is ~3% towards the 0% grade fen peatland) surrounded by the other relatively steep landforms. The natural slope is composed of natural soils characteristic of the AOSR and is not included in this study. The two reclaimed slopes that are adjacent and run parallel to the upland-fen valley (i.e., sloping to the west and east; see Figure 4-1) are the focus of this study. However, the third reclaimed slope (located in the south east portion of the watershed) is occasionally discussed in this study as well. The final watershed design is described in detail by Daly *et al.* (2012) and Pollard *et al.* (2012).

4.2.2 Reclaimed slopes

The east slope (8.1 ha) was reclaimed in 2007 (soils placed) and revegetated in 2008 (herein referred to as the 2007 slope). In contrast, the west (2.4 ha) slope was reclaimed in 2011 and revegetated in 2012 (herein referred to as the 2011 slope). Planting on the slopes was guided by the Cumulative Environmental Management Association (CEMA) Revegetation Manual (Alberta Environment, 2010) and consisted primarily of white spruce (*Picea glauca*), aspen (*Populus tremuloides*), white birch (*Betula papyrifera*), green alder (*Alnus viridis*), as well as an assortment of shrubs (e.g., Saskatoon berry (*Amelanchier alnifolia*), pincherry (*Prunus pensylvanica*) and chokecherry (*Prunus virginiana*)). Both slopes are composed of overburden substrate from the Cretaceous Clearwater formation, which is dominated by shale and siltstone (Hackbarth and Nastasa, 1979). The Clearwater overburden material is overlain by a ~100 cm secondary capping layer of suitable overburden material and capped with a ~40 - 50 cm thick 'peat/mineral mix' cover soil. Overburden material is typically salvaged from deeper within the soil profile (below the solum) and is considered to be suitable for use as a secondary capping layer by Suncor Energy Inc. if the pH is less than 8, the electrical conductivity is less than 5 dS m^{-1} and the sodium adsorption ratio, which is a measure of the sodicity of the soil, is below 8 (J. Martin, personal communication). The 'peat/mineral mix' reclamation soil type is typically an amalgamation of organic peat and mineral soils obtained by over-stripping natural peat deposits underlain by glacial mineral soils (Meiers *et al.*, 2006). This soil layer was directly placed (i.e., not from stockpile) on the slopes in this study. Particle size distribution and organic matter content of the secondary capping and peat-mineral mix layers are included in Appendix 2. The 2011 slope was reclaimed using a similar reclamation prescription as the 2007 slope. However, these slopes demonstrated considerable contrast, which likely arose due to variability in the source and properties of the reclamation materials coupled with the immature vegetation stand and anticipated changes in soil structure following placement (Meiers *et al.*, 2006; Kelln *et al.*, 2007; Meiers *et al.*, 2011). The current study focuses on comparing and contrasting the 2007 slope primarily with the west 2011 slope. The southeast 2011 slope in the constructed watershed (8.2 ha; see Figure 4-1) was reclaimed at the same time and using the same material and technique as the west 2011 slope. The southeast 2011 slope is not explicitly addressed (although included in one dataset, as expressed below) in this study, however, it is expected that the processes operating on this slope are similar to those of the west 2011 slope, given their nearly identical construction timeframe, source material and reclamation prescription.

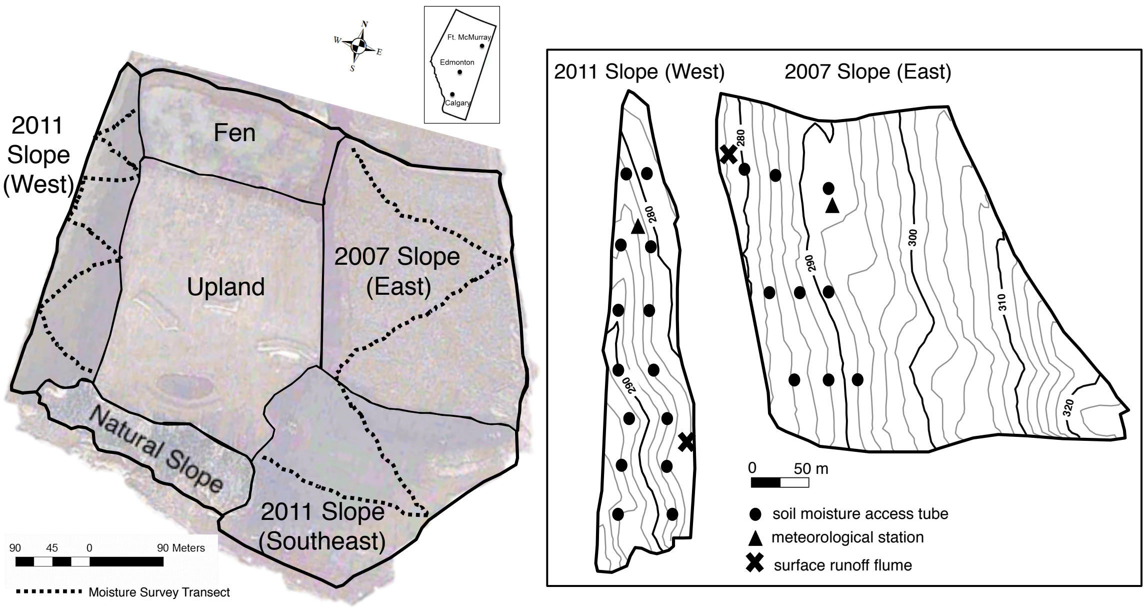

Figure 4-1 – LEFT: Location and general landform arrangement of the constructed Nikanotee Fen watershed including the shallow soil moisture survey transects. RIGHT: Detailed topographic maps of the 2007 (East) and 2011 (West) slopes. Minor contours (grey) are 2 m elevation increments. Subsurface flow trenches were located directly to the south of the surface runoff flume (2007 slope only).

4.3 Methods

4.3.1 Field methods

Meteorological stations were deployed on each the 2007 and 2011 (west) slopes in June 2012. Measurements of net radiation (NR-LITE2 net radiometer; 2.5 m height), ground heat flux (REBS HFT-3; 0.01 m depth) wind speed and direction (R.M. Young Wind Monitor; 2.75 m height), relative humidity and air temperature (Hobo U23 Pro v2 dataloggers; 1.0 and 2.3 m heights) were taken every minute and average values were recorded every 30 minutes using Campbell Scientific CR5000 dataloggers and Hobo dataloggers (relative humidity and air temperature data only). Soil moisture probes (CS-650) were installed into the peat/mineral mix reclamation surface soil layer at 2.5, 10 and 32.5 cm depths, as well as within the underlying secondary capping material at depths of 75 and 60 cm on the 2007 and 2011 slopes, respectively. Independent volumetric water content (*VWC)* calibration curve functions were derived for soils from each of the 2007 and 2011 slopes in the laboratory using soil samples extracted in the field, following standard procedures (e.g., Jacobsen and Schjønning, 1993). Transects of soil moisture profile access tubes were installed across the mid and lower portions of each slope (Figure 4-1). A Troxler Sentry 200CP moisture probe was used to measure soil moisture at depths of 7.5, 15, 25, 35, 50 and 75 cm within the access tubes (5.08 cm I.D. PVC pipe; n = 9 and 14 locations on the 2007 and 2011 slopes, respectively) on a weekly basis (2012 – 2014). Calibration curves were developed for both the 2007 and 2011 slope soils. Due to equipment failure, a Delta-T Devices PR2 Soil Moisture Profile Probe replaced the Troxler moisture probe in June 2014. New access tubes (2.8 cm I.D.) appropriate for the PR2 probe were installed within ~1 m of the Troxler access tubes. The depth intervals of the *VWC* measurements made using the PR2 probe (10, 20, 30, 40, 60, 100) are slightly different than those made previously with the Troxler probe. However, for illustrative and consistency purposes, they are shown and grouped as being made at the same depth for some of the analyses in this study. It is clearly stated that this has been done wherever relevant. Since this change applied to all measurements in the 2007 and 2011 slopes concurrently, they remain comparable. Shallow soil moisture surveys were conducted along transects through the 2007, 2011 (southeast) and 2011 (west) slopes approximately every ten days (2013 only; Figure 4-1). Measurements of the average *VWC* in the upper 7 cm (i.e., 0 - 7 cm) of the soil were made every 20 m using a Delta-T Devices WET Sensor (type WET-2) portable water content probe. Slope-specific calibration curves were developed in the laboratory and applied to these measurements using intact soil samples extracted from the field.

Soil pits coupled with the access tube measurements at three locations on each slope permitted measurement of the in-situ infiltration rate (*f*) using a single-ring infiltrometer at the surface, 10 and 30 cm depths as well as at the top of the secondary capping soil layer on each slope. Soil cores were also extracted at the same depth intervals for laboratory estimation of standard soil parameters and hydrophobicity (see details on laboratory methods below). In-situ *f* measurements were completed in both 2012 and 2013 while soil cores were only extracted in 2012. In 2014, two shallow trenches (each ~7 m long) were dug near the toe (lower slope) of the 2007 slope to estimate water movement via subsurface interflow. Trenches were dug to just below the top of the secondary capping material (~50 cm depth), lined with polyethylene and perforated PVC pipes that drained into 80 L buckets for collection of water and covered at the surface with plywood boards. Following rain events that produced interflow, the total volume of water in the buckets was measured and the buckets were emptied. A logging pressure transducer (Schlumberger Mini-Diver) was installed in one of the trench buckets to provide information on the timing of interflow generation. A surface runoff flume was installed near the toe of the 2007 and 2011 slopes, which consisted of plastic resin landscape edging set and sealed (with hydraulic cement) approximately 5-10 cm into the ground. This edging directed water flowing along the surface through a trough and into a bucket containing a v-notch and a logging pressure transducer (Schlumberger Mini-Diver). Manual measurements of discharge made during the spring freshet in 2013 provided independent rating curves for each flume. The surface runoff flume on the 2011 slope was only monitored during the 2014 season (in addition to the spring freshet period in 2013, when the rating curve was developed), while the 2007 slope flume was monitored throughout 2013 and 2014.

Detailed topographic surveys were completed for delineation of the sub-catchment gross drainage area for each of the runoff flumes. However, accurate delineation of the gross drainage area for the 2011 slope runoff flume was not possible due to dynamic erosional rill development and evolution during rainfall events and throughout the study period, which spontaneously directed water flows out of the topographically derived flume 'catchment' (this was not an issue on the 2007 slope due to the absence of rill erosion). Although this is unsuitable for expressing runoff depths quantitatively, due to the uncertainties associated with deriving a gross drainage area on the 2011 slope, these observations were instead used to validate precipitation-derived runoff generation thresholds. For example, data analyses identified the timing and occurrence of runoff at (i.e., water flowing through) the 2011 slope flume and compared this response at the flume to the precipitation intensity of each event. This provided information on the minimum precipitation intensity required to produce a surface runoff response from the 2011 slope (i.e., precipitation intensity threshold). The depth flux of runoff generated from the 2011 slopes was derived empirically using this precipitation intensity threshold and the storage capacity of the near-surface (0 – 2.5 cm) soil layer. This storage capacity, or fillable porosity, was calculated by subtracting the average pre-event *VWC* from the total soil porosity (see Laboratory methods section). Accordingly, surface runoff generation from the 2011 slope was presumed to occur once the storage capacity of the near-surface layer was satisfied and the precipitation intensity exceeded the observed threshold from the runoff flume observations. The location and elevation of all instrumentation was surveyed annually (± 0.005 m vertical accuracy) using a Topcon HiPER GL RTK GPS system (2012 and 2013) and a Leica Geosystems Viva GS14 GNSS RTK GPS system (2014).

4.3.2 Laboratory methods

Intact soil samples were extracted in the field using hollow steel (Shelby-type) soil tubes (5.5 cm I.D. x 5 cm height) driven into the ground at the specified depth intervals, wrapped in polyethylene film and carefully transported back to the laboratory. The bottoms of soil samples were protected with screening to minimize loss of sediments during analyses. Soil samples were analysed for total porosity (ϕ), specific yield (S_y) and bulk density (ρ_b) following standard methods (e.g., Freeze and Cherry, 1979; Klute, 1986), with the exception that samples were oven-dried at 80ºC. Saturated hydraulic conductivity (K_{sat}), soil water characteristic (retention) curves and hydrophobicity (see below) were determined for a sub-set of samples prior to oven drying. K_{sat} was determined on each sample using a constant head test (Freeze and Cherry, 1979). Samples with very low K_{sat} that required measurements over several days were carefully covered with polyethylene film to limit evaporation of ponded water. Soil water characteristic curves were determined using a 5 bar ceramic pressure plate extractor (Soil Moisture Equipment Corp. model #1600) and an air compressor controlled by a throttle valve and measured with a manometer tube. The pressure inside the chamber was raised above atmospheric pressure in incremental steps, which forced water out of the soil samples via a porous ceramic plate on which the soil samples were placed. *VWC* of the soil samples was determined gravimetrically at each pressure step once a stable mass was reached. A ceramic plate with a 1 bar air-entry pressure was used for the lowest pressure ranges (0 - 1 bar) and a 5 bar ceramic plate was used thereafter.

Hydrophobicity (soil water repellency) was estimated at the stabilized *VWC* at several pressure steps using the water drop penetration time (WDPT) method (Letey, 1969). This test involves recording the time taken for the complete penetration of a water drop placed on the surface of a soil (Letey, 1969). The standardized WDPT test procedure followed that outlined in (Doerr, 1998) and involved application of five drops of distilled water (at ~20ºC) to the soil surface using a syringe and hypodermic needle. The median penetration time was considered to be representative of the WDPT of each sample (cf. Doerr, 1998). Samples were categorized in terms of level of hydrophobicity severity according to Bisdom *et al.* (1993); < 5 s WDPT (hydrophilic), 5 - 60 s (slightly hydrophobic), 60 - 600 s (strongly hydrophobic), 600 - 3600 s (severely hydrophobic) and > 3600 s (extremely hydrophobic). Although somewhat arbitrary, the categorization of soil samples by level of hydrophobicity provides a useful summary and comparison between different soils (Doerr, 1998) and demonstrates the effect of moisture content on soil hydrophobicity.

4.3.3 Statistical methods

A Shapiro-Wilk normality test was performed on the data (ϕ, ρ_b, Troxler/PR2 access tube *VWC* measurements and shallow soil *VWC* survey data) and the results were verified by graphical assessment of quantile-quantile plots. For data with non-normal distributions (ϕ, ρ_b, Troxler/PR2 access tube *VWC* measurements), Wilcoxon rank sum tests were conducted to determine if there was a statistical difference between *VWC* measurements on the 2007 and 2011 slopes (H_o: the differences between distributions of both populations is zero). The significance of linear regression models (shallow soil *VWC* survey data; normally distributed) was assessed using *t*-tests (H_o: the slope of the *VWC* and surface elevation relationship is zero, thus, they are independent). All statistical analyses was completed in R Statistical Software (Version 0.98.1056; R Core Team, 2013).

4.4 Results

4.4.1 Hydrophysical properties and hydrophobicity

Peat/mineral mix soils on the more recently reclaimed 2011 slope had a higher median ρ_b and lower median ϕ than soils on the older 2007 slope (Figure 4-2). The results of the Wilcoxon rank sum tests indicate statistical differences in ϕ (W = 115.5; p = 0.04) but not ρ_b (W = 55; p = 0.23) between the 2011 and 2007 slope soils. However, differences in ρ_b between slopes were significant (W = 6; p = 0.03) in the upper 20 cm of the soil profile (i.e., when depths greater than 20 cm were excluded from the statistical analyses). The secondary capping material, which exhibited similar hydrophysical properties on both slopes, had a much higher ρ_b (average = 1.7 g cm^{-3}; n = 6) and lower ϕ (average = 0.36; n = 6) than the overlying peat/mineral mix soils on both slopes. The infiltration rate, f (geometric mean values stated), at the surface of the 2007 slope was 195 mm hr^{-1}. This was more than five times greater than f at the surface of the 2011 slope (35 mm hr^{-1}), which declined sharply to 1 mm hr^{-1} in the upper 10 cm (Figure 4-2). Similarly, the near-surface K_{sat} (9 x 10^{-5} m s^{-1}) of the 2007 slope was nearly two orders of magnitude greater than that of the 2011 slope (1 x 10^{-6} m s^{-1}). K_{sat} and f declined with depth in the upper 30 cm of both slopes, with K_{sat} on the 2011 slope increasing deeper in the profile. The lowest K_{sat} and f on the 2007 slope was within the secondary capping soil layer (~60 cm depth), whereas these minima occurred closer to the surface within the peat/mineral mix soil layer (~20 – 30 cm depth) on the 2011 slope (Figure 4-2).

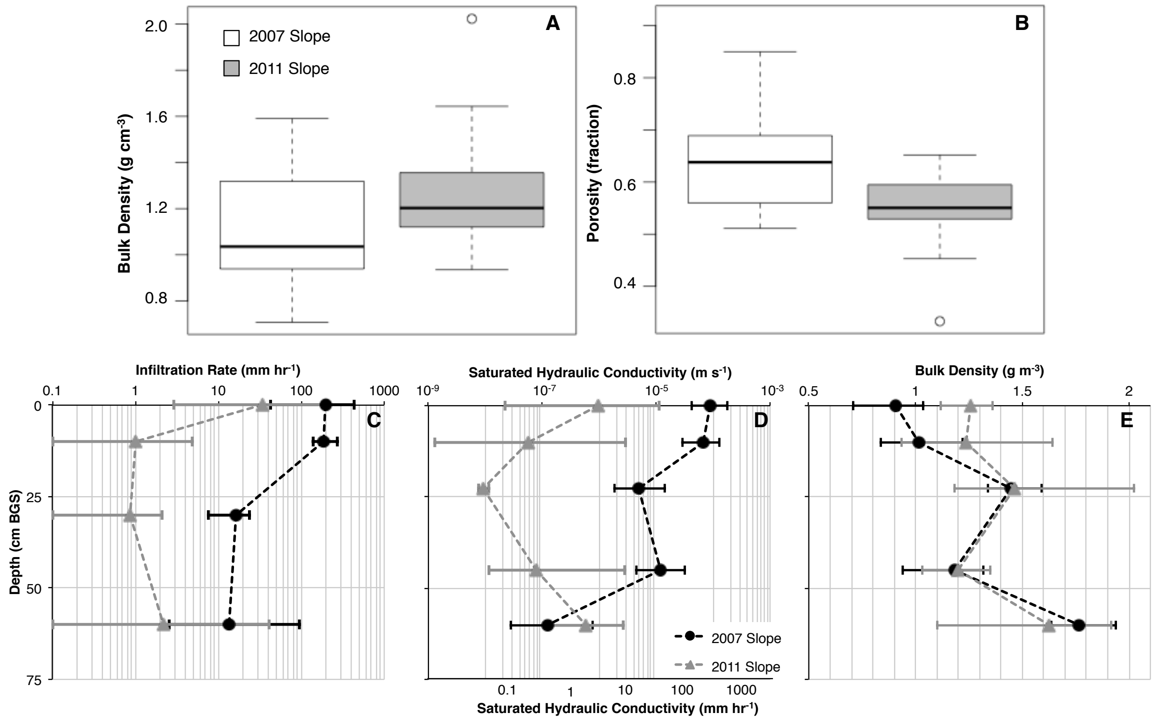

Figure 4-2 – A & B: Boxplots of soil bulk density, ρ_b, (A) and porosity (B) for the peat/mineral mix soils on the 2007 and 2011 slopes (n = 12 for each slope). Note the boxplots do not include data from the secondary capping soil layer. C, D & E: infiltration rate, f (C), saturated hydraulic conductivity, K_{sat} (D) and ρ_b (E) with depth for the 2007 and 2011 soils (n = 4 to 12 per depth for f and n = 3 per depth for K_{sat} and ρ_b). Horizontal bars on C, D & E indicate the range in data (i.e., maximum and minimum values) and the solid points represent the geometric (C & D) and arithmetic (E) mean. Note that the 60 cm depth on C, D & E is within the secondary capping soil layer and all other depths are within the peat/mineral mix reclamation soil layer.

For the lowest pressure tested (-4000 mb), soil water retention followed the trend of 2011 slope > 2007 slope (for the same depth) and deeper soils > surficial soils (for the same slope; Figure 4-3). Thus, soils from the 2011 slope retained water more strongly than soils of the same depth from the 2007 slope. Surface soil samples (i.e., 0 – 5 cm) from both slopes had a higher saturated *VWC* but lower water retention than soils from deeper within the soil profile (i.e., 20 – 25 cm). For example, surface soil samples from the 2007 and 2011 slopes declined from saturated *VWC* by 0.45 and 0.24, respectively, while the *VWC* of deeper soil samples was only reduced by 0.22 and 0.09 for the 2007 and 2011 slopes, respectively. The secondary capping material displayed a similar trend to that of the 2011 slope deep peat/mineral mix soil (i.e., WS 22.5 cm), however, at a consistently lower *VWC* than the peat/mineral mix soils.

Soil hydrophobicity decreased rapidly with increasing *VWC* for all soils (Figure 4-4). Soils from both the 2007 and 2011 slopes were classified as strongly hydrophobic at the lowest soil water pressure tested (~25 – 40% *VWC*, depending upon the soil water characteristic curve). At the same moisture content, the surface soils (0 – 5 cm) on the 2011 slope were more hydrophobic than the surface soils on the 2007 slope. Surface soils on both slopes exhibited less hydrophobicity than soils deeper in the soil profile. The most hydrophobic soil was the secondary capping soil layer, which was classified as extremely or strongly hydrophobic across the range of moisture contents tested, with the exception of the highest *VWC* where it was classified as only slightly hydrophobic.

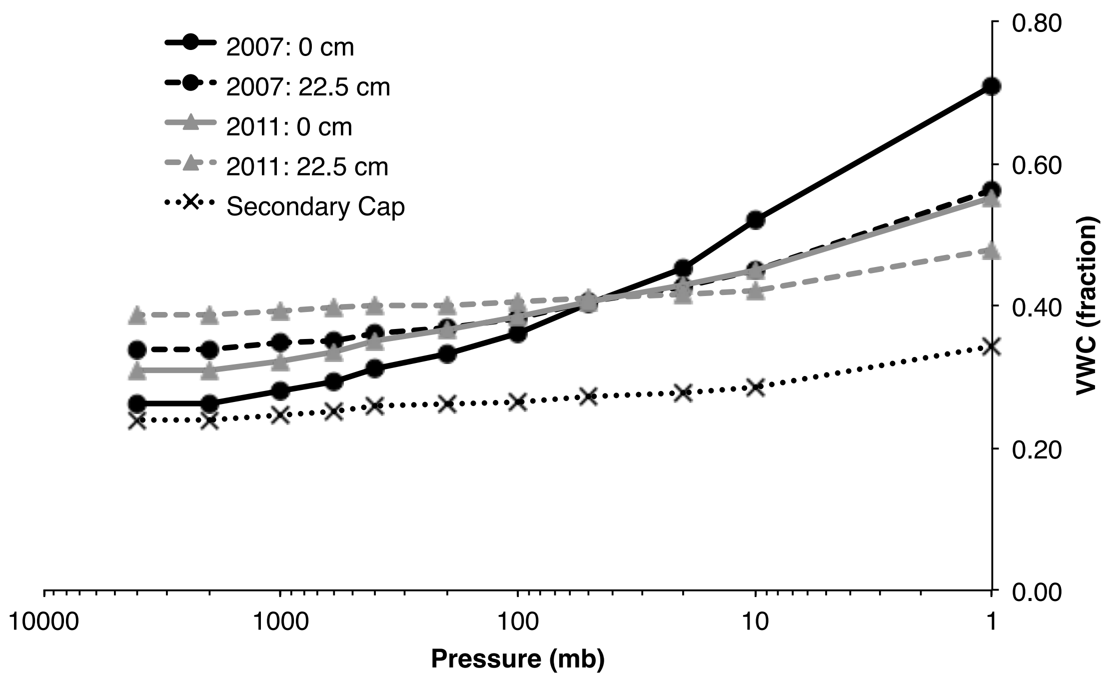

Figure 4-3 – Soil water characteristic (retention) curves. 0 cm and 22.5 cm represent soil samples extracted from 0 – 5 cm and 20 – 25 cm depth intervals. The secondary capping soil material is denoted as “Secondary Cap”. Each curve represents the average of triplicate soil samples. Soil samples from both the 2007 (n = 2) and 2011 (n = 2) slopes comprise the secondary capping soil layer curve.

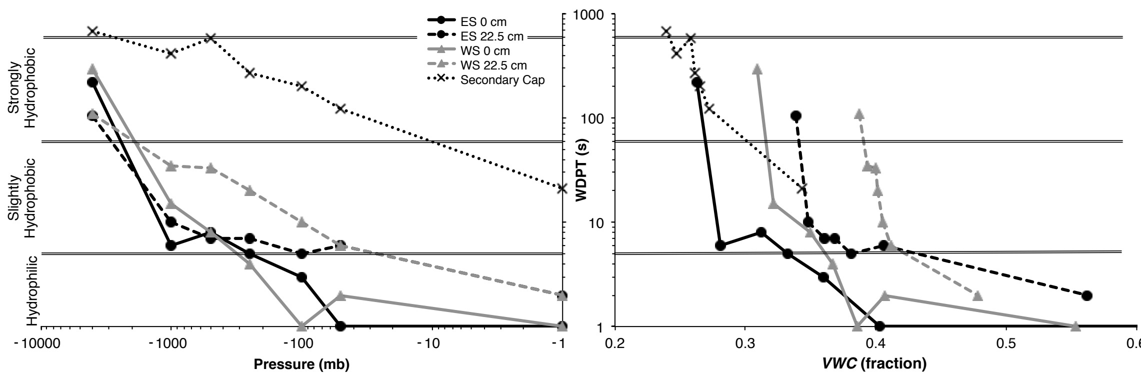

Figure 4-4 – The extent of soil hydrophobicity and the influence of soil water pressure (left) and soil water content (right). Hydrophobicity severity was categorized according to Bisdom *et al.* (1993).

4.4.2 Soil water regimes

During 2013 and 2014, the near-surface *VWC* responded strongly to *P* events on the 2007 slope, with increasingly dampened responses deeper in the soil profile (Figure 4-5). The soil water regime of the 2007 slope also demonstrated seasonality, with wetter conditions apparent in the early to mid summer period and a drying trend during the later summer and autumn months of both years. In contrast, *VWC* remained relatively stable at all depths throughout the soil profile on the 2011 slope during both 2013 and 2014. *VWC* on the 2011 slope generally increased with depth, with the exception of a period in early May when the majority of water at the top of the secondary capping layer (60 cm depth) was still frozen, as indicated by soil temperatures below 0°C (data not shown). Since measurements of the *VWC* of frozen soils using time domain reflectometry does not include ice content (Patterson and Smith, 1981), the *VWC* measurements during this period of time only include the unfrozen water content and, thus, appear low. Upon thawing, the secondary capping soil layer *VWC* was fairly stable and remained slightly below saturation on both slopes during both years. The only notable exception to this was when this layer briefly reached saturation during a very wet period in early June 2013.

Similar to the time-series *VWC* measurements, the spatially distributed *VWC* access tube measurements made across the slopes (n = 9 and 14 locations on the 2007 and 2011 slopes, respectively; Figure 4-1) indicated that the 2011 slope *VWC* generally increased with depth in the soil profile (Figure 4-6). However, the greater measurement resolution with depth revealed that the 2011 slope exhibited a fairly uniform soil moisture distribution at depths greater than ~25 cm. In contrast, *VWC* on the 2007 slope tended to increase with depth throughout the soil profile. The *VWC* within the secondary capping soil layer on both slopes (75 cm depth in Figure 4-6) was typically more spatially variable than the peat/mineral mix soil layers. These distinct trends were consistent at the upper and lower slope positions on both slopes. However, the *VWC* at lower slope positions on the 2007 slope was consistently higher than the *VWC* at upper slope positions at the same depth ($p < 0.02$; Table 4-1), except for at 75 cm (Figure 4-6). A similar trend was not observed on the 2011 slopes where there was no discernable difference in *VWC* at upper and lower slope positions. Furthermore, the near-surface (0 – 7 cm depth) *VWC* survey measurements made along transects that spanned the entire topographic range of the slopes (see Figure 4-1) indicated that *VWC* within the upper 7 cm of the soil was typically highest at topographically low slope positions on the 2007 slope (i.e., lower *VWC* towards the slope crest, Figure 4-7). Conversely, the near-surface *VWC* tended to increase with increasing surface elevation (i.e., higher *VWC* towards the slope crest) on the 2011 slopes (note that the southeast 2011 slope is included in this analyses to increase the topographic range of the data from the 2011 slope). *t*-tests indicated that the slope of this relationship was significant ($p < 0.01$) on both slopes.

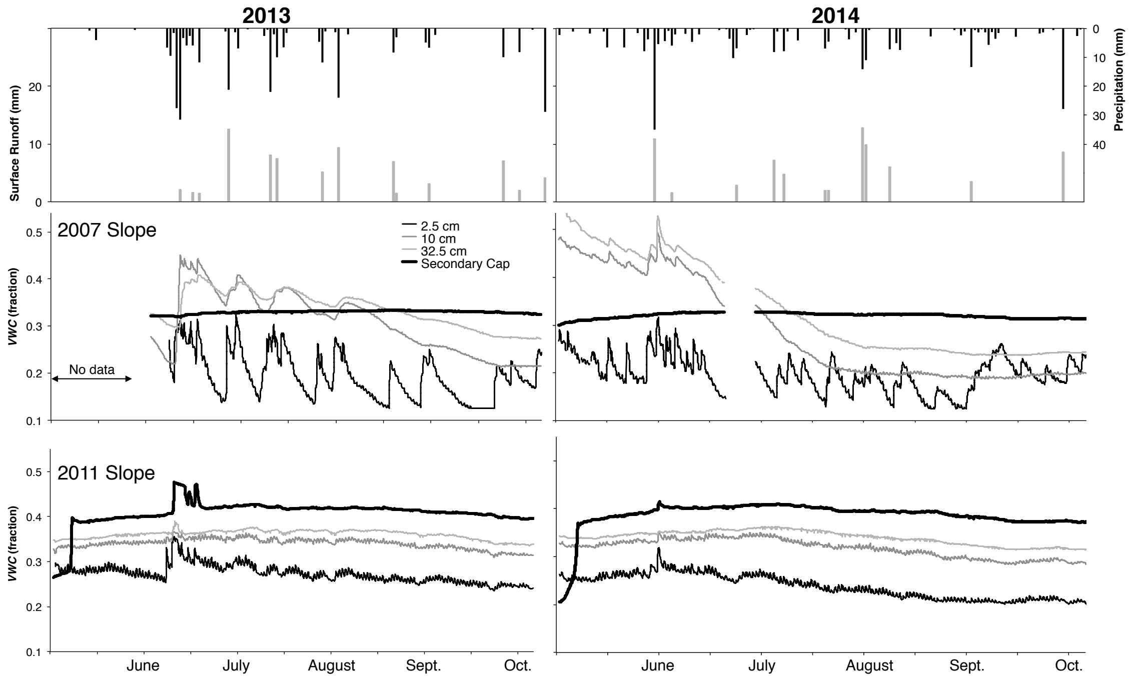

Figure 4-5 – In-situ *VWC* measurements on the 2007 (middle) and 2011 (bottom) slopes for the periods of May to October in 2013 and 2014. The black and gray bars (top) represent precipitation and surface runoff (2011 slope only), respectively.

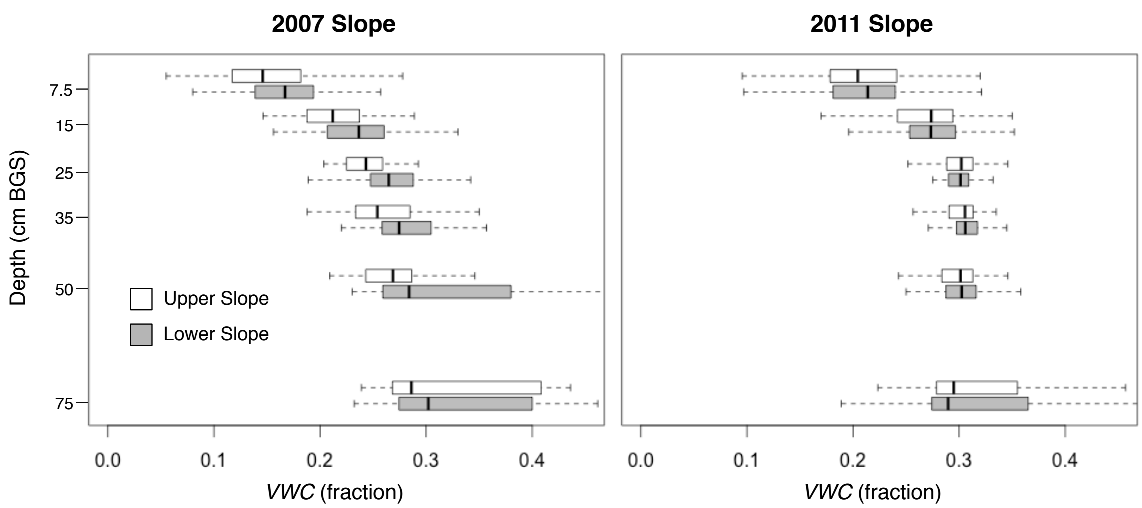

Figure 4-6 – Soil water distribution profiles from *VWC* measurements made within access tubes located throughout both slopes (n = 9 and 14 locations on the 2007 and 2011 slopes, respectively; outliers removed from plot to increase clarity of trends). See Figure 4-1 for measurement locations. Data from 2012 – 2014; 85 measurements per location over this time. Note that the actual measurement depths of data collected between June – August 2014 are slightly, but consistently at all locations, different than the depths that appear on the y-axis (see Field methods section).

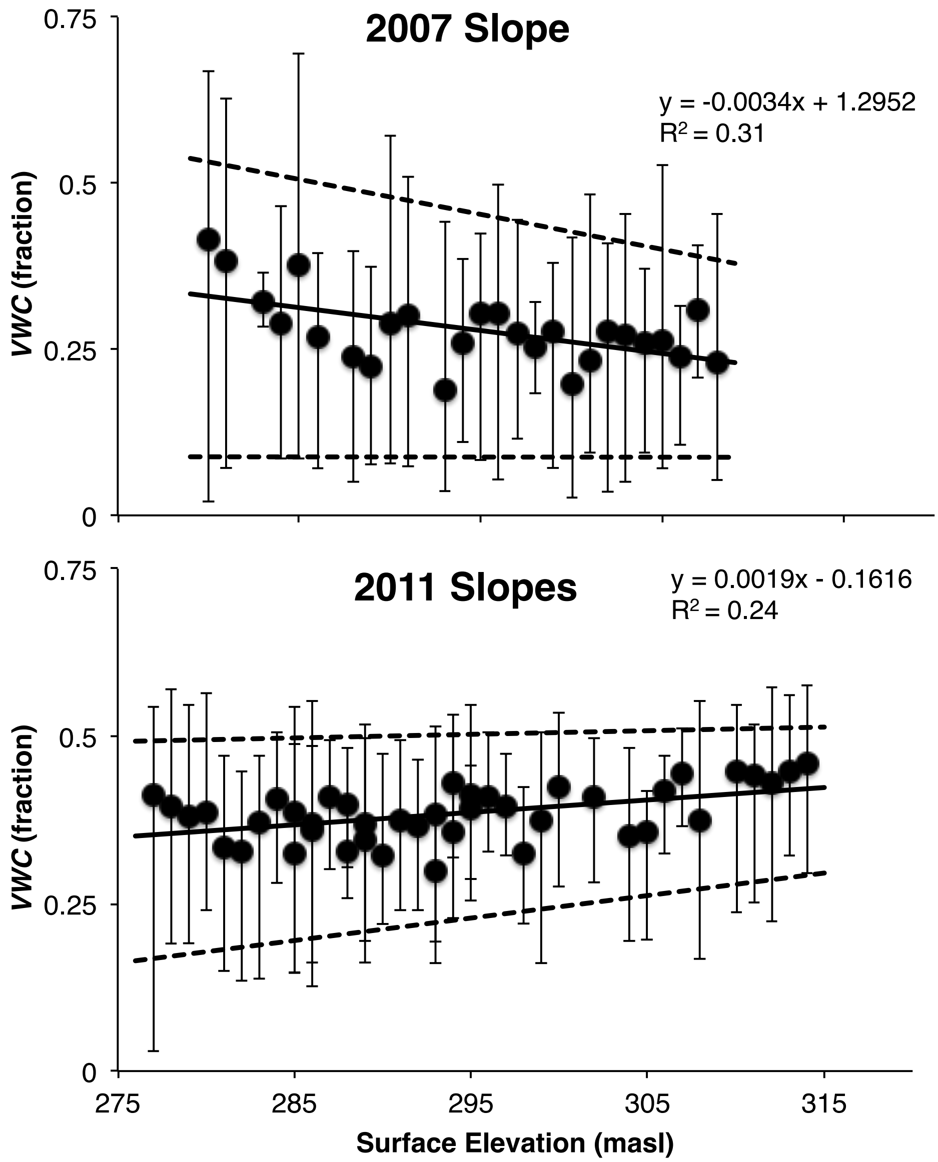

Figure 4-7 – Average *VWC* measurements in the upper 7 cm of the soil versus surface elevation of the 2007 and 2011 slopes during 2013 (2011 slopes includes data from both the southeast and west 2011 slopes to increase the elevation range). Error bars represent the range (max, min) observed at each elevation. Dashed lines are the trendlines for the max and min data series.

Table 4-1 – Wilcoxon rank sum tests of difference of *VWC* between upper and lower slope position for the 2007 and 2011 slopes; absolute difference in median *VWC* (fraction) and *p*-value results are shown (significant test results at $p < 0.02$ shown in bold).

Depth	2007 Slope			2011 Slope		
	VWC Difference	*p*-value	*W*	*VWC* Difference	*p*-value	*W*
7.5	**0.02**	**0.017**	**4432**	< 0.01	0.19	20261
15	**0.02**	**< 0.001**	**4767**	< 0.01	0.21	20084
25	**0.02**	**< 0.001**	**5108**	< 0.01	0.47	17918
35	**0.03**	**< 0.001**	**5076**	< 0.01	0.28	19896
50	**0.02**	**0.002**	**4627**	< 0.01	0.17	20123
75	0.01	0.53	3639	< 0.01	0.71	17936

The influence of topography on slope response to precipitation events also varied between the 2007 and 2011 slopes. For example, the 2007 slope demonstrated differing responses at upper and lower slope positions following a 60 mm precipitation event (8/9-June-2013) whereas the 2011 slope responded in a similar (and more muted) manner irrespective of slope position (Figure 4-8). The *VWC* at the lower slope position on the 2007 slope responded strongly to the water input, as *VWC* increased by 0.15 to 0.2 at all but the shallowest depth. The *VWC* profile at the upper slope position of the 2007 slope increased slightly following the *P* event, but to a much lesser extent than the lower slope position. The exception was the response in the secondary capping material (i.e., 75 cm depth in Figure 4-8), which increased by 0.15 – 0.2 at both the upper and lower slope positions on the 2007 slope. Note that some of the *VWC* measurements made within the secondary capping material exceeded the measured ϕ of this layer, which indicates that some preferential percolation might have occurred between the access tube and the soil that could cause temporary ponding of water at depth (i.e., around the bottom of the access tube) and cause a slight overestimation of *VWC*. Nevertheless, the 2011 slope *VWC* did not increase to the same extent as the 2007 slope, and the upper and lower slope positions responded in a similar manner. On this slope, the *VWC* responded by only 0.04 – 0.08 in the upper 15 cm and only very slightly (i.e., ~0.01) at greater depths. As with the 2007 slope, the secondary capping soil layer increased by 0.15; however, this response was only observed at the upper slope position on the 2011 slope.

4.4.3 Runoff generation and interflow

Monitoring of surface runoff flumes indicated that overland flow occurred infrequently on the 2007 slope and typically generated only small amounts of runoff (usually << 1 mm; Table 4-2). One anomalous exception to this occurred in the early summer period of 2014 under conditions of high antecedent soil *VWC* (30/31-May-2014; Figure 4-5) during a large (41 mm) rainfall event, which was preceded by an additional 20 mm of precipitation over the previous nine-days. This event generated 6 mm of runoff and was the only substantial runoff observed from the 2007 slope in either 2013 or 2014 (excluding the spring freshet). Conversely, overland flow from the 2011 slopes occurred more frequently. For example, during the period of 1-May to 1-October 2014, 14 separate surface runoff events were observed at the runoff flume on the 2011 slope, whereas only two surface runoff events were observed at the 2007 slope flume during the same time period (Table 4-2). These field measurements indicated that surface runoff was produced on the 2011 slopes during most precipitation events that exhibited a precipitation intensity (*i*) greater than ~3 mm hr^{-1} (Figure 4-9). This field-based runoff threshold (3 mm hr^{-1}) is lower than the *f* measured at the surface of the 2011 slope (35 mm hr^{-1}) but higher than the *f* measured at 10 cm depth (1 mm hr^{-1}; Figure 4-2). Thus, it can be considered as within the range of near-surface *f* measured on the 2011 slopes. Due to the uncertainties associated with deriving a gross drainage area for the 2011 slope flume discussed previously (see Field methods section), and a lack of data at the 2011 slope flume during the 2013 field season, the depth flux of runoff generated from the 2011 slope was determined empirically for 2013 and 2014 using the *i* threshold derived from the flume observations (3 mm hr^{-1}) and the antecedent storage capacity of the near-surface (0 – 2.5 cm) soil layer. In order for runoff to be generated in this analyses, both the near-surface soil storage capacity and *i* threshold must be exceeded. This empirical runoff generation analyses showed good agreement with the field-based runoff observed in the flume (Table 4-2) and revealed that infiltration-excess (Hortonian) overland flow generation events were short in duration (<1.5 hrs) but capable of producing substantial surface runoff (Figure 4-5). These surface runoff events occurred more frequently and generated considerably more runoff on the 2011 slope (19 occurrences, 125 mm total in 2013 and 2014 combined) than the 2007 slope (five occurrences, 7 mm total in 2013 and 2014 combined (Table 4-2). Interflow also occurred infrequently on the 2007 slope, with a total of 140 L of water measured in the two subsurface interflow collection pipes between 20-June and 18-August 2014, which represented a flux of < 1 mm.

Table 4-2 – Surface runoff and subsurface (interflow) event characteristics on the 2007 and 2011 slopes. Data includes the empirically derived infiltration excess runoff analyses (based on *i* and antecedent soil storage capacity; 2011 slopes only), field measurements of runoff through the surface flumes (2007 and 2011 slopes) and the interflow trenches (2007 slope only).

Slope	Method of runoff estimation	2013 17-June to 20-August			2014 1-May to 1-October		
		Number of events	Runoff total (mm)	Average duration (hr)	Number of events	Runoff total (mm)	Average duration (hr)
2011 Slope	Empirical	8	52	1.0	11	73	1.1
2011 Slope	Flume	NA	NA	NA	14	NA	1.25
2007 Slope	Flume	3	< 1	6.5	2	6	29.5
2007 Slope	Subsurface interflow	NA	NA	NA	6	< 1	40

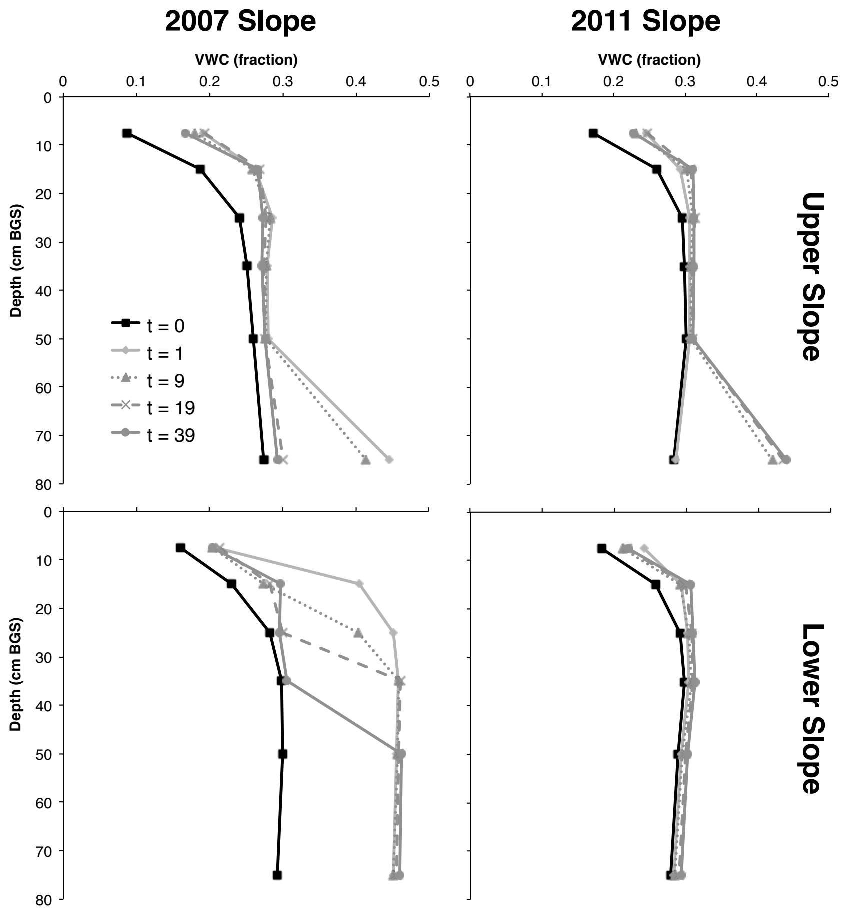

Figure 4-8 – *VWC* profiles before (t = 0) and following (t = 1 through 39 days) a 60 mm precipitation event at upper and lower slope positions on the 2007 and 2011 slopes (8/9-June-2013).

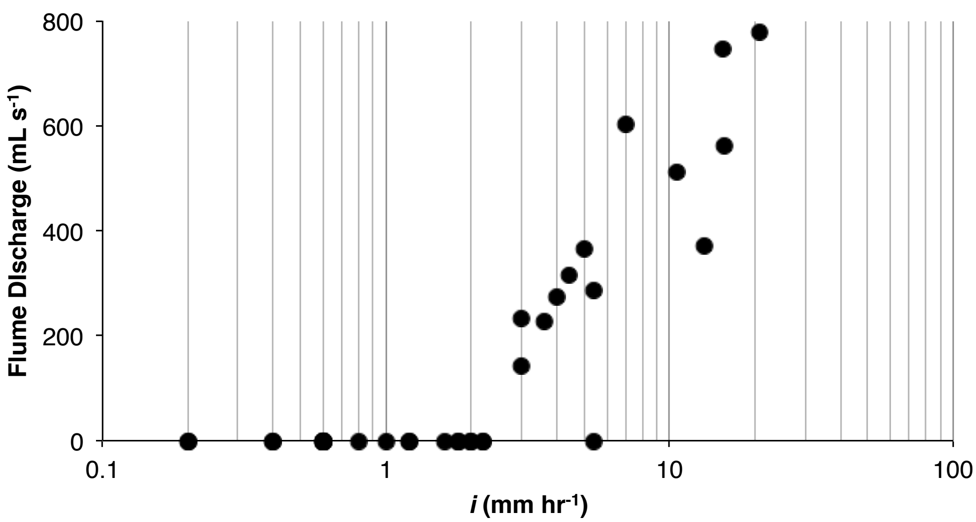

Figure 4-9 – Maximum discharge measured in the runoff flume versus precipitation intensity (i) during each event on the 2011 slope.

4.5 Discussion

4.5.1 Controls on the distribution of water within reclaimed slopes

This study demonstrates that water distribution, storage and release from reclamation soil covers are strongly controlled by the soil hydrophysical properties. For example, the differences in ϕ and ρ_b exhibited by the slopes (Figure 4-2) contributed to the contrasting storage properties of the soils, as evidenced by differing soil characteristic curves. These demonstrated that water was released from the 2007 slope soils more easily than soils from the same depths on the 2011 slope (Figure 4-3). Thus, it is probable that the higher ϕ on the 2007 slope soils is due to the presence of large pores. Additionally, the higher f on the 2007 slope contributed to greater percolation and storage of precipitation inputs than the more recently constructed 2011 slope, which had a surface f that was 20% that of the 2007 slope (Figure 4-2). These differences in f are also a reflection of the contrasting hydrophysical properties of the two slopes, since the f of a soil is directly related to the saturated hydraulic conductivity of the soil profile (Dingman, 2002) and, in turn, soil parameters such as ϕ and ρ_b. Peat/mineral mix soils on the 2007 slope had a consistently higher K_{sat} with depth than the 2011 slope (except for the underlying secondary capping soil layer, which had similar properties on both slopes), in spite of similar ρ_b at depths greater than ~20 cm. Furthermore, soils from the 2011 slope were more hydrophobic than soils from the older 2007 slope, which can further constrain infiltration (Doerr *et al.*, 2000). According to the classification of Bisdom *et al.* (1993), surface soils on the 2011 slope were classified as strongly hydrophobic at the lowest *VWC* tested (~31%), whereas surface soils on the 2007 slope at the same *VWC* were only classified as slightly hydrophobic (Figure 4-4). Since soil hydrophobicity is generally higher under dry soil moisture conditions (Doerr *et al.*, 2000), and near-surface *VWC* measurements from both slopes were typically lower in the field than the moisture conditions under which hydrophobicity was assessed in the laboratory, soils in the field were likely more strongly hydrophobic than the estimates reported in the current study (i.e., drier soils in the field would produce more severe hydrophobicity). Nevertheless, reclamation soils from both slopes were classified as strongly hydrophobic at the lowest *VWC* tested and, thus, hydrophobicity likely influenced infiltration dynamics on both slopes. Reclamation soils with hydrophobic tendencies can contribute to decreased infiltration and increased runoff from reclaimed slopes in the AOSR (Leatherdale *et al.*, 2012). The severe hydrophobicity of the 2011 slope soils likely contributed to the observed low near-surface *f,* and the higher frequency and larger amount of surface runoff generated from this slope (Table 4-2).

The contrasting hydrophysical properties of the 2007 and 2011 slopes are also reflected in the observed *VWC* regimes. For example, the greater near-surface K_{sat} and *f* of the 2007 slope resulted in a moisture regime that was more variable than that of the 2011 slope (Figure 4-5). Consequently, the 2007 slope was more closely coupled to atmospheric processes (e.g., precipitation). In contrast, the 2011 slope moisture regime was relatively stable and only responded to precipitation events under extreme conditions. Further, the high K_{sat} on the 2007 slope enabled more efficient water redistribution, as evidenced by the stronger topographic control on moisture distribution on the 2007 slope relative to the 2011 slope. For example, *VWC* was consistently greater (often with statistical significance; Table 4-1) at lower slope positions on the 2007 slope relative to the *VWC* at upper slope positions (Figure 4-6). This concurs with the results of Kelln *et al.* (2007), who observed higher *VWC* at lower slope positions on reclaimed slopes that had been reclaimed for ~seven years. However, *VWC* was similar at upper and lower slope positions on the more recently reclaimed 2011 slope because the lower K_{sat} (Figure 4-2) restricts water redistribution downslope. In the near-surface soil (i.e., upper 7 cm), topography also had a statistically significant and contrasting influence on the *VWC* of each slope. For example, *VWC* was higher at topographically high slope positions on the 2011 slope (i.e., increasing *VWC* towards the slope crest, Figure 4-7; slope of linear regression model significant at $p < 0.01$). Conversely, *VWC* was higher at topographically low slope positions on the 2007 slope (i.e., decreasing *VWC* towards the slope crest; significant at $p < 0.01$). These trends were strongest under dry conditions on the 2011 slopes, as indicated by the relatively steep slope of the lower dashed line in Figure 4-7. The 2007 slope demonstrated little variation in *VWC* with elevation under dry conditions (near-zero slope of lower dashed line). The opposite was true under wet conditions, when topography more strongly controlled the distribution of water on the 2007 slope (steep slope on upper dashed line) and had little influence on the 2011 slopes (near-zero slope of the upper dashed line). Similar to the significant yet contrasting influence of topography on the soil water distribution demonstrated by the two slopes in the current study, Leatherdale *et al.* (2012) found that slope position did not have a consistent effect on moisture distribution on reclaimed slopes that ranged in age from ~two to 13 years. The differences observed in the near-surface soil of the current study are likely a function of the differences in the soil-water characteristic curves of each soil, since the 2007 slope has low water retention and, thus, minimal topographic influence on near-surface *VWC* during dry periods when water was limited. Since water was retained more strongly on the 2011 slope, near-surface *VWC* values remained fairly high under dry conditions. However, the trend on the 2011 slope (higher *VWC* with higher topography) is not intuitive and reflects the constrained water redistribution on this slope caused by the low K_{sat}. Thus, the distribution of soil water more closely followed topographic position in the older 2007 slope (five to seven years since reclamation) with a substantially higher K_{sat}, but did not on the newer 2011 slope (one to three years since reclamation) with a K_{sat} ~two orders of magnitude lower. Since the K_{sat} of reclamation materials can increase substantially in the first few years following reclamation (Meiers *et al.*, 2011), it can be expected that topography will have an increasing influence on soil water distribution on the 2011 slope as the K_{sat} increases over the following few years.

Similar topographic patterns are also apparent in the response and subsequent drainage of precipitation inputs from the 2007 and 2011 slopes. For example, the *VWC* at the lower slope position on the 2007 slope increased substantially following a large (60 mm) precipitation event in early June 2013 (Figure 4-8). The 2011 slope responded more weakly to the same event and exhibited a similar response at both upper and lower slope positions. An exception to this was the deepest measurement point (i.e., 75 cm) in the secondary capping material at the upper slope position on the 2011 slope. The magnitude of the response in the secondary capping layer relative to the limited response in the peat mineral mix soil layer indicates that some precipitation water percolated into the slope via preferential flow paths, similar to that observed by Kelln *et al.* (2007). This is supported by the comparable responses observed in the secondary capping layer at the upper and lower slope positions on the 2007 slope. Since secondary porosity develops over time following soil placement (Guebert and Gardner, 2001; Kelln *et al.*, 2007), infiltration via preferential flowpaths was likely greater on the 2007 slope relative to the 2011 slope due to the greater time since reclamation. Further, the secondary capping layer *VWC* responded at both slope positions on the 2007 slope, while this layer only responded at the upper slope position on the 2011 slope, since the secondary porosity is likely not as extensively developed. The *VWC* profile on the 2007 slope slowly returned to the pre-event conditions over the following several weeks (during which several smaller *P* events occurred) at the lower slope position, as the water stored in the slope was lost to the atmosphere or seeped further downslope.

4.5.2 The role of reclaimed slopes in constructed watershed hydrology

The results of the current study suggest that surface infiltration capacity and rainfall intensity and quantity are the strongest controls on runoff generation from recently reclaimed slopes (i.e., the 2011 slope). For example, surface runoff generation from the 2011 slope occurred much more frequently and produced substantially more runoff than the 2007 slope. In contrast, surface runoff generation on the 2007 slope, which had a surface f (195 mm hr^{-1}) that far exceeded the highest i, occurred infrequently and was usually an unsubstantial flux of water. Runoff from the 2011 slope typically occurred during rainfall events that were large enough to satisfy the (limited) soil water storage of the upper 2.5 cm of soil, as well as of sufficient intensity (>3 mm hr^{-1}; Figure 4-9) to exceed the f of the near-surface soil layer after soil storage was satisfied. Similarly, Nicolau (2002) found that rainfall volume was the major parameter responsible for runoff response from low permeability overburden slopes where most rainfall was converted into runoff (Nicolau, 2002). Although the measured f at the surface of the 2011 slope (35 mm hr^{-1}) was higher than the i threshold, f rapidly declined to 1 mm hr^{-1} in the upper 10 cm. This decline in f likely occurred within the upper few centimeters, as indicated by the weak response to precipitation events in the near-surface soil (-2.5 cm; Figure 4-5). Thus, it was assumed that surface runoff generation on the 2011 slope occurred once the storage capacity of the near-surface (0 – 2.5 cm) layer was satisfied and i exceeded the observed threshold of 3 mm hr^{-1} (Figure 4-9). Comparisons of the empirically derived estimate of surface runoff from 1-May to 1-October 2014 *VWC* (11 runoff events) and field observations of runoff measured in the flume over the same time period (14 events) showed good agreement (Table 4-2). The current study does not account for the influence of different interception rates on surface runoff generation. General conclusions about interception losses from vegetation communities are difficult to make since interception typically depends on several climatic factors (e.g., amount/intensity/duration of rainfall, wind speed) in addition to characteristics of the vegetation canopy (e.g., canopy storage capacity, leaf area index; Crockford and Richardson, 2000). The vegetation community on the 2007 slope is more mature and has a higher leaf area index than the 2011 slope (data not shown), which likely results in a higher canopy storage capacity that could contribute to higher rates of interception on the 2007 slope relative to the 2011 slope. However, the near-surface *VWC* on the 2007 slope responded strongly to *P* events (Figure 4-5), which suggests that a substantial amount of *P* was still reaching the soil surface on this slope. In addition, rainfall in the AOSR is often delivered as convective storms of high intensity and short duration (Carey, 2008). Since rainfall events of high intensity and short duration result in lower interception values than low intensity long duration events (Crockford and Richardson, 2000), interception differences between slopes would be minimized during intense rainfall events. Surface runoff was typically only generated from the 2011 slopes during rainfall events of high precipitation intensity (e.g., > 3 mm hr^{-1}; Figure 4-9). Thus, interception rates likely had a negligible impact on the surface runoff generation observed in the current study.

Visual field observations of occasional near-saturated conditions at several locations along the toe of the 2007 slope suggested that some downslope interflow occurred when the storage capacity of the 2007 slope was exceeded during precipitation events. Infiltration measurements made at depth within the 2007 slope suggest that this interflow likely occurred as perched shallow subsurface stormflow development over underlying layers with low *f* (e.g., secondary capping material). Measurements of cumulative interflow made between June and August 2014 equated to less than 1 mm, which indicated that interflow from the 2007 slope was not a hydrologically substantial flux of water. Similarly, Kelln *et al.* (2006) found that interflow on reclaimed slopes during the snow-free period occurred infrequently; however, interflow can continue intermittently throughout the summer and fall of an exceptionally cool and wet year (Kelln *et al.*, 2007). Interflow on the 2011 slope (not measured) was likely less than the 2007 slope, since the K_{sat} was typically two to three orders of magnitude lower than that of the 2007 slope (Figure 4-2). Further, the soil profile on the 2011 slope responded weakly to precipitation events (e.g., low variability in *VWC* profile in Figure 4-5), thus indicating that percolation was sufficiently constrained to inhibit the occurrence of interflow.

The hydrophysical properties of materials used in mine reclamation can change substantially over the first several years following placement (e.g., Guebert and Gardner, 2001; Kelln *et al.*, 2007; Meiers *et al.*, 2011). The observed differences in water distribution and runoff generation, between the older 2007 and more recently reclaimed 2011 slopes, could be considered a surrogate for the changes that can be anticipated in the years following reclamation. For example, Meiers *et al.* (2011) found that K_{sat} increased by one to two orders of magnitude over the first two years following reclamation of an overburden dump in the AOSR. In the current study, soils on the 2011 slope exhibited a K_{sat} two orders of magnitude lower than the soils on the 2007 slope. However, changes to the K_{sat} on the 2011 slope, similar to those observed by Meiers *et al.* (2011), are probable over the subsequent several years following reclamation. Furthermore, the surface f of the 2011 slope could also increase as preferential flow paths and secondary porosity develop, which can occur in as little as three to four years (Guebert and Gardner, 2001). Hence, it is reasonable to anticipate a shift in the properties of the soils on the 2011 slope towards those exhibited by the 2007 slope over time. In this hypothesized scenario, which is not directly supported by the findings of the current study but rather supported by observations from studies in similar reclaimed landscapes (Guebert and Gardner, 2001; Kelln *et al.*, 2007; Meiers *et al.*, 2011), the 2011 slope could begin to behave in a similar manner as the 2007 slope within a few years. However, it is prudent to note that the hydrological processes and trends identified herein represent those measured on two reclaimed slopes within the AOSR, as replication at additional reclaimed slopes was not possible. Data were collected at various locations throughout each slope, as specified in the Methods section and throughout the paper. This provided the requisite information on the variability of the hydrological processes operating on each slope so inferential statistics could be validly applied to test the null hypothesis that the parameter in question was the same on both slopes (Hurlbert, 1984). Thus, the sample sizes reported throughout this paper represent the sampling locations within each of the two reclaimed slopes, while the overall comparison of the hydrological processes presented in this paper is limited to those operating on the two slopes (i.e., n = 2). Similar industry-wide requirements with respect to reclamation procedures and soil specifications (as contained within provincial operational approvals) should minimize differences between slopes of comparable nature (e.g., reclaimed overburden material) and timeframe in the AOSR. Nonetheless, considering the magnitude of reclamation operations and the number of variables that could influence the hydrophysical properties of reclamation materials, differences between reclaimed slopes are inevitable and likely contributed in part to the differences observed between the 2007 and 2011 slopes in the current study.

The contrasting hydrophysical properties of the materials on the 2011 and 2007 slopes produced differing hydrological roles of recently reclaimed slopes on a watershed scale. The importance of near-surface f and i as controls on runoff generation from reclaimed slopes appears to diminish with time since reclamation. For example, the near-surface f of the older 2007 slope, which produced limited surface runoff, was more than five times greater than that of the 2011 slope, which produced a substantial amount of surface runoff. Consequently, if the hydrophysical properties of the 2011 slope change over time and the near-surface f and K_{sat} of the soil profile increase, as discussed above, surface runoff generation would occur less frequently. The likely exception to this is during the snowmelt period, when large amounts of runoff were observed from both the 2007 and 2011 slopes (as demonstrated in Chapter three). Nevertheless, the 2011 slope will likely become a more efficient water storage landform (during the snow-free period) and could begin to exhibit a hydrological regime more similar to that observed on the 2007 slope. This evolution of the hydrological regime is similar to other research in recently reclaimed landscapes, where substantial increases in the surface f of recently reclaimed hillslopes has been observed (Guebert and Gardner, 2001). Although these potential changes would ultimately result in less water being conveyed from these landforms (due to reduced surface runoff generation) to adjacent low-lying systems in the constructed landscape, increased percolation and subsequent storage of precipitation water would result in greater available water for vegetation establishment and maturation on the reclaimed slope itself. From an ecosystem creation perspective, integrated landscape reconstruction is important (Johnson and Miyanishi, 2008; Devito *et al.*, 2012), hence interconnectivity of landforms is desired. However, the likely evolution of reclaimed slopes appears to favour water storage within landforms over hydrologic landscape connectivity. Nevertheless, recently reclaimed slopes can provide substantial amounts of water to adjacent, low-lying/downstream ecosystems in the first few years following construction. This additional water from reclaimed slopes could serve to alleviate water availability issues (i.e., supplement limited precipitation inputs) associated with reclamation projects that occur at the beginning of a dry climate cycle.

4.6 Summary and conclusions

Soil water storage characteristics and hydrophysical parameters controlled the soil water regime of reclaimed slopes and, thereby, influenced the transmission of water within the reconstructed landscape. Soils on the recently reclaimed 2011 slope had a higher bulk density, lower saturated hydraulic conductivity and a low near-surface infiltration capacity. Consequently, the soil water regime was less variable with time (less water infiltrated) and topography did not influence water distribution. Accordingly, more frequent and substantial surface runoff was generated from the 2011 slope relative to the older 2007 slope, which exhibited a lower bulk density, higher saturated hydraulic conductivity and increased near-surface infiltration capacity relative to the 2011 slope. Hence, the 2007 slope was more closely coupled to atmospheric processes (more variable soil water regime) and stored most of the precipitation inputs received during the snow-free period. Both slopes exhibited hydrophobicity at low moisture contents. Soils on the 2011 slope tended to be more hydrophobic and, thus, contributed to the low surface infiltration rates.

If the anticipated changes in hydrophysical properties of soils on recently reclaimed slopes are realized, these landforms could start to produce less overland flow and shift from water conveyors to water storage features in constructed watershed systems.

4.7 Acknowledgements:

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5 AN INITIAL ASSESSMENT OF THE HYDROLOGICAL FUNCTIONING OF A CONSTRUCTED FEN WETLAND WATERSHED IN THE ATHABASCA OIL SANDS REGION, ALBERTA, CANADA

5.1 Introduction

Wetlands, most of which are fen peatlands, cover up to half of the landscape in Canada's Western Boreal Plain (WBP; Vitt *et al.*, 1996) within Northern Alberta. Approximately 2500 km^2 of the Athabasca Oil Sands Region (AOSR) in the WBP has been deemed suitable for surface mining (Woynillowicz *et al.*, 2005), which involves the removal of large expanses of undisturbed peatlands to access the oil sands beneath (Daly *et al.*, 2012; Rooney *et al.*, 2012). Accordingly, oil companies are obligated by law to return the mined landscape to equivalent land capability, as defined by the conservation and reclamation regulation (Government of Alberta, 2014). Peatlands are now included in reclamation designs, however the feasibility of successfully constructing peatlands in mine reclamation landscapes remains unknown. Although hydrologically isolated fen peatlands are common in the WBP (Riddell, 2008), fen peatlands situated in low-lying topographic positions in the reconstructed landscape may receive a combination of atmospheric, groundwater and surface water inputs. The surface and groundwater inputs will help to supplement limited atmospheric water availability during the summer months when potential evapotranspiration (*PET*) can exceed precipitation (*P*) in the WBP region (Bothe and Abraham, 1993; Marshall *et al.*, 1999). Nonetheless, the design and modelling (Price *et al.*, 2010; Daly *et al.*, 2012) of an upland-fen watershed ecosystem constructed in a post-mining landscape in the AOSR indicates that the system should be sufficient to withstand periods of climatic stress (Price *et al.*, 2010). However, this concept has not yet been supported by field-based research. Thus, the goal of this study is to characterize the dominant hydrological processes operating in a constructed fen peatland watershed.

The first step in most reclamation processes is the restoration/creation of functioning hydrologic systems (Elshorbagy and Barbour, 2007), which relies heavily upon water storage properties that are suitable for supplying water to meet the demands of revegetation schemes (Qualizza *et al.*, 2004). Accordingly, the hydrophysical properties of the reclamation materials will determine the release and provision of water throughout the constructed watershed. For example, the near-surface soils must have a sufficiently high infiltration capacity to facilitate percolation of precipitation waters. Most soil covers placed during upland reclamation are designed to maximize water storage and minimize deep percolation into stockpiled overburden or waste materials (Elshorbagy *et al.*, 2005; Kelln *et al.*, 2007; Meiers *et al.*, 2011). However, successful establishment of integrated hydrological connectivity between different landforms within the reconstructed landscape is essential in oil sands reclamation (Johnson and Miyanishi, 2008; Devito *et al.*, 2012). Infiltrating precipitation water inputs must be partitioned between local soil water storage and recharge to larger-scale groundwater aquifers within certain locations in the reconstructed landscape, both to meet the requirements of local vegetation as well as to provide groundwater fluxes to adjacent landforms. The hydraulic conductivity (K_{sat}) of the aquifer materials will ultimately control this water partitioning and the magnitude of groundwater exchanges, as influenced by the distribution of hydraulic heads throughout the different landscapes. However, the K_{sat} of reclamation materials is not constant, and has been shown to increase over time following placement in constructed landscapes due to freeze/thaw cycling (Meiers *et al.*, 2011) and the development of macropores (Guebert and Gardner, 2001). The implications of these changes on the hydrological functioning of constructed reclaimed landscapes must be addressed as the system evolves. Previous research efforts have focused primarily on the hydrological performance of shallow (< 100 cm) near-surface soil-capping layers; thus, little information exists on the evolution of the hydrophysical properties of reclamation materials used to construct deeper groundwater aquifers. Furthermore, this research represents one of the first attempts to construct a fen peatland in a post-mining landscape and, as such, little is known about the hydrological properties of placed peat as a reclamation substrate. The reclamation process, which includes soil salvage/extraction, transportation and placement, can change the structure of reclaimed peat soils thereby altering the soil hydraulic properties (Nwaishi *et al.*, 2015b). However, there has yet to be a comprehensive assessment of the hydrophysical properties of reclaimed, placed peat soils and little is known about the nature and magnitude of the potential changes in these peat materials following placement.

Constructed catchments present new opportunities as field-scale research facilities to characterize ecohydrological processes in a relatively controlled setting (Gerwin *et al.*, 2009; Hopp *et al.*, 2009). Since integrating fen peatlands into reclamation and closure landscape designs is a relatively new concept, the current understanding of important hydrological processes in constructed fen peatlands and their associated watersheds is inadequate due to insufficient experimental and field data. Thus, the goal of this study is to characterize the distribution, storage and movement of water within a constructed upland aquifer – fen peatland system over the range of conditions encountered in the field. The specific study objectives are to:

1) Characterize the spatial and temporal variability in the hydrophysical properties of reclamation materials during the first three years following placement
2) Identify the dominant water fluxes within the designed upland – fen system
3) Quantify the connectivity between the upland aquifer and lowland fen
4) Evaluate the hydrological performance of the designed constructed fen watershed

5.2 Study Site

The Nikanotee Fen watershed is a reclaimed catchment that was constructed in a post-mining landscape within the Millennium mine lease at the Suncor Energy Inc. oil sands mining operations approximately 40 km north of Fort McMurray, Alberta (56°55.944'N 111°25.035'W; average watershed elevation ~288 masl). The site selection process for the location of the Nikanotee Fen watershed is outlined in detail in Daly *et al.* (2012). An area within the mine termed the "tailings line corridor" (TLC) was selected for the construction of the watershed, which was a pit previously mined for bitumen and later filled in with overburden materials (Daly *et al.*, 2012). The stratigraphic profile underlying the watershed includes Middle and Lower McMurray formations that overlay a thin layer (~5 m) of fluvial sands situated atop Devonian limestone. This profile was capped with a mixture of lean oil sand, glacial material, clay, shale and loamy sand (Daly *et al.*, 2012). The first phase of the construction included placing a geosynthetic reinforcement material (geogrid) and a 1 m thick engineered compacted clay underlay beneath the base of the constructed watershed in response to anticipated settling of the backfilled overburden materials.

In the constructed system, fen peat from newly developed lease areas was placed at the toe of an upland aquifer (~3% basal grade towards the fen) designed to supply the requisite groundwater flow to sustain fen processes and functions. The upland aquifer was constructed using tailings sand placed over a basal geosynthetic clay liner and capped with a thin (30 – 50 cm thick) LFH reclamation soil-capping layer (Figure 5-1). This LFH soil-capping reclamation material is different than the typical LFH soils as defined by the Canadian System of Soil Classification in natural ecosystems, which are composed of organic soil horizons L, F, and H (Soil Classification Working Group, 1998). Instead, due to operational feasibility, the LFH material used in reclamation is salvaged with varying amounts of upper horizon mineral soil (Naeth *et al.*, 2013). Accordingly, the term 'LFH soil-capping layer' used throughout this paper refers to the overstripped LFH / mineral soil reclamation material. Approximately 5000 m^3 (~65 mm) of water was applied to the tailings sand material in the upland during the construction phase (summer 2012) to aid in material compaction. This water consequently contributed to the water stored in the upland aquifer (in addition to precipitation inputs).

The fen peat (2 m thick) is underlain by a 50 cm layer of petroleum coke (termed the 'underdrain' layer) and a 50 cm layer of tailings sand over the basal liner, with the intention to more evenly distribute hydraulic head beneath the fen. This underdrain layer was also extended part way up the slope (beneath the zone of the upland termed the 'transition zone'; Figure 5-1) to reduce the potential for groundwater (and salt) discharge at the surface of the upland-fen interface. The designed fen (2.9 ha) and upland (7.7 ha) system is situated within a larger watershed (total watershed area = 32.1 ha) that includes three previously reclaimed (hence also constructed) slopes of varying age and a natural remnant slope (Figure 5-1). The geosynthetic liner was beveled to the surface of the natural slope in a way that precluded potential groundwater input. Further, surface infiltration capacity measurements made on the natural slope (data not shown) suggest that it did not contribute water to the system via surface flow either. The east slope (8.1 ha; herein referred to as the 2007 slope) was reclaimed in 2007 and has a well-established vegetation cover relative to the south-east (8.2 ha) and west (2.4 ha) slopes, which were both reclaimed in 2011 (referred to collectively as the 2011 slopes). Several landform features were incorporated into the design of the upland area. This included four hummocks, which are small (~400 to ~1500 m^2) landforms raised ~1 m above the surrounding area, as well as an experimental basin lined with a thin (0.5 m) layer of peat / mineral mix reclamation material (herein referred to as the 'peat-lined basin'). The peat-lined basin is a 0.2 ha depression situated ~0.5 m below the surrounding upland surface and directly adjacent to an upland hummock (Figure 5-1). The stratigraphy in this basin is a 50 cm layer of peat / mineral mix soil situated atop the tailings sand aquifer material. A berm was constructed around the perimeter of the Nikanotee Fen watershed to isolate the watershed from any surface water interactions from the adjacent landscapes and mine operations. Accordingly, the focus of this thesis is on the processes that operate within the boundary of the Nikanotee Fen watershed. A map that places the Nikanotee Fen watershed into the context of the surrounding landscape within Suncor's Millennium mine lease is included in Daly *et al.* (2012).

The surface of the LFH soil-capping layer in the upland was tilled in autumn 2013 in an effort to increase the recharge to the upland aquifer by increasing the detention of surface water and the surface infiltration capacity. A total of 297 tilled furrows were created in the upland, oriented perpendicular to the slope of the surface topography, using a single dozer ripper shank (average dimension: 24 cm wide, 10 cm deep, 83 cm spacing between furrows). At the same time, the LFH soil-capping layer was removed from a small area directly behind each of the upland hummock landforms (except for the hummock adjacent to the peat-lined basin), with the objective of creating enhanced recharge zones. The intention was to remove the soil water storage capacity associated with this soil layer and to expose the tailings sand aquifer materials directly to atmospheric water inputs and surface runoff from the adjacent reclaimed slopes. These areas were targeted due to field observations of ponded water behind hummocks following rain events. The excess LFH material was used to slightly extend the shape of the hummocks to the base of the adjacent slope (where possible).

The focus of the current study is on the evaluation of the hydrological processes operating within the designed upland aquifer - fen system (e.g., the 'Suncor Pilot Fen', as outlined in Price *et al.*, 2010; Daly *et al.*, 2012; Pollard *et al.*, 2012). This upland-fen system, along with several additional reclaimed and natural remnant landforms, comprises the greater Nikanotee Fen watershed. While fluxes from other components within the constructed watershed are also considered here (e.g., the 2007 and 2011 reclaimed overburden slopes), they are evaluated in greater detail in Chapter four.

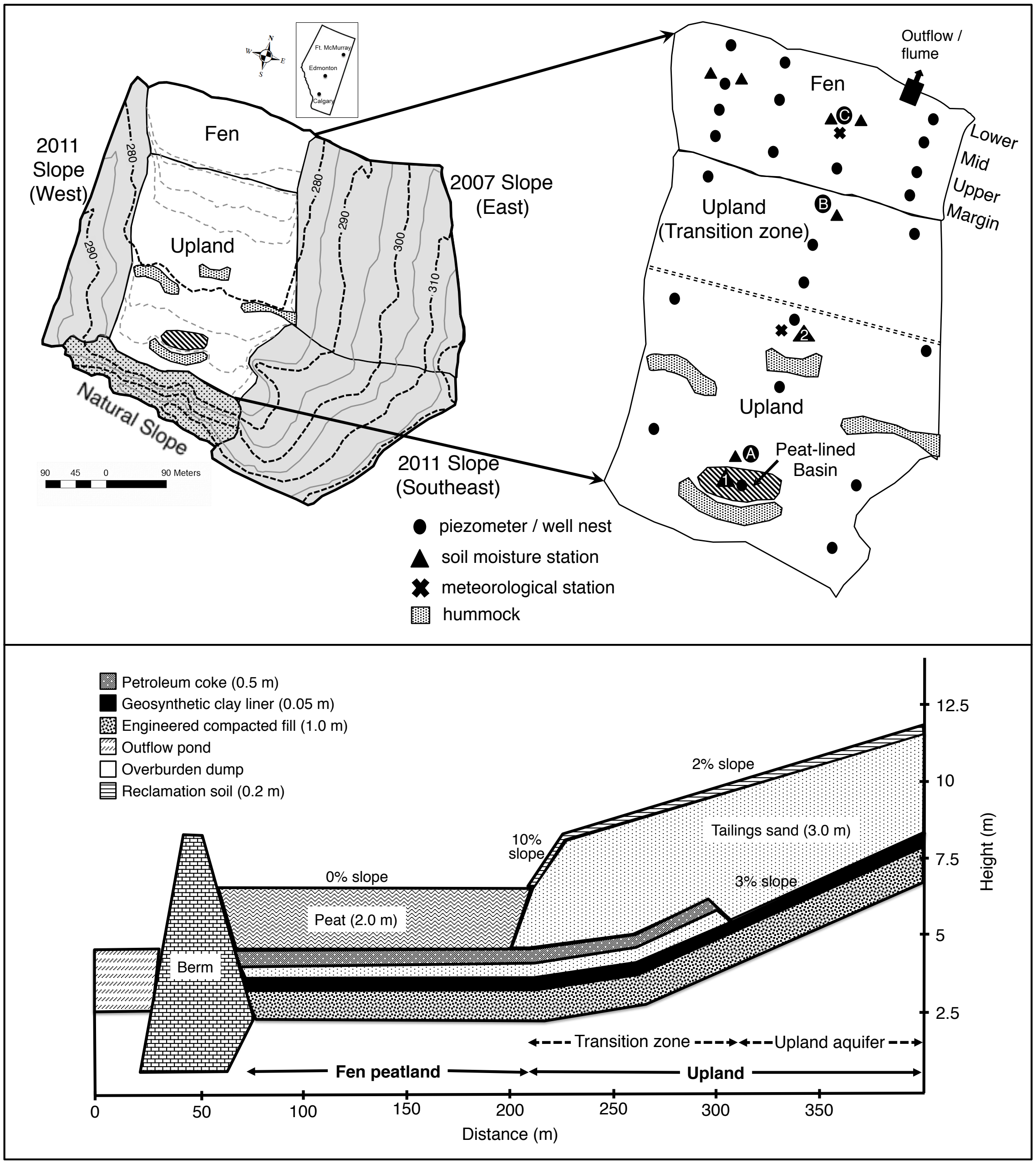

Figure 5-1 – Map of the Nikanotee Fen watershed in plan view (top) and cross-section (bottom). Enlarged symbols with labels are referred to specifically in-text. Grey dashed and grey solid lines are 1 m and 5 m topographic contours, respectively.

5.3 Methods

5.3.1 Hydrophysical properties

The hydrophysical properties of the reclamation materials were characterized using a combination of in-situ measurements conducted in the field, as well as laboratory analyses of intact soil samples extracted from the field using hollow steel Shelby tubes (5.5 cm I.D. x 5 cm height). Soil samples from the field (2013 only; sample sizes specified in the results section) were wrapped in polyethylene film and carefully transported back to the laboratory for analyses. Once in the laboratory, soil samples were protected with screening on the bottom to minimize sediment loss during analyses. Standard soil analysis methods (e.g., Freeze and Cherry, 1979; Klute, 1986) were followed for measurement of soil parameters (e.g., total porosity, ϕ; specific yield, S_y; and bulk density, ρ_b). Saturated hydraulic conductivity (K_{sat}) was measured on a sub-set of samples in the laboratory prior to oven drying using a constant head test (Freeze and Cherry, 1979). Following oven drying (to a constant mass at 80ºC), soil samples were homogenized and clumps were broken using a mortar and pestle. Particle size distribution was analyzed using a Horiba Partica LA-950V2 laser scattering particle size distribution analyzer. Soil samples were subjected to a 20 second ultrasonic treatment and dispersed using a 0.1% sodium hexametaphosphate solution.

A hydrological monitoring network that consisted of a combination of wells and piezometers was installed throughout the fen, transition zone and upland aquifer (Figure 5-1). Wells and piezometers within the fen were constructed using slotted 2.54 cm I.D. polyvinylchloride (PVC) pipes (piezometers were only slotted at the bottom 20 cm) and wrapped with well screening to limit clogging. Screens were typically centered at 50, 75, 90 and 150 cm below ground surface (cm bgs) within the peat, as well as in the petroleum coke layer at 225 cm bgs and in the underlying tailings sand layer at 275 cm bgs. In the transition zone and upland aquifer, stainless steel drive-point piezometers (Solinst Canada Ltd. model 615) were installed to 225 cm bgs (transition zone only) and 275 cm bgs using a Pionjar 120 percussion rock hammer and extended to the surface with steel drive pipe. Low-density polyethylene (LDPE) tubing (1.2 cm I.D.) was attached to the screened stainless steel drive-point and all measurements were made within, and water samples extracted from, the LDPE tube. Wells within the transition and upland zones were constructed in the same manner as previously described for the fen. Initial well installation in 2013 was done cautiously to avoid puncturing the thin geosynthetic clay liner that was deemed critical in maintaining a saturated zone within the upland (Price *et* *al.*, 2010). An assumed thickness of the reclamation materials in the upland was approximately 320 cm (300 cm tailings sand and 20 cm LFH reclamation soil-capping layer). Accordingly, wells were installed to a maximum targeted depth of ~275 cm bgs (maximum actual depth of installation was 294 cm bgs). This was a sufficient depth for the far southern portion of the upland, where the tailings sand layer was designed to be placed at a reduced thickness (Daly *et al.*, 2012); however, the water table remained deeper than 275 cm bgs across a large swath of the middle of the upland aquifer throughout 2013. Accordingly, wells were extended and new (deeper) wells were installed throughout the 2014 field season to rectify this. Consequently, there was no information on the water table within the middle section of the upland during 2013, except that it was deeper than 275 cm below ground surface.

Measurements of the surface infiltration capacity (f) of the LFH reclamation material in the upland were conducted in the field using a single-ring infiltrometer in both 2013 (26 locations) and 2014 (37 locations). Measurements made in 2014 facilitated an estimate of the efficacy of remediation efforts undertaken in the autumn of 2013 (surface soil tilling), with f measured within tilled furrows (f_{furrow}, 17 locations) and between tilled furrows ($f_{between}$, 20 locations). Field measurements of K_{sat} were made using bail tests within all wells and piezometers in the fen, transition and upland zones following the hydrostatic time-lag method (Hvorslev, 1951) in 2013, 2014 and 2015. The estimate of K_{sat} was considered as the arithmetic mean of triplicate measurements at each location and depth. Spatial heterogeneity of K_{sat} was also assessed in the shallow (50 cm bgs) peat by conducting triplicate bail tests on piezometers at 63 different locations across the fen (part of a different study conducted at the Nikanotee Fen). Note that K_{sat} data from 2015 is included in this study to provide a third year of data to support the evaluation of the evolution of the hydrophysical properties of the reclamation materials used in the construction of the aquifers within the Nikanotee Fen watershed. All other hydrometric data and analyses pertain only to 2013 and 2014.

5.3.2 Meteorological variables

The components of the water budget were estimated for the constructed upland-fen system from 17-May to 29-August in 2013 and 2014. Meteorological stations located in the upland and fen consisted of Campbell Scientific CR1000 dataloggers that recorded 30-minute average values of measurements taken every minute. These measurements included net radiation (Q^*; Kipp and Zonen NR-LITE2 net radiometer in 2013, Kipp and Zonen CNR4 net radiometer in 2014; 2.5 m height), ground heat flux (Q_g; REBS HFT-3; 0.01 m depth), wind speed and direction (R.M. Young 05103 Wind Monitor; 2.75 m height), relative humidity and air temperature (Rotronic HC2S3; 2.5 m height) and precipitation (*P*; Texas Instruments TR-525M tipping bucket). Precipitation was only recorded at the upland meteorological station, but a secondary tipping bucket rain gauge (Hobo RG3) was located at a meteorological station on the reclaimed slope to the east of the upland-fen system for verification and gap-filling. Both rain gauges were located within the 32.1 ha watershed.

An eddy covariance (EC) system was also deployed at both the upland and fen meteorological stations for estimation of actual evapotranspiration (*AET*). Each EC system included a 3-dimensional sonic anemometer (Windmaster Pro, Gill Instruments, Lymington, United Kingdom) and closed-path infrared gas analyzer (IRGA; LI7200, LI-COR Inc., Lincoln, Nebraska, USA) placed 2.5 m above the ground surface in the Upland and 2.5 m above the vegetation surface in the Fen. Both EC systems sampled at a frequency of 20 Hz and measurements were averaged every 30 minutes. IRGAs were calibrated at the beginning and end of each study period using a zero gas and two-point span calibration to account for any drift in sensor sensitivity, which remained less than 5% over the duration of each study period. Raw EC data were processed using EddyPro software (version 5.2.1; LI-COR Inc., Lincoln, Nebraska, USA) where corrections were applied for coordinate rotation (double rotation; Kaimal and Finnigan, 1994), time lag and sensor separation (Fan *et al.*, 1990), density effects (Burba *et al.*, 2012) and periods of low turbulence based on the inflection point of frictional velocity (u^*) and energy balance closure (Foken, 2008; Brown *et al.*, 2014; Petrone *et al.*, 2015). Approximately 30% of data were lost and gap filled using the mean over 14-day periods (Falge *et al.*, 2001). A footprint analysis (Kljun *et al.*, 2004) was used to ensure water fluxes from outside the boundaries of the constructed Fen and Upland were not included in flux calculations for each distinct landscape. These estimates of *AET* were compared to potential evapotranspiration (*PET*) estimated using the radiation-based Priestley-Taylor equation and an alpha coefficient equal to one (Priestley and Taylor, 1972).

5.3.3 Soil moisture and groundwater dynamics

Volumetric water content (*VWC*) was measured at least hourly during the study period, with reduced measurement frequency during the autumn (every two hours) and winter (twice daily) months using soil moisture probes (Stevens Hydra II Probe) connected to Campbell Scientific CR1000 dataloggers. Probes were installed at four locations within the fen in arrays of 5, 10, 15, 30 cm bgs (two locations) and 0, 5, 10, 30 cm bgs (two locations). Four probe arrays were also installed at soil moisture stations throughout the upland, including one array in the transition zone portion of the upland and one in the peat-lined basin (Figure 5-1). These probes were installed according to the actual thicknesses of the capping soil layer, with the general arrangement at 5, 10, 15 cm bgs, base of capping soil layer, top of tailings sand layer, 60, 100, 150 cm bgs. The calibration function developed for the Hydra II probe by Seyfried *et al.* (2005) was used for mineral soils, while independent calibration curve functions were derived for organic soils (peat within the fen and the peat / mineral mix in the peat-lined basin) following standard methods (e.g., Jacobsen and Schjønning, 1993) in the laboratory using intact soil samples extracted from the field.

Water levels in all piezometers and wells were manually measured every 5 – 7 days (with minimal exception) from May to August each year. Concurrent measurements of the depth to ground frost were made at each piezometer nest (fen only) using an incremented steel rod inserted into the ground until an ice layer was encountered. The average value of five measurements taken randomly within an (undisturbed) area of ~4 m^2 around each nest was considered to be representative. Water levels in a sub-set of wells and piezometers were recorded every 30 – 60 minutes using a combination of logging pressure transducers (Schlumberger Mini-Diver) and capacitance water level recorders (Odyssey Dataflow Systems Ltd.). Water table contour maps were generated using Surfer® 12 (Golden Software, LLC) and a point kriging gridding technique. Annual surveys were conducted to determine the location and elevation (± 0.005 m vertical accuracy) of all instrumentation using a Topcon HiPER GL RTK GPS system (2013) and a Leica Geosystems Viva GS14 GNSS RTK GPS system (2014).

Change in storage of the unsaturated zone at each soil moisture station was estimated as the summation of the seasonal change in *VWC* multiplied by the thickness of the soil layer within which the *VWC* measurement was centered. The seasonal change in water table level was used to provide an estimate of storage changes in the saturated zone within the upper, mid and transition zones of the upland, as well as for the fen peatland. These estimates were aerially weighted to provide separate change in storage values for each the upland and fen, which were subsequently combined and aerially weighted again to provide an estimated total change in storage (unsaturated and saturated zones) for the combined upland-fen system each year.

5.3.4 Groundwater fluxes

Groundwater fluxes from the upland aquifer to the fen were calculated using Darcy's law,

$$q = \frac{Q}{A} = -K_{sat}\frac{dh}{dl} \tag{5-1}$$

where q is the specific discharge (m s^{-1}), Q is the volumetric discharge (m^3 s^{-1}), A is the cross-sectional area of the flow face (m^2) and dh/dl is the hydraulic gradient (i.e., the change in head, dh, divided by the change in length, dl, between the measurement points; unitless).

Specific discharge fluxes to the Nikanotee Fen through the petroleum coke underdrain and underlying tailings sand layers were estimated using the vertical hydraulic gradient between the piezometer installed in the underdrain layer (extends beneath entire fen) and the elevation of the water table in the peat for each nest in the fen and each date of measurement individually, using Equation (5-1). Since the K_{sat} of the peat within the Nikanotee Fen is isotropic (Nwaishi *et al.*, 2015b) but displayed layered heterogeneity with depth (i.e., K_{sat} varied with depth), the equivalent vertical hydraulic conductivity through the system of layers within the peat deposit (K_z) was estimated at each nest according to Freeze and Cherry (1979),

$$K_z = \frac{d}{\sum_{i=1-3}^{n} d_i / K_i} \tag{5-2}$$

where d is the total thickness of the peat deposit (2.0 m), and d_i and K_i are the thickness and saturated hydraulic conductivity of each peat layer, respectively. Most nests had measurements of K_{sat} at 50, 90 and 150 cm depths, which were used as the center of each of the (three) peat layers used to estimate K_z. The geometric mean of all of the peat K_{sat} measurements in the fen was used for the flux estimates at one of the 13 nests (due to unreliable K_{sat} measurements there). If the vertical gradient was not available for a nest on a particular date, the average vertical gradient from all of the nests within the fen for that date was used. Fluxes at all nests were then averaged for each measurement date to provide an estimate of the site-scale vertical groundwater fluxes (q_{vert}) within the fen. Vertical fluxes were considered to be zero at nests where ground frost was present. Once the ground frost became patchy at an individual nest (indicated by depth-to-frost measurements in excess of ~60 cm, or where frost was not encountered), fluxes from this nest were included in the estimate and scaled proportionally to the number of nests that had frost remaining.

Horizontal groundwater fluxes from the upland aquifer to the fen through the petroleum coke underdrain and underlying tailings sand layer at the toe of the upland aquifer are accounted for in the estimate of q_{vert}. Driven by the large variation in the K_{sat} of the reclamation materials, the horizontal fluxes across the fen peat / tailings sand interface (i.e., above the underdrain layer) at the toe of the upland aquifer could not be estimated using the Dupuit-Forchheimer approximation, since vertical hydraulic gradients were present (Freeze and Cherry, 1979). Thus, it was assumed that flow was primarily refracted downwards and that the primary flux was through the petroleum coke underdrain layer. For the seasonal groundwater flux estimate, the daily site-scale flux estimates were multiplied by the number of days between measurements. This introduced some additional uncertainty to the estimates of groundwater flow, since an implicit assumption is that the hydraulic gradients are constant between measurements, which is not the case. The average time between measurements was six days, with the exception of two measurement intervals that were longer (~2 weeks) due to site access and personnel issues. Estimating the seasonal fluxes in this manner, as opposed to computing a daily average for the study period and multiplying this by the number of days in the study period, should minimize the impact of this assumption. Note that these groundwater fluxes were only estimated for the 2014 study period because the presence and persistence of ground ice during the first half of the 2013 season delayed the installation of many of the wells and piezometers necessary for this analysis until later in the study period.

5.3.5 Runoff

Runoff (R) from the catchment in 2013 was measured at a Palmer-Bowlus type flume equipped with a logging pressure transducer (Schlumberger Mini-Diver) and located directly downstream of a spillbox installed at the discharge point of the fen (Figure 5-1). The majority of discharge flow rates measured within the flume in 2013 were less than the lower limit of the flow rates appropriate for use of the engineering equation developed specifically for the flume. Accordingly, an independent rating curve was developed for conditions of low flow using periodic (~weekly) manual measurements of discharge made within the flume (using a current velocity meter) and at the outlet of the discharge pipe using a bucket and stopwatch. In 2014, runoff was measured at a v-notch weir that was installed in a distinct channel that developed directly upstream of the flume and spillbox. Stage was recorded every 30 minutes using a logging pressure transducer (Schlumberger Mini-Diver) and manual discharge measurements were made every other day to develop a rating curve.

5.3.6 Isotopes

Water samples were collected from selected wells, piezometers, the fen outlet and ponded water within the fen on an approximately monthly basis during 2013 and 2014. Samples of rainwater were also obtained at least monthly using a rain gauge specially designed for isotopic sampling of precipitation (constructed following the design developed by the International Atomic Energy Agency - Global Network of Isotopes in Precipitation; IAEA/GNIP). Water samples from the field were filtered within 24 hours using 0.45 μm nitrocellulose membrane filters and stored in tightly sealed 10 mL scintillation vials with no head space at 4°C for isotope analyses. Isotopic analyses for $\delta^{18}O$ and δD were completed at the Biotron Experimental Climate Change Research Centre at Western University using a Picarro L2120-i Cavity Ring-Down Spectroscopy analyzer. This technique yields an analytical precision of ±0.5‰ for δD and ±0.1‰ for $\delta^{18}O$.

5.4 Results

5.4.1 Hydrophysical properties of reclamation materials

Standard soil hydrophysical properties for all materials used in the construction of the Nikanotee Fen watershed are reported in Table 5-1. All materials exhibited a considerable range of variability in K_{sat}, as demonstrated by frequency distribution analyses (Figure 5-2). This variability was greatest in the fen peat, in which K_{sat} varied by approximately three orders of magnitude. The fen peat tended to have the lowest K_{sat}, followed by the tailings sand material used to construct the upland aquifer and the petroleum coke underdrain layer, while the LFH soil-capping layer had the highest K_{sat}. Each of these reclamation materials is discussed in greater detail below.

5.4.1.1 LFH soil-capping layer

Particle size distributions of the LFH reclamation materials used as a soil-capping layer in the upland were variable, with a mean soil classification of sandy loam (52% sand, 42% silt and 6% clay; n = 26). The soil classification of individual LFH soil samples included clay loam, sandy clay loam, loam and sandy loam. In-situ measurements of f resulted in geometric mean f values of 41 and 91 mm hr^{-1} in 2013 and 2014, respectively (Figure 5-3). The 2013 f value is in good agreement with the laboratory-based estimates of K_{sat} (47 mm hr^{-1}) measured on cores that were extracted from the field in 2013 (Table 5-1). Infiltration measurements from 2014 that were conducted within tilled furrows (f_{furrow} = 128 mm hr^{-1}) were nearly two times greater than measurements made between tilled furrows ($f_{between}$ = 68 mm hr^{-1}; Figure 5-3), although the overlapping notches on the boxplots in Figure 5-3 indicates that their medians are not statistically different at p = 0.05 (Chambers *et al.*, 1983). Similarly, the notches of the 2013 and 2014 f data also overlap, which indicates that the measured inter-year increase in f is not statistically significant.

Table 5-1 – Hydrophysical properties of the materials used in the construction of the Nikanotee Fen watershed. Ksat values for the tailings sand, peat (50 – 200 cm) and petroleum coke represent the geometric mean of all field Ksat tests conducted at all depths in 2013 – 2015. Ksat of the LFH, peat / mineral mix and shallow peat (0 – 50 cm) are lab-based estimates.

		ρ_b (g cm^{-3})			ϕ (fraction)			K_{sat} (m s^{-1})			
Material		Average	± SD	n	Average	± SD	n	Average*	Max	Min	n
LFH		1.33	0.19	21	0.50	0.07	21	1 x 10^{-5}	2 x 10^{-4}	5 x 10^{-7}	21
Tailings sand		1.45	0.14	19	0.45	0.05	19	4 x 10^{-6}	3 x 10^{-5}	1 x 10^{-7}	58
Peat	0 – 50 cm	0.18	0.04	36	0.92	0.02	36	8 x 10^{-5}	2 x 10^{-4}	5 x 10^{-5}	12
	50 – 200 cm	0.22	0.03	28	0.87	0.02	28	2 x 10^{-6}	4 x 10^{-5}	3 x 10^{-8}	127
Petroleum coke		-	-	-	-	-	-	6 x 10^{-6}	5 x 10^{-5}	9 x 10^{-8}	44
Peat / mineral mix		1.02	0.12	13	0.64	0.05	13	6 x 10^{-7}	2 x 10^{-6}	1 x 10^{-7}	6

Average = arithmetic mean; Average* = geometric mean; SD = standard deviation.

5.4.1.2 Fen peat

In the constructed fen, K_{sat} generally decreased with depth (Figure 5-4), with the geometric average K_{sat} in the upper (0 – 50 cm) peat layers nearly two orders of magnitude higher than that of the deeper (50 – 200 cm) peat layers (Table 5-1). At all depths within the fen, K_{sat} increased substantially from 2013 to 2014 (Figure 5-5), with the greatest increase at 90 cm depth. In 2015, K_{sat} only continued to increase at 150 cm depth in the peat; however, 2015 values remained above the initial K_{sat} measured in 2013 throughout the peat profile (Figure 5-5). In addition to the values of K_{sat} measured at the locations that comprised the routine monitoring points (e.g., well/piezometer nests in Figure 5-1), K_{sat} was estimated at 63 supplementary locations in 2014 to quantify the extent of spatial heterogeneity within the placed peat deposit. These data indicated that

K_{sat} at 50 cm depth spanned nearly two orders of magnitude (3 x 10^{-5} to 2 x 10^{-7} m s^{-1}) throughout the fen (data not shown), and were, on average, lower (geometric mean = 4 x 10^{-6} m s^{-1}) than at the same depths at the routine monitoring points (1 x 10^{-5} m s^{-1}).

5.4.1.3 Tailings sand and petroleum coke underdrain

The tailings sand from the upland aquifer was classified as either sand (68% of samples) or loamy sand (32% of samples), with the mean classification of sand (88% sand, 11% silt, < 1% clay; n = 26). Saturated hydraulic conductivity varied by approximately two orders of magnitude in the upland tailings sand aquifer (Figure 5-2 and Table 5-1) and tended to be relatively stable over time, with a slight increase in K_{sat} measured in 2015 (Figure 5-5). In contrast, the K_{sat} of the petroleum coke underdrain layer varied by three orders of magnitude and demonstrated a larger inter-year increase than the tailings sand material. The layer of tailings sand material located beneath the fen (250 – 300 cm bgs; see Figure 5-1) had a lower and more variable K_{sat} than the same material used to construct the upland aquifer (Figure 5-4).

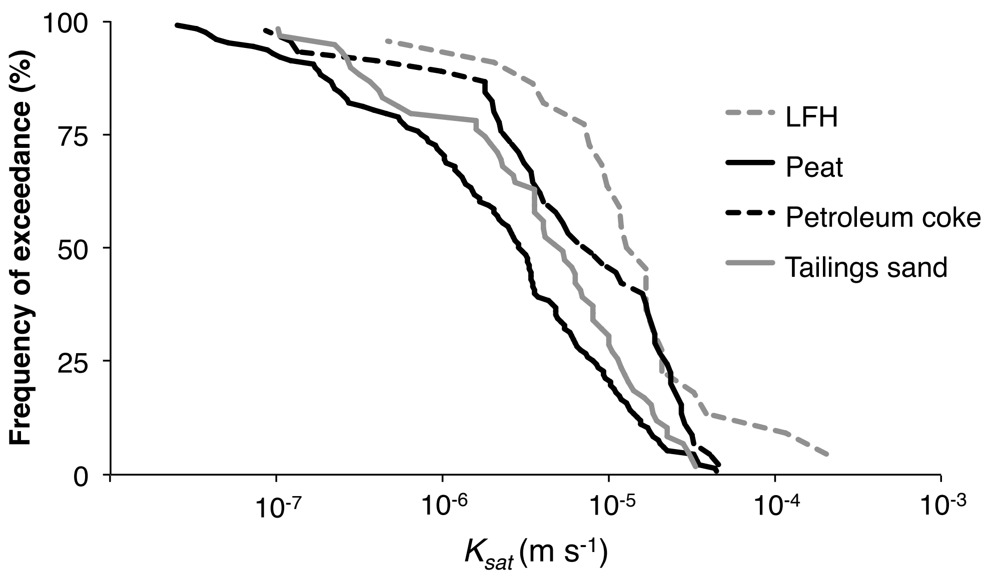

Figure 5-2 - Cumulative frequency distribution of K_{sat} for the reclamation materials used in the construction of the Nikanotee Fen watershed. Note that the fen peat curve represents K_{sat} from 50 – 200 cm depth. All materials represent field-based estimates of K_{sat} except for LFH, which is based on measurements made in the laboratory (see methods section). All data from all years are included.

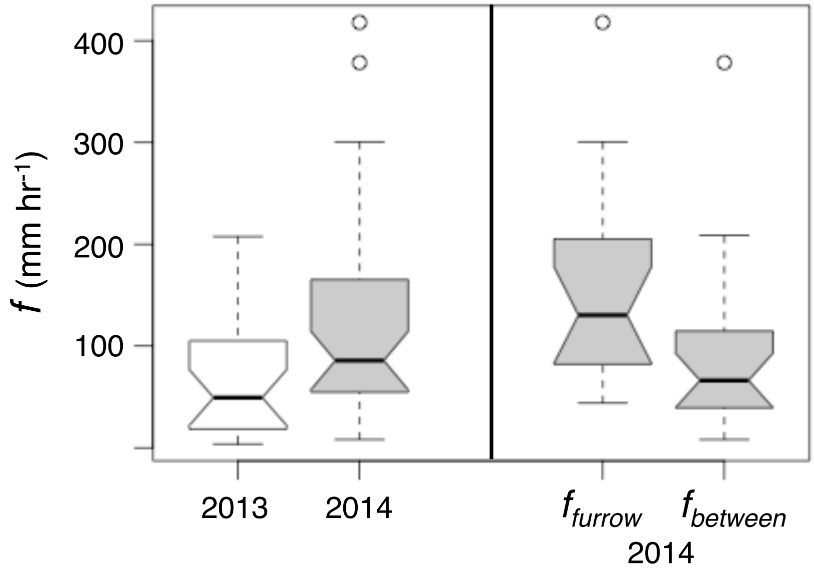

Figure 5-3 - Notched boxplots of the surface infiltration capacity of the LFH soil-capping layer in 2013 and 2014 (left side) as well as within tilled furrows (f_{furrow}) and between tilled furrows ($f_{between}$) (2014 only, right side). n = 26 and 37 locations for 2013 and 2014 , respectively (n= 17 and 20 for tilled furrow and between, respectively). Significant differences (at p = 0.05) occur if adjacent notches do not overlap.

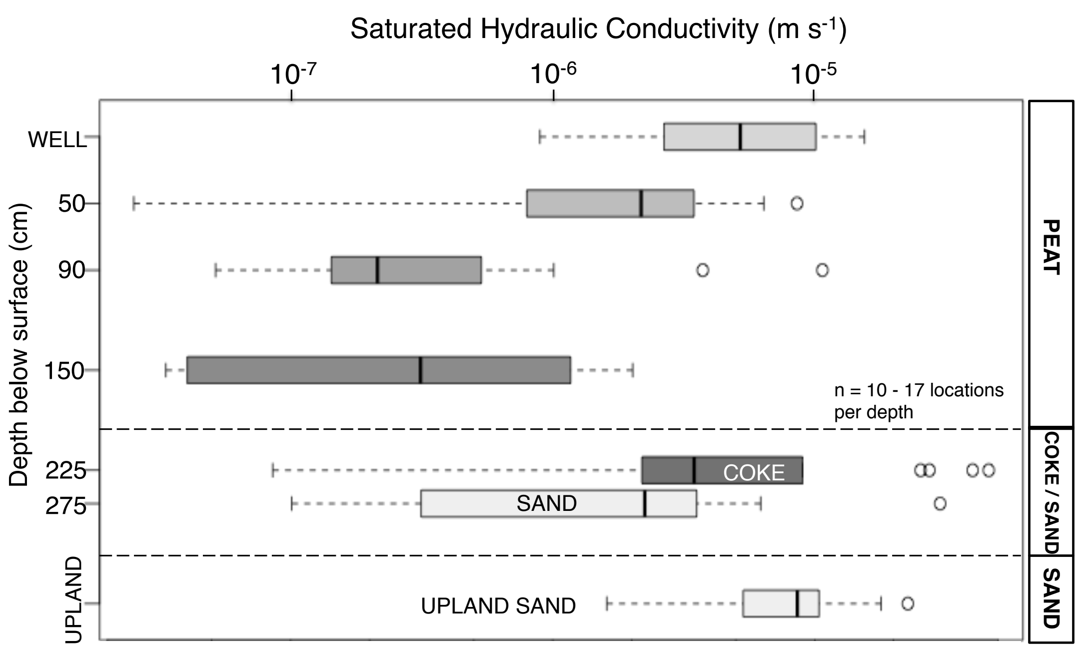

Figure 5-4 - K_{sat} with depth in the fen and upland (2013 data shown). Material type noted on the secondary y-axis. Original design specifications targeted K_{sat} of 10^{-5}, 10^{-2} and 10^{-4} m s^{-1} for peat, petroleum coke and tailings sands materials, respectively (Daly *et al.*, 2012).

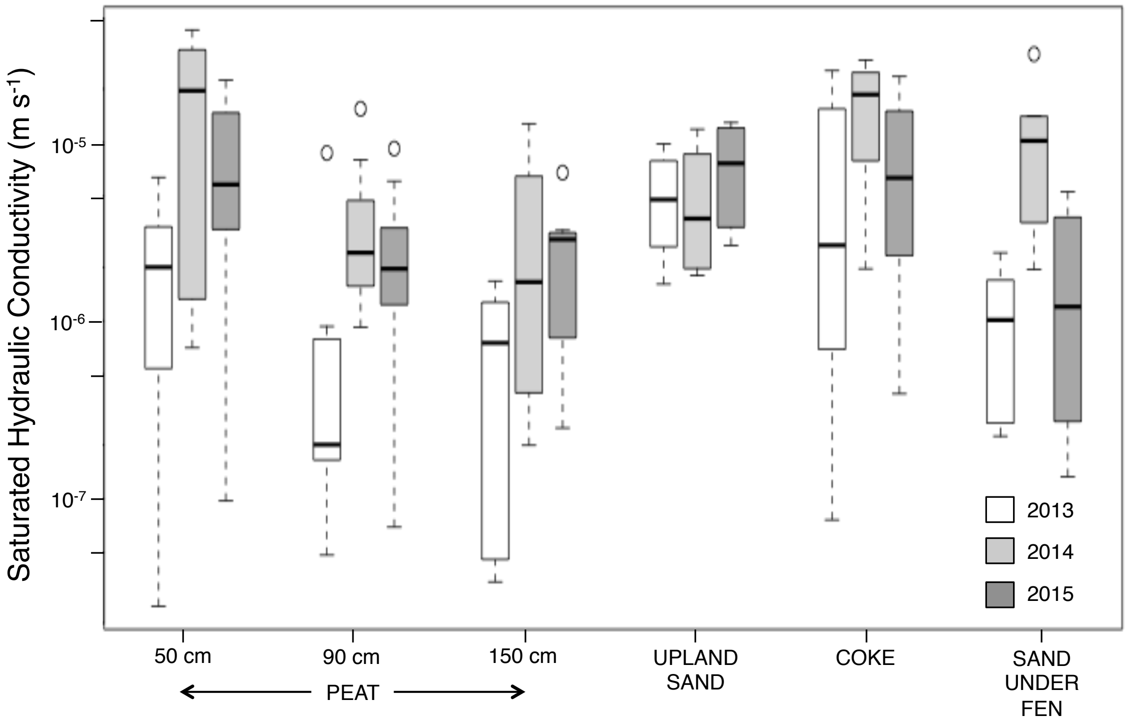

Figure 5-5 - K_{sat} of the different reclamation materials over the first three years following placement (in 2012). Note: the data displayed here only represent locations where repeated measurements were possible each year.

5.4.2 Water fluxes in the upland – fen system

5.4.2.1 Precipitation

The Nikanotee Fen watershed received 257 and 201 mm of *P* during the 2013 and 2014 study periods (17-May to 29-August), respectively, which represented approximately 114% and 89% of the long-term average precipitation for the same time period (Environment Canada, 2011). Both 2013 and 2014 were dominated by small (median < 3 mm), short-duration *P* events (Figure 5-6), with over 60% of the total *P* in the first half of both study periods. However, the start of the 2013 study period was dry, with less than 1 mm of *P* received during the first two and a half weeks. This dry period was followed by an atypically wet June, when the monthly total *P* received at the study site (139 mm) was 190% the monthly climatic *P* normals (Environment Canada, 2011). Precipitation was more evenly distributed throughout the study season in 2014, which started with a wet period (relative to monthly climate normals; Figure 5-6D) in May and monthly *P* totals that remained below or comparable to the climatic normals for the remainder of the study period. Large *P* events occurred infrequently in both years, with 24% (2013) and 18% (2014) of *P* events greater than 10 mm. In 2013, large *P* events were typically low intensity (only one event exceeded 10 mm h^{-1}) relative to the smaller, high intensity events observed in 2014 (six > 10 mm h^{-1}). The largest storm in 2013 delivered 61 mm of *P* over a 48-hour period (maximum intensity of 3.2 mm h^{-1}), whereas the largest storm in 2014 was 41 mm over 19 hours and more intense (maximum intensity of 5.4 mm h^{-1}).

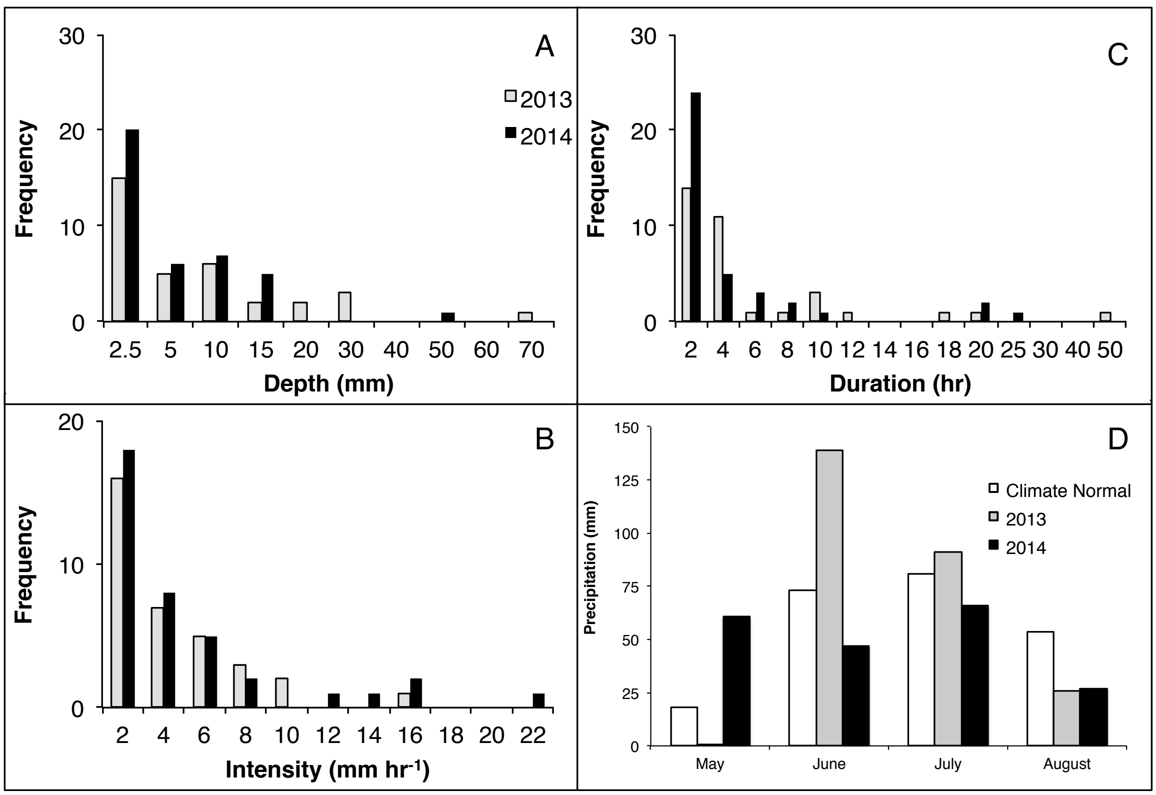

Figure 5-6 - Frequency distribution of A) depth, B) intensity and C) duration for precipitation events during 2013 (34 events) and 2014 (39 events). D) Total monthly precipitation during the 2013 and 2014 study periods (17-May to 29-August) and the long-term average (1981 – 2010) total monthly precipitation for Fort McMurray (Environment Canada, 2011).

5.4.2.2 Evapotranspiration

Cumulative *PET* exceeded *AET* in the fen in 2013 and in the upland in both 2013 and 2014. Average daily *AET* rates were much higher in the fen than in the upland, which resulted in the total *AET* from the fen exceeding the upland by 80 and 219 mm in 2013 and 2014, respectively (Table 5-2). This is a consequence of the substantial variation in the partitioning of available energy between the upland and the fen systems. Although the average fluxes of Q^*, Q_g, sensible (Q_h) and latent (Q_e) heat exhibited the typical diurnal parabolic rise and fall in both the upland and fen, daily average midday (11:00 to 17:00) Q_e exceeded Q_h in the fen, while they remained comparable in the upland (Figure 5-7). This resulted in average midday β of 1.05 and 0.44 for the upland and fen, respectively (2014 values), which reflects the influence of the wet conditions within the fen on the energy partitioning in constructed systems. The seasonal total *AET* from the fen was similar to the *P* inputs in 2013 (*P*-*AET* = 6 mm); however, *AET* greatly exceeded *P* in 2014, which resulted in a water deficit (i.e., *P*-*AET* < 0) of 181 mm within the fen. Conversely, lower *AET* fluxes from the upland generated a water surplus of 86 and 38 mm in 2013 and 2014. *AET* rates from the fen and upland were weighted proportional to their respective areas (2.9 and 7.7 ha) to evaluate the losses from the combined upland – fen system (10.6 ha). This yielded daily average *AET* rates of 1.8 and 2.1 mm d^{-1} and seasonal *AET* losses of 193 and 223 for the 2013 and 2014 study periods, respectively.

Table 5-2 – Evapotranspiration fluxes within the fen and the upland.

	FEN		UPLAND	
	2013	2014	2013	2014
Total *AET* (mm)	251	382	171	163
Daily average *AET* (mm d^{-1})	2.4	3.6	1.6	1.6
AET*/*PET	0.87	1.07	0.83	0.72

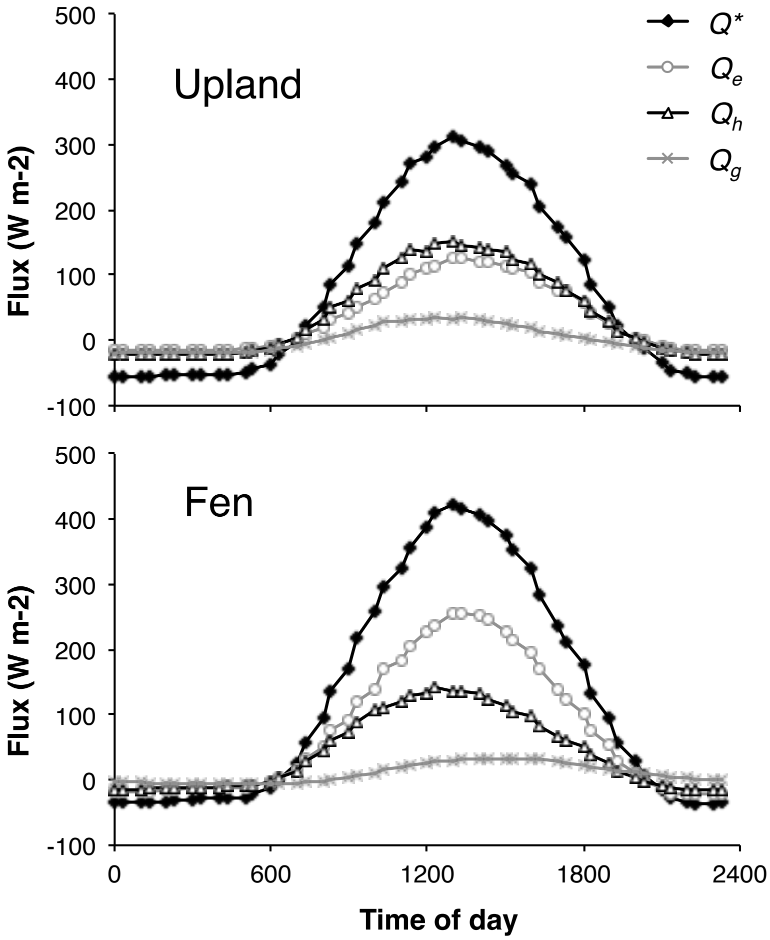

Figure 5-7 - Seasonal average diurnal variability in net radiation (Q^*), latent (Q_e), sensible (Q_h) and ground (Q_g) heat flux in the upland and fen in 2014.

5.4.2.3 Soil water dynamics

Near-surface *VWC* responded to daily cycles of *P* and *AET* within the soil capping layers (i.e., the peat / mineral mix in the peat-lined basin and the LFH throughout the rest of the upland), with a generally dampened response towards the base of this layer where *VWC* was typically highest (Figure 5-8). The *VWC* regime at the top of the underlying tailings sand layer was distinct from that of the overlying soil capping layers, as it did not demonstrate the same extent of diurnal variability. In spite of being more consistently decoupled from atmospheric processes, *P* inputs did percolate through the soil-capping layer and into the tailings sand layer during and following *P* events. The magnitude of the response within the tailings sand layer was influenced by the timing (i.e., antecedent moisture conditions) and magnitude of each *P* event. For example, negligible *P* was received at the start of the 2013 study period in mid-May, which was followed by a wet period in early-June and several large *P* events that occurred with some regularity throughout the study period (approximately every two weeks; Figure 5-8). Much of the *P* water inputs received during these events drained through the profile of the soil-capping layer and into the tailings sand layer, as evidenced by the strong response in the *VWC* at the top of the tailings sand throughout the 2013 study period as well as by the response in the water table (Figure 5-9). In contrast, the predominance of small *P* events in the relatively dry mid-summer period of 2014 were, for the most part, insufficient to exceed the soil-water storage of the overlying soil-capping layer and, thus, the *VWC* response to *P* events within the top of the tailings sand layer occurred less frequently in 2014. Hence, substantial *VWC* responses within the tailings sand only occurred during the largest two *P* events in 2014 (late May and late July). Further, the tailings sand beneath the peat-lined basin exhibited a prolonged return to pre-event moisture conditions following *P* events relative to areas that were overlain by the LFH soil-capping layer. This occurred due to the presence of a transient perched water table that developed within the peat / mineral mix soil-capping layer of the depressional peat-lined basin during large *P* events (only measured in 2013; Figure 5-8). The perched water table within the peat-lined basin persisted for an average period of over two days following a single *P* event (i.e., excluding perched water table levels that were sustained by more than one *P* event), with a perched water table present for over 28 days in 2013 (27% of study period). Note that this perched water table was observed above the persistent underlying water table within the upland aquifer at the same location.

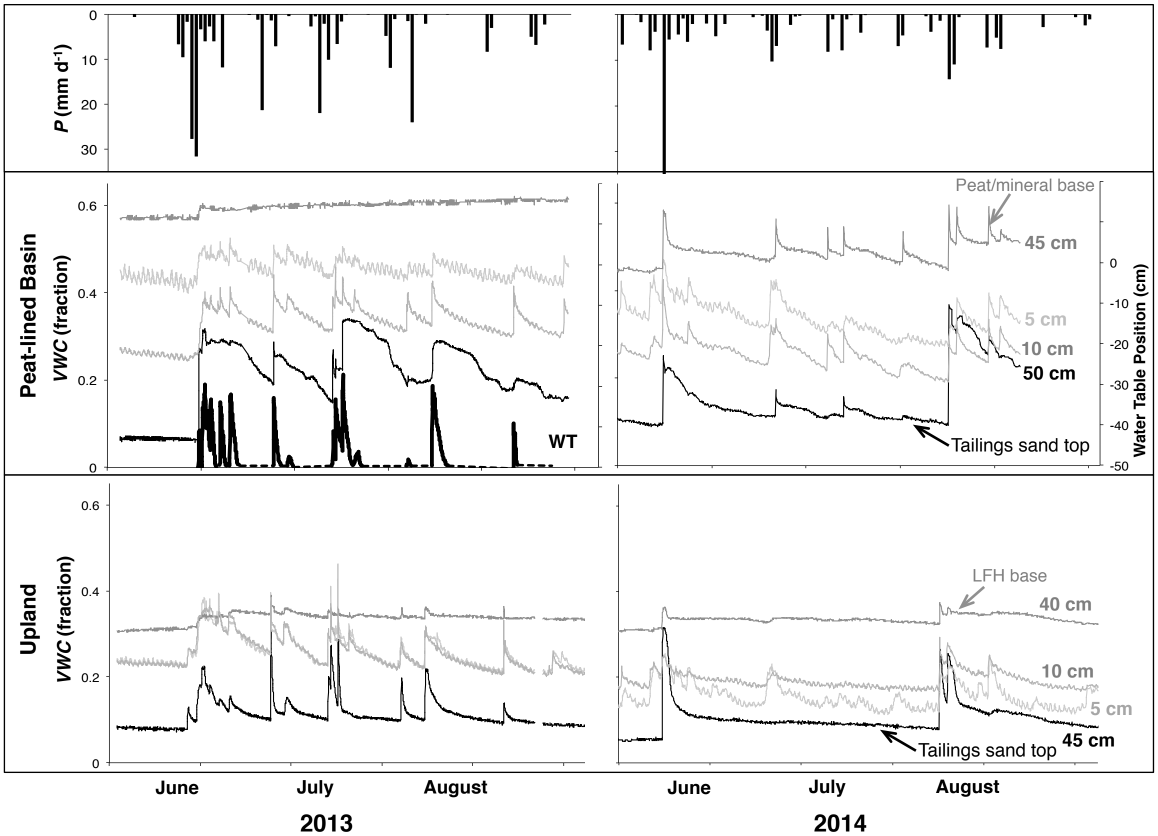

Figure 5-8 - Precipitation (A) and volumetric water content (*VWC*) within the peat-lined basin (B) and the upland (C) during the 2013 and 2014 study periods. The bold line in B indicates the perched water table (WT) within the peat-lined basin (only measured in 2013). All measurement depths (indicated on the figure) are expressed as cm below ground surface. Note that the discrepancy in the depth of the top of the tailings sand layer is the result of variations in the thickness of the soil-capping layer. Data in (B) and (C) are from the soil moisture stations labeled as 1 and 2 on Figure 5-1, respectively.

5.4.2.4 Water table dynamics

The water table was relatively deep in the upland, transition and fen portions of the Nikanotee Fen watershed at the start of the 2013 study period (Figure 5-9). This was an artifact of the placement of the reclamation materials at a relatively low water content (in spite of the water applied to the upland and precipitation recharge during the construction phase). Following this initially dry phase, water table levels throughout the watershed responded strongly to several large rainfall events in early June 2013. For example, water table elevation increased by 22, 60 and 46 cm in wells in the upland, transition (near-fen zone of the upland) and fen, respectively, over a 12-day period in early June 2013. Variations in the water table elevation in the fen and the transition zone of the upland were smaller in 2014 than 2013. Annual patterns of early-season groundwater recharge (i.e., water table rise) were apparent in the upland aquifer in early to mid-June in both 2013 and 2014 (Figure 5-9), which was well after the spring snowmelt period ended. However, many of the wells that were installed in the upland during the first half of the 2013 season remained dry until they were extended to greater depths in May 2014 (see Methods section). Nonetheless, the routine monitoring of these (dry) wells indicated that the water table remained deeper than 275 cm bgs within much of the upland throughout 2013. Upon extending the depth of the wells (and installing new, deeper wells) in the middle section of the upland in 2014, the average water table level was 290 cm bgs, which increased to 273 cm bgs by August 2014.

In the fen, water table levels stabilized by mid-June 2013 and remained high for the remainder of 2013 and throughout 2014 (Figure 5-9). Persistent ponded water was present in localized depressions in the surface of the placed peat and near-saturated conditions were sustained elsewhere across the fen. For example, frequency distributions of water table position during the 2014 study period indicated that the water table in the fen was at or above the peat surface nearly 50% of the time (Figure 5-10A). In addition, the water table position was within ±10 cm of the surface of the fen for approximately 60% of the water table measurements. Monthly water table data from 2014 indicated a slight drying of the fen and deeper water table levels during June and July following a wet period in May, with a slightly higher median water table in August than the preceding two months (Figure 5-10B). The water table sloped gently from the southwest towards the discharge point of the fen in the northeast, with small horizontal hydraulic gradients across the fen (average = 0.001 ± 0.0005 standard deviation; Figure 5-11). The horizontal gradients, or slope of the water table within the fen, showed little difference between wet and dry conditions, with an overall range of 0.002 to 0.0007.

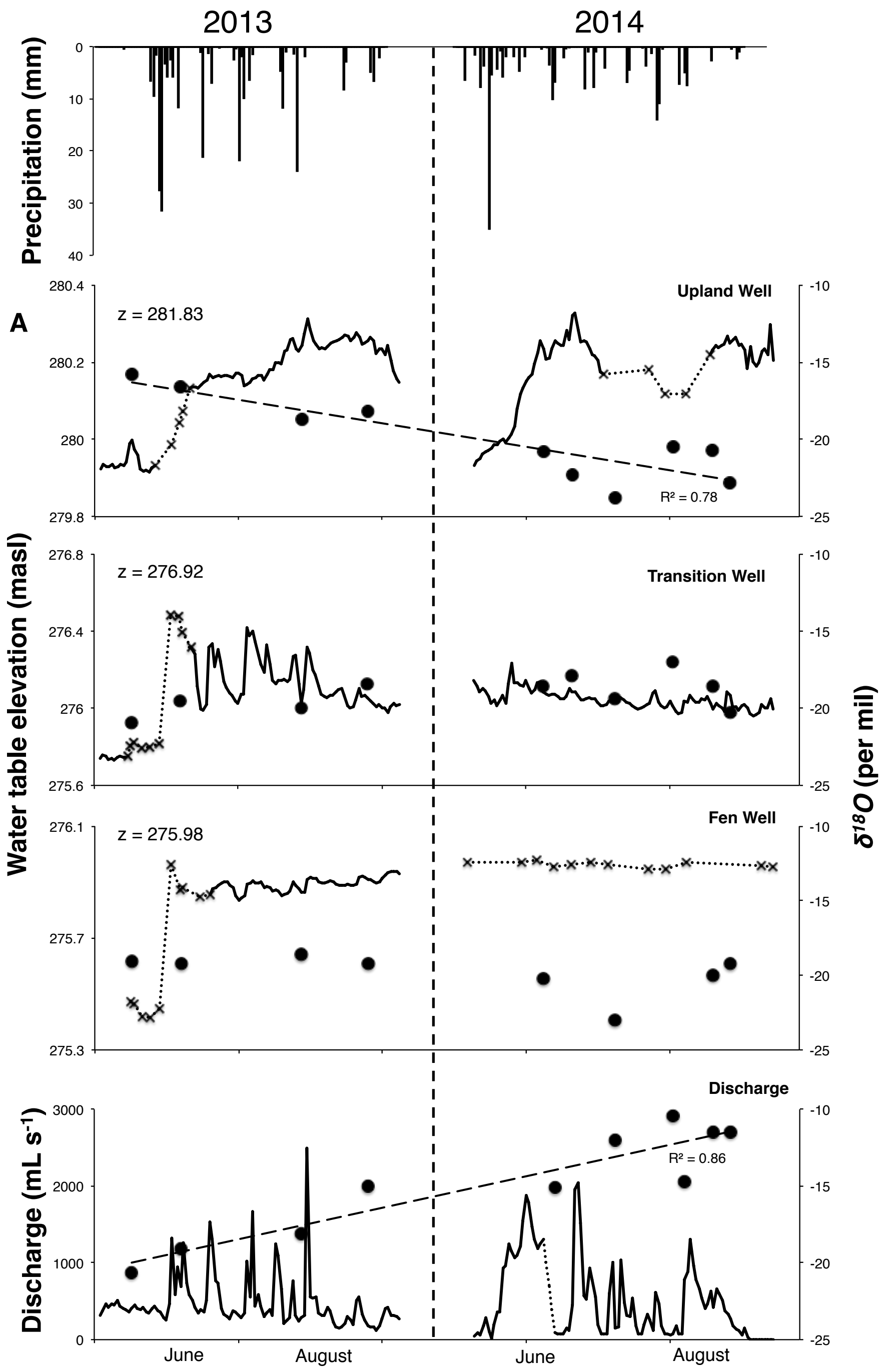

Figure 5-9 - Precipitation (black bars; top panel), water table elevation (middle three panels) and discharge (bottom panel) for the Nikanotee Fen watershed in 2013 and 2014. Water table elevations expressed as absolute elevation (meters above sea level, masl; z = ground surface elevation). Circles represent $\delta^{18}O$ signatures of groundwater sampled from each well / surface water sampled at the fen outlet. Data for the upland, transition and fen wells are from the wells labeled A, B and C on Figure 5-1, respectively.

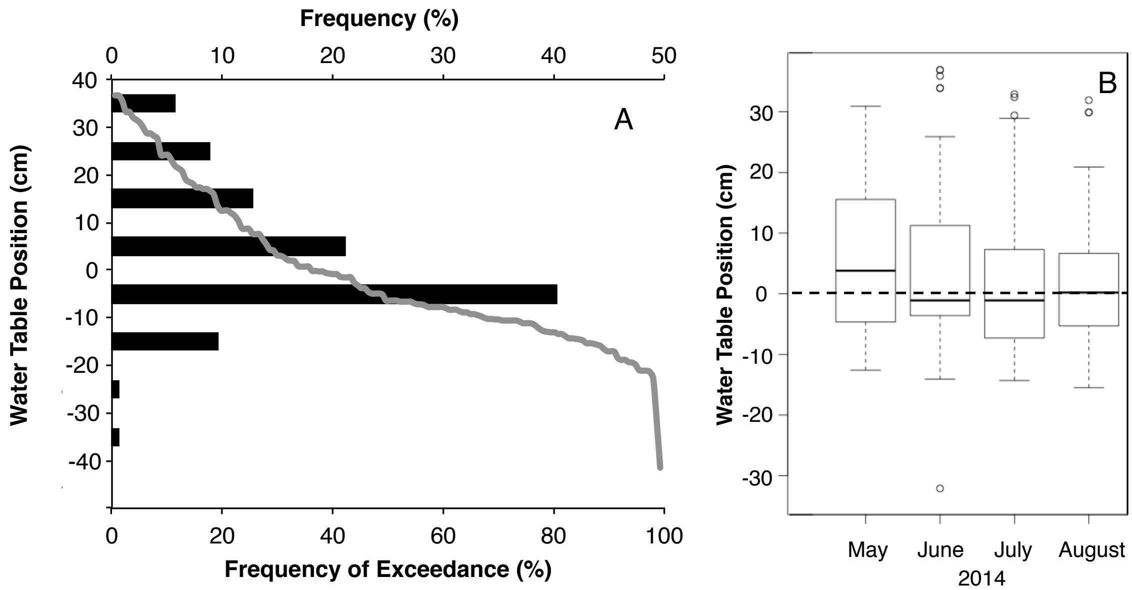

Figure 5-10 – A) Frequency histogram (bars; upper horizontal axis) and frequency distribution (line; lower horizontal axis) for the water table position within the Nikanotee Fen during the 2014 study period. B) Boxplots of monthly water table position within the Nikanotee Fen. All water table positions expressed as cm relative to ground surface; positive = depth of ponded water; negative = distance below ground surface.

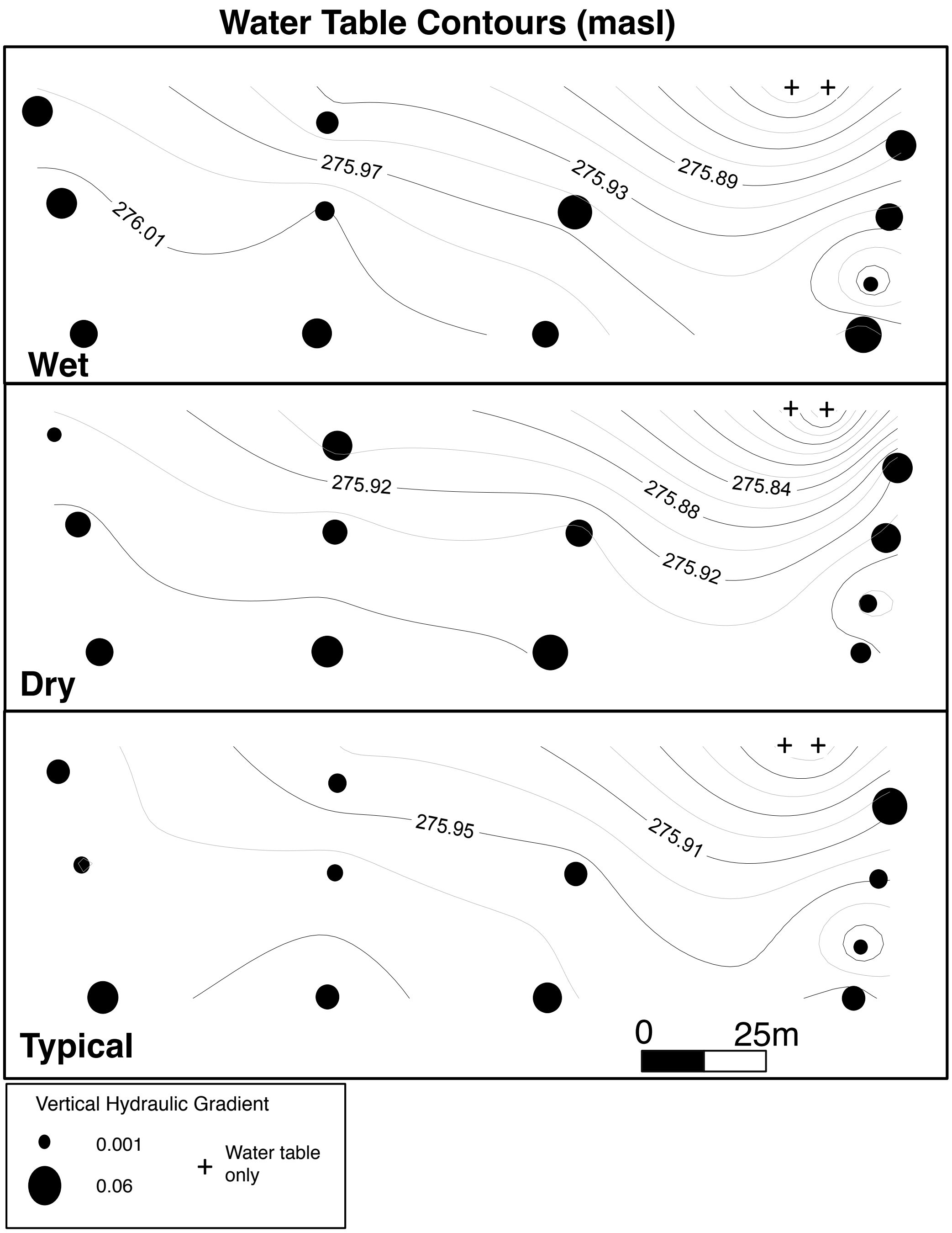

Figure 5-11 - Water table elevation contours in the Nikanotee Fen during wet (19-June-2014), dry (22-July-2014) and typical (2-July-2014) conditions (meters above sea level; 2 cm contours). Circles are measurement points (nest locations) with the symbol size scaled relative to the magnitude of the average vertical hydraulic gradient at each nest on the date measured (upwards gradients).

5.4.2.5 Storage changes

The lack of reliable observation points in much of the upland (due to wells that remained dry all study season) introduces considerable uncertainty in the estimates of groundwater recharge to the upland aquifer. Nevertheless, an aerially weighted change in water table position at the known measurement points, coupled with the assumption that this water table change was the same in areas where measurements were not possible (saturated zone below deepest measurement point at start of 2014 season), provided an estimated change in storage of the saturated zone of 90 and 52 mm within the upland aquifer over the 2013 and 2014 study periods, respectively. The large water table rise in the fen in early 2013 resulted in large saturated zone storage gains (103 mm). However, the small size of the fen relative to the upland reduces the influence of these large storage changes on the overall storage term for the combined upland – fen system. Higher *VWC* within the unsaturated zone throughout the upland aquifer and fen at the beginning of the 2014 study period resulted in a slight loss of water from storage (9 mm) during the course of the season, which partially offset water storage gains due to water table rise. The storage term for the 2014 study period was less than that of the 2013 period, mostly due to the large water table rise observed throughout the watershed in early 2013 (Figure 5-9).

5.4.2.6 Groundwater fluxes from the upland aquifer to the Nikanotee Fen

The seasonal average vertical hydraulic gradient within the Nikanotee Fen was 0.015, with a site-averaged range of 0 to 0.035 for all of the 2014 measurement dates. The vertical hydraulic gradient varied considerably between nests within the fen on any given measurement date, often by as much as two or three orders of magnitude. However, gradients measured near the toe of the upland (median = 0.02) were consistently greater than the gradients measured towards the discharge point of the fen (0.01; Figure 5-12). Both upwards (positive) and downwards (negative) gradients, hence groundwater fluxes, were occasionally measured within the fen on the same measurement date, with downward gradients comprising less than 15% of all measurements. Negative gradients were typically small and, thus, were masked in the calculation of the site-averaged groundwater fluxes and hydraulic gradients. Vertical hydraulic gradients were highest when ground frost was present, with an average of 0.02 and 0.009 with and without ground frost, respectively, and exhibited a general decreasing trend as the summer progressed. However, vertical fluxes were strongly reduced by the presence of ground frost within the fen in the early portion of the season, which persisted at some locations until early July (Figure 5-13). The estimated average daily vertical groundwater flux from the upland aquifer to the fen during the 2014 study period was ~1.8 mm d^{-1}. The total vertical groundwater flux from the upland aquifer to the fen was approximately 177 mm over the 2014 study period, although this could change depending on the manner in which K_{sat} is averaged at each nest (i.e., according to Equation 5-2 or using the geometric mean – see Discussion section). Horizontal hydraulic gradients based on the water table elevation between the upland aquifer and fen were typically small, with a seasonal average gradient of ~0.007 between the peat and upland tailings sand aquifer in the near-upland (transition) zone of the upland. However, since the K_{sat} of the petroleum coke undrain layer exceeded that of the fen peat and the tailings sand aquifer (2014 data; Figure 5-5), groundwater from the tailings aquifer would be refracted downward to the higher hydraulic conductivity petroleum coke underdrain layer (Freeze and Witherspoon, 1968), and then become part of upward flux of water from the petroleum coke underlying the fen, towards the surface. Had we used the Dupuit assumption to calculate flow through the 440 m^2 flow face between the sand and the peat, the flux (148 m^3) represents only 5 mm of water to the fen over the course of the 2014 study period. Since this represents < 3% of the net vertical groundwater flux to the fen, the uncertainty caused by the complex groundwater flowpaths is considered negligible and ignored. It is also possible that the overall slope of the underlying GCL basal liner (3%) controlled horizontal groundwater fluxes from the upland to the fen. Although this conceptual model is not tested in this thesis, it warrants consideration in future interpretations of groundwater fluxes.

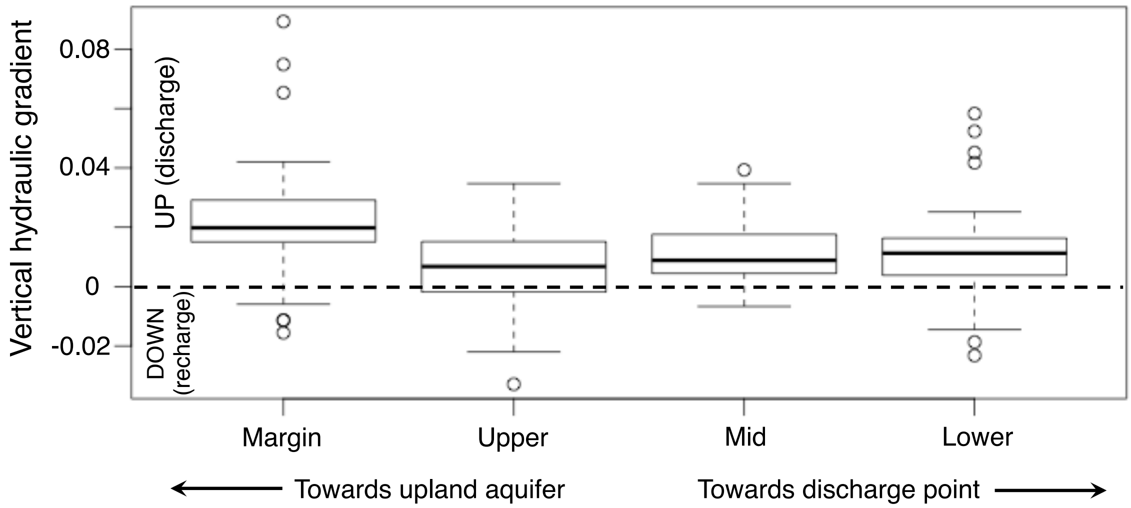

Figure 5-12 - Vertical hydraulic gradients at different transect positions across the Nikanotee Fen (2014 data only). The 'margin' transect is the closest to the upland aquifer, while the 'lower' transect is the closest to the discharge point of the fen. See Figure 5-1 for transect positions.

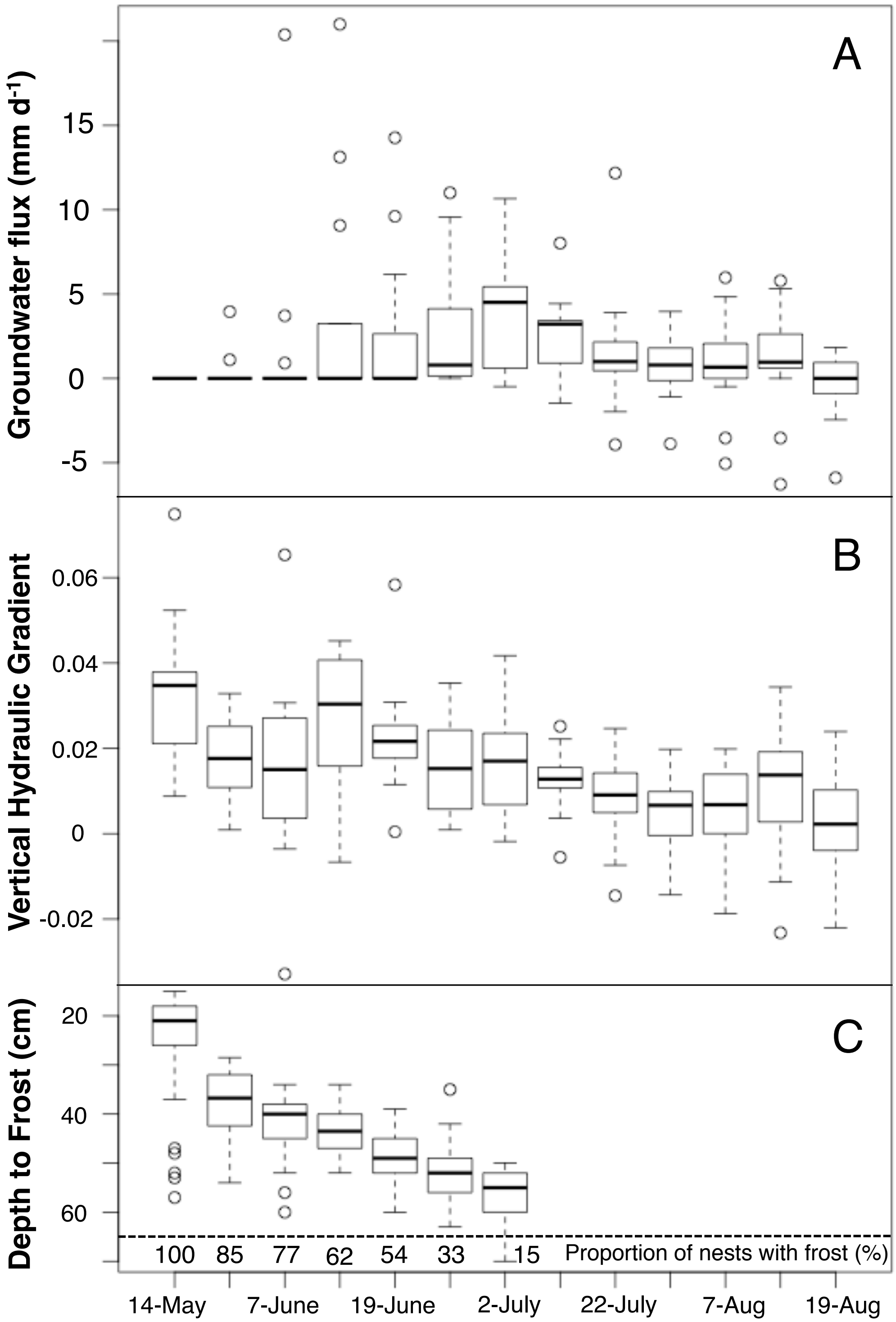

Figure 5-13 – Vertical groundwater fluxes from the upland aquifer to the Nikanotee Fen (A), vertical hydraulic gradients between the petroleum coke underdrain layer and the fen water table (B) and depth to ground frost (and proportion of nests where continuous ground frost was encountered) measured within the Nikanotee Fen (C). All data are from the 2014 study period.

5.4.2.7 Runoff

Runoff at the outlet of the fen responded rapidly to intense *P* events in both years (Figure 5-9). Similar average daily runoff rates (~0.4 mm d^{-1}) and total seasonal runoff (41 mm) were observed in 2013 and 2014 for the upland – fen system. However, runoff tended to be flashier (i.e., higher peak runoff and steep hydrograph recession limbs) in 2013 than 2014, with a greater tendency for sustained low daily runoff rates in 2013 (85% of daily runoff rates < 0.5 mm d^{-1}). Conversely, although the maximum observed daily runoff rate was lower in 2014, there was a greater tendency for mid-range (i.e., 0.5 – 1.0 mm d^{-1}) runoff rates compared to 2013. For example, 30% of daily runoff rates exceeded 0.5 mm d^{-1} in 2014 compared to 15% of those observed in 2013. During 2013, water was occasionally manually pumped out of the fen to facilitate planting of vegetation in the fen. This pumping was directed through the spill box / flume and accounted for; however, the short pumping duration (~12 hours combined over a total of six days) contributed minimally to the daily and seasonal runoff rates (total water pumped from fen was ~4 mm).

5.4.3 Isotopes

The local meteoric water line (LMWL) determined using the $\delta^{18}O$ and δD of individual summer rainfall samples (collected between May to September 2013 and 2014) and snow samples collected during March and April 2013, has the form,

$$\delta^2 H = 7.9\delta^{18} O + 7.2 \,. \tag{5-3}$$

This is similar to that defined for Syncrude Canada's Mildred Lake mine (δ^2H = 7.0 $\delta^{18}O$ -18.6) located ~20 km northwest of the Nikanotee Fen watershed (Baer, 2014). The isotopic composition of summer rainfall events demonstrated minimal variability, with $\delta^{18}O$ values between -11.8 and -16.8‰ and δD values between -78.6 and -133‰ (Figure 5-14). The volume-weighted mean $\delta^{18}O$ and δD was -15.0‰ and -112.7‰, respectively, for all rain samples collected in 2013 and 2014. The isotopic composition of rainwater was considerably heavier than that of snow samples, which clustered between $\delta^{18}O$ values of -24.7 to -28.2‰ and δD values between -190.8 and -211.4‰. Fen discharge water had enriched $\delta^{18}O$ values, especially later in the 2014 season (see Figure 5-9), which indicates evaporative effects. Groundwater samples from the upland generally plotted along the LMWL, which implies minimal isotopic enrichment via evaporation at the surface. However, upland groundwater samples from 2013 are slightly offset to the right of the LMWL, which is a partial reflection of the source of the water (surface water) that was applied to the upland during construction. Accordingly, groundwater from the upland aquifer had lower $\delta^{18}O$ values (-18.4) than the volume-weighted mean rainfall value (-15.0), trending towards the depleted signature of snow during the course of the 2013 and 2014 seasons (Figure 5-14 inset and Figure 5-9). This suggests that snowmelt might be an important component of the annual groundwater recharge.

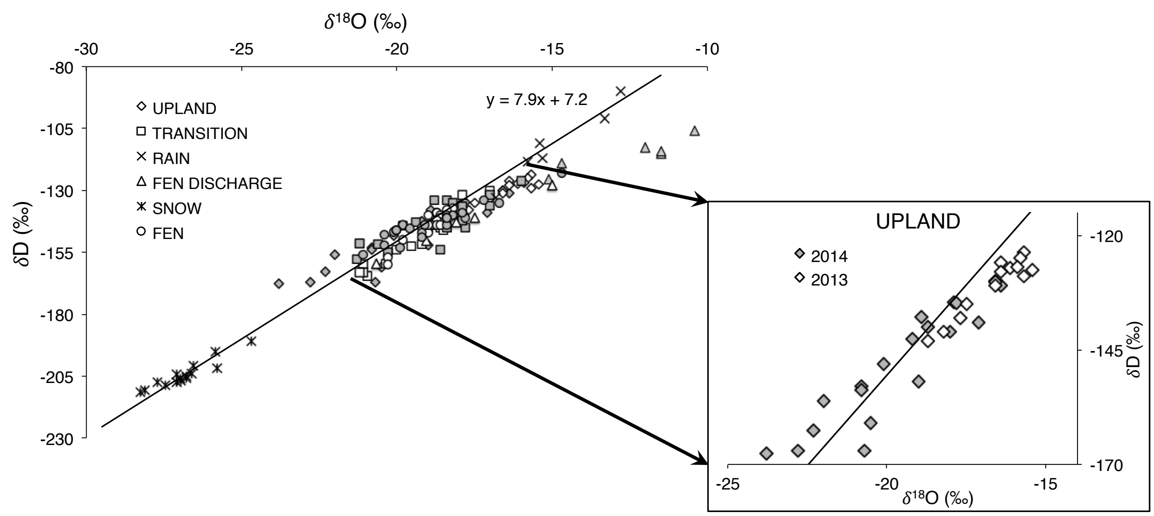

Figure 5-14 - Isotopic signatures of water sampled throughout the Nikanotee Fen watershed during 2013 (open symbols) and 2014 (shaded symbols). Groundwater samples from the upland in 2013 and 2014 are shown in the inset figure. All groundwater samples are from wells, except for the FEN samples, which were from shallow piezometers (50 cm depth).

5.5 Discussion

5.5.1 Summary of water budget components in the upland – fen system

Based on the results presented above, the water budget identifies the magnitude and distribution of water fluxes within a watershed, such that

$$P + R_{slope} + GW_{in} = AET + R + GW_{out} + \Delta S \pm \varepsilon \qquad (5\text{-}4)$$

where R_{slope} is surface runoff from the reclaimed slopes (includes shallow subsurface flow, when present); GW_{in} and GW_{out} are the groundwater exchanges between the upland – fen system and the underlying substrates (both considered negligible owing to the isolating effect of the basal liner); R is the runoff measured at the outflow of the fen; ΔS is the total change in storage of the unsaturated and saturated zones; and ε is the residual term (other terms as previously defined).

The largest hydrologic flux from the constructed upland – fen system was AET, which represented 75% and 111% of P inputs during the 2013 and 2014 study periods, respectively (Table 5-3). Daily AET rates in the fen were much greater than in the upland (Table 5-2), as driven by persistent near-saturated conditions within the fen (Figure 5-10) and the dominant partitioning of available energy to Q_e (Figure 5-7). Precipitation dynamics exhibited a strong control on R_{slope}, which represented an occasional but important contribution of water for the upland-fen system. The majority of this water influx occurred via infiltration-excess overland flow generated on the recently reclaimed 2011 slopes to the south-east and west of the upland-fen system during P events that exceeded an intensity of 3 mm h^{-1} (as discussed in Chapter four). This occurred on the 2011 slopes during 25% (total = 60 mm) and 17% (total = 61 mm) of P events during 2013 and 2014, respectively. In contrast, the reclaimed 2007 slope to the east stored most of the precipitation inputs and provided only infrequent water fluxes to the designed upland-fen system (< 1 mm and 6 mm in 2013 and 2014, respectively). The total water inputs from all reclaimed slopes in the watershed to the upland-fen system were 60 and 67 mm in 2013 and 2014, respectively, with water fluxes from the 2007 slope comprising less than 10% of all water inputs to the designed system.

Total runoff over the 2013 and 2014 study periods was similar (41 mm) but with different runoff ratios of 16% and 20% for 2013 and 2014, respectively (expressed relative to the upland and fen only). The lower runoff ratio in 2013 is a reflection of differing *P* characteristics and soil storage dynamics in each year. For example, over 50% of the *P* input during the 2013 study season was received during June (Figure 5-6). However, much of this water went into groundwater recharge and soil water storage, as reflected in the large water table rise observed throughout the watershed in June 2013 (Figure 5-9) and the prominent response in *VWC* in the unsaturated zone (Figure 5-8). Hence, the runoff response at the outlet of the fen was low during the first half of this wet period in 2013 (Figure 5-9) and the seasonal change in storage was large (Table 5-3). In contrast, water table levels were already high at the start of the 2014 study period in the transition zone of the upland and the fen (Figure 5-9), owing to the 109 mm of water stored during the 2013 study period (Table 5-3), which was partitioned between soil water storage (16 mm) and groundwater recharge (93 mm). Consequently, in 2014 runoff was favoured over water storage in the transition zone and fen, as reflected by their high and stable water table levels. Groundwater recharge was prominent in the upper reaches of the upland aquifer early in the 2014 study period (Figure 5-9).

Groundwater recharge to the uplands aquifer was constrained somewhat by the high soil water storage capacity of the LFH reclamation soil-capping layer, which was 50 to 125% thicker than the 20 cm targeted thickness. The *f* of the LFH materials was highly spatially variable, with a range of ~4 to 400 mm hr^{-1} (Figure 5-3), which was sufficient to facilitate percolation of *P* water through this soil-capping layer and into the tailings sand layer under wet conditions (Figure 5-8). Consequently, groundwater recharge to the upland aquifer was controlled by *P* dynamics and tended to occur during *P* events that exceeded ~10 – 15 mm, as well as during events that occurred within the few days following a larger event. Thus, in spite of the increased *f* of the LFH soil-capping layer in 2014 (Figure 5-3), recharge to the upland aquifer was greater in 2013 due to the more even distribution of larger *P* events compared to the relatively dry mid-summer period of 2014 when recharge was minimal (Figure 5-8). Accordingly, total storage change in the upland – fen system was 109 and 29 mm in 2013 and 2014, respectively (Table 5-3).

Table 5-3 - The components of the water budget for the constructed upland-fen system in 2013 and 2014, and for the Nikanotee Fen ('FEN ONLY') in 2014 (all values in mm). P is precipitation; R_{slope} is surface runoff from the reclaimed slopes; R is the runoff measured at the outflow of the fen; ΔS is the change in storage of the saturated zone; ε is the residual term; % Error is calculated by dividing ε by the amount of P each year and multiplying by 100.

	P	R_{slope}	GW_{in}	AET	R	GW_{out}	ΔS	ε	% Error
2013	257	60	-	193	41	-	109	-26	10
2014	201	67	-	223	41	-	29	-25	12
FEN ONLY (2014)	201	67*	177	382	148	0	1	-86	43

* assumes that all of R_{slope} is received in the fen. Implications of this assumption are discussed in-text.

5.5.2 Hydrological processes within the Nikanotee Fen

Quantification of the hydrologic fluxes into and out of the Nikanotee Fen permits an assessment of the hydrological performance of the fen itself. Thus, computing a water budget where the fen is the area of interest can identify the relative importance of these hydrologic fluxes on sustaining wet conditions in constructed fen systems. The water budget of the Nikanotee Fen can be estimated by

$$P + R_{slope} + GW_{in} = AET + R + GW_{out} + \Delta S \pm \varepsilon \qquad (5\text{-}5)$$

where GW_{in} is the total groundwater flux from the upland aquifer to the fen, and GW_{out} is the groundwater flow out of the fen. Note that all fluxes are expressed relative to the area of the fen (2.9 ha) instead of the area of the combined upland – fen system (10.6 ha). This results in differences in some depth-normalized water budget components common to both the fen and the combined upland-fen systems (Table 5-3). However, these apparent discrepancies are an artifact of the difference in the area of interest to which the hydrologic fluxes are computed (e.g., R within Equation (5-5) was normalized to the area of the fen, whereas it was normalized to the area of the combined upland – fen system in Equation (5-4)). Since the water contributions from the reclaimed slopes surrounding the upland-fen system (R_{slope}) were computed as a depth-flux estimated from precipitation data, it was assumed that the same flux as for the combined upland-fen system (67 mm) was also representative for the fen only. This likely underestimated R_{slope}, since some of the water flowing off of the reclaimed slopes was also delivered to the fen via overland flow from the upland. However, evaporation, surface detention, soil water storage and groundwater recharge within the upland likely minimized the magnitude of this underestimation.

Evapotranspiration was the largest component of the water budget for the Nikanotee Fen (Table 5-3). *AET* was highest in the fen in 2014 (3.6 mm d^{-1}), as sustained by higher and more stable water table levels (Figure 5-9), coupled with the persistence of flooded areas (Figure 5-10B) and extensive vascular vegetation cover. The partitioning of available energy within the fen favoured Q_e over Q_h in 2014 (Figure 5-7). Cumulative *AET* within the fen exceeded *PET* in 2014 (*AET*/*PET* = 1.07; Table 5-2). Substantial groundwater fluxes into the fen system from the upland aquifer helped to partially offset the large atmospheric losses from the fen via *AET*. Over the course of the 2014 study period, the fen received approximately 177 mm of groundwater input from the upland tailings sand aquifer. These groundwater fluxes were delivered to the fen almost entirely through the petroleum coke underdrain layer. This predominance is due to the design of the underdrain layer that was located beneath nearly the entire area of the fen (i.e., over an area of ~29 000 m^2) and was also extended ~100 m into the upland aquifer (in the zone termed the transition zone of the upland, Figure 5-1). Thus, this layer facilitated widespread distribution and delivery of groundwater fluxes from the upland aquifer, while the horizontal groundwater fluxes were constrained by the small flow face of the upland tailings sand aquifer – fen peat interface (~440 m^2). Additionally, the strength of the vertical hydraulic gradients within the fen (i.e., between the underdrain and fen peat layers; average of ~0.015) was greater than the horizontal gradients (average of ~0.007 in the near-fen zone). While undisturbed peat soils typically exhibit horizontal / vertical K_{sat} anisotropy ratios greater than 1 (Beckwith *et al.*, 2003), which would tend to favour horizontal over vertical groundwater flow, the highly disturbed peat within the Nikanotee

Fen has an anisotropy ratio of 1 (Nwaishi *et al.*, 2015b). Thus, neither vertical nor horizontal flow was favoured based on the hydrophysical properties of the placed peat.

Ground frost controlled the vertical groundwater fluxes within the fen by both influencing the magnitude of the vertical hydraulic gradients (highest while ground frost present; Figure 5-13) as well as by physically impeding water fluxes across the layer of frozen soil, since frozen saturated peat soils have very low permeability (Roulet and Woo, 1986). This consequently constrained groundwater recharge to the fen until the majority of the ground frost had melted by the mid-summer (Figure 5-13). Although the water table was higher in the early portion of the 2014 study period (Figure 5-10), which was likely an artifact of the high *P* received in May (Figure 5-6), groundwater influxes to the fen were important to help sustain high water table levels in the mid-summer when daily *AET* rates peaked. Regardless, wet conditions were sustained in the Nikanotee Fen (water table within 10 cm of the fen surface) for the majority of the 2014 study period (Figure 5-10), which also resulted in a minimal change in storage. Similarly, variations in the water table elevation in the fen were smaller in 2014 than 2013 (Figure 5-9).

Estimates of groundwater flows are prone to a large degree of uncertainty and are especially sensitive to K_{sat} in Equation (5-1). Although reasonable assumptions were employed (e.g., use of K_z for vertical fluxes), groundwater estimates can vary by up to ±70% (Ferone and Devito, 2004). The method used to compute a representative value of K_{sat} (i.e., Equation (5-2)) yielded a seasonal total groundwater flux of 177 mm. Under identical field conditions, the estimated seasonal groundwater flux increased to 282 and 499 mm when the K_{sat} at each nest was computed using the geometric and arithmetic mean values, respectively, of the K_{sat} values measured at each piezometer in the nest. Thus the groundwater flux estimated using K_z and that using the arithmetic mean K_{sat} varied nearly by a factor of 3 (> 300 mm), owing to the several orders of magnitude variability exhibited by the individual measurements of K_{sat} within the peat deposit (Figure 5-2). Further, the discrepancies between the vertical and horizontal groundwater flux estimations can be partially attributed to the sensitivity of these calculations to the K_{sat} of the petroleum coke underdrain layer, which might be underestimated in the current study based on the trend of increasing K_{sat} in Figure 5-5. Also, this study only considered estimates of K_{sat} made using piezometers fully slotted within the material / layer of interest and those that could be measured manually. Additional K_{sat} measurements made using fully slotted wells (i.e., wells that were screened across the tailings sand and petroleum coke layers) within the transition zone of the upland, and a few piezometers within the petroleum coke layer beneath the fen, recovered too quickly to be accurately measured and, thus, were not included in this analyses. Accordingly, horizontal groundwater fluxes could have occurred predominantly through portions of the underdrain layer where the petroleum coke exhibited the highest K_{sat} and would be insufficiently accounted for in the current study.

The errors associated with estimating atmospheric fluxes are substantially smaller than the groundwater estimates. For example, estimates of annual *P* can be accurate to ±10% (Ferone and Devito, 2004), which would equate to ±20 mm in the current study (in 2014) and is an order of magnitude smaller than the groundwater flux estimation error. Likewise, *AET* uncertainty was calculated according to Kroon *et al*. (2010) and Wang *et al.* (2015) and found to average only ±13% over the two study seasons. Consequently, the error associated with estimating the magnitude of the groundwater fluxes to the fen as the residual term of the water budget (excluding the groundwater component) could be substantially smaller than those associated with attempting to compute the groundwater fluxes to the fen using field-based hydrometric measurements. If the groundwater components of the fen water budget are excluded from Equation (5-5) and Table 5-3 in the current study, the residual term is 263 mm. This value is most closely represented by the groundwater flux estimated using the geometric mean K_{sat} (282 mm). However, representing K_{sat} at an individual location using Equation (5-2) is more physically representative than using a geometric mean, since K_z accounts for the character of the layered heterogeneity through incorporating the thicknesses of each of the layers with a known K_{sat}. However, this technique (i.e., using K_z) results in a groundwater flux of 177 mm and may be an underestimation of the actual groundwater fluxes to the fen. It was anticipated that the combination of a relatively small fen (2.9 ha), dense measurement network (> 4 locations per hectare within the fen) and high frequency of measurement (usually every 6 days) in the current study would minimize errors in the groundwater fluxes. It is possible that 'windows' of high K_{sat} might have contributed substantially to the groundwater fluxes to the fen, since the estimate of vertical groundwater flux is highly sensitive to K_{sat}. However, this phenomenon was not accounted for in the groundwater flux estimation.

5.5.3 Hydrologic performance and hydrophysical evolution of the reclamation materials

Original design specifications derived from numerical modelling simulations (Price *et al.*, 2010), as well as modifications thereafter (Daly *et al.*, 2012), resulted in the development of targeted K_{sat} values for each of the reclamation materials used to construct the Nikanotee Fen watershed. These targeted K_{sat} values were 10^{-5}, 10^{-4} and 10^{-2} m s^{-1} for the fen peat, tailings sand and underdrain material, respectively. Measurements of K_{sat} from 2013 indicated that all of the construction materials had a lower initial K_{sat} than targeted in the original design (e.g., as in Price *et al.*, 2010; and Daly *et al.*, 2012). Specifically, the initial K_{sat} (i.e., 2013 data) of the peat and upland tailings sand were approximately one order of magnitude lower than targeted (3×10^{-6} and 8×10^{-6} m s^{-1}, respectively) and K_{sat} of the petroleum coke underdrain layer (4×10^{-6} m s^{-1}) was over three orders of magnitude lower than expected. However, inter-year comparisons of materials placed in 2013 revealed that K_{sat} within the peat increased at all depths in 2014 compared to 2013 (Figure 5-5). This trend of increasing K_{sat} within the peat profile continued through 2015 only at 150 cm depth, while slight reductions in K_{sat} between 2014 and 2015 were observed at 50 and 90 cm depths. However, 2015 values remained above the initial K_{sat} measurements from 2013 at all depths in the peat profile. A similar trend was observed within the petroleum coke underdrain layer, where an increase in K_{sat} from 2013 to 2014 was followed by a slight decrease in 2015, which remained above the initial K_{sat} measured in 2013. Conversely, the placed tailings sand material showed negligible change (very slight reduction) from 2013 to 2014, but increased marginally in 2015 (Figure 5-5). The placed peat material also exhibited a decreasing trend of K_{sat} with depth (Figure 5-4), which could be a reflection of both the technique used for the placement of the peat (in lifts, with more compaction of deeper layers likely) as well as due to the increased total stress deeper within the peat profile caused by the weight of the overlying peat.

Several mechanisms could have contributed to the inter-year increase in K_{sat} observed for some of the reclamation materials in the current study. For example, since oil sands tailings materials can contain high concentrations of salts (Rezanezhad *et al.*, 2012a), it is possible that the observed inter-year increase in K_{sat} within the peat profile could have been caused by chemical dilation of pores, as driven by the interaction of salts flushed from the tailings sand materials with organic-acid functional groups within the fen peat (Ours *et al.*, 1997). In a laboratory column experiment, K_{sat} within peat soils increased by up to five times due to chemical dilation of pores exposed to chloride (Cl^-) concentrations of 250 ppm (Ours *et al.*, 1997). Although maximum Cl^- concentrations of up to 250 ppm have been measured in the upland tailings sand aquifer, the average Cl^- concentration is much lower (40 ppm; n = 157). The maximum and average observed Cl^- concentrations within the fen peat profile during 2013 and 2014 were 104 and 22 ppm, respectively (n = 204; unpublished data). Thus, although chemical pore dilation might have contributed to the inter-year increase in K_{sat} in the fen peat, the Cl^- concentrations measured within the fen are well below those observed in Ours *et al.* (1997), which makes it unlikely that changes of a similar magnitude have been realized in the peat within the Nikanotee Fen. Another variable that could influence the K_{sat} within the peat is the growth of vascular vegetation, which was much better established throughout the fen in 2014 and 2015 compared to 2013. However, the growth of vascular plants does not necessarily increase the K_{sat} in constructed wetlands (Brix, 1997) and it is unlikely that the rooting zone extended to the deeper measurement points within the peat profile that also demonstrated an increased K_{sat} (Figure 5-5). Also, a persistently high water table in 2014 could result in peat volume change via surface level rebound due to reduced effective stress within the peat deposit, which could increase the K_{sat} (Price, 2003; Ketcheson and Price, 2011). However, the only substantial rebound in the surface level of the peat corresponded with the large initial rise in water table in early 2013 (Figure 5-9) and this phenomenon was not ubiquitous. Lastly, differences in the water temperature between K_{sat} measured at different times during the field season could influence the hydraulic conductivity values through the viscosity term, however, this effect is usually small, even between measurements made under field and laboratory (i.e., room temperature) conditions (Freeze and Cherry, 1979).

In the petroleum coke underdrain layer and, to a lesser extent, the upland tailings sand and fen peat, the increase in K_{sat} could be an artifact of some flushing of finer-grained sediment from the reclamation materials with repeated measurements of K_{sat} (i.e., pumping of wells during bail tests), both during successive tests within one year, as well as from tests conducted in previous years. Standard field protocols for conducting bail tests to determine K_{sat} typically include 'developing' the wells and piezometers prior to starting the measurements by pumping water out of the pipe to allow interstitial water to flow in and flush out fine debris (Butler, 1998). Accordingly, wells and piezometers were developed extensively in the days and weeks following installation and prior to the measurements of K_{sat}. Nonetheless, measurements of K_{sat} conducted in sequence on each individual pipe during a single season (conducted either over the course of weeks throughout the season or in as little as within a single day) demonstrated a trend of increasing K_{sat} across the measurement repetitions (typically triplicate). Thus, the inter-year increase in K_{sat} is partially an artifact of the mobilization and movement of soil (or peat) particles within the near-well zone of influence of the bail test in a manner that induced an increase in K_{sat} between successive tests. The magnitude of these changes in K_{sat} during sequential tests was greatest in 2013, with an average increase in the estimate of K_{sat} by a factor of 2.3, 3.3 and 1.5 for the peat, petroleum coke and tailings sand, respectively, over the triplicate measurements. These factors were reduced to 1.5, 1.3 and 1.3 for the peat, petroleum coke and sand, respectively, for tests conducted in 2014 (similar factors were observed in 2015). This type of systematic increase in K_{sat} between successive tests could be attributed to insufficient well development (Butler, 1998). This hypothesis is supported by the reduced magnitude of inter-test K_{sat} changes from 2013 to 2014. Accordingly, the values of K_{sat} in the current study are likely slight underestimations.

It is difficult to confidently state which of the several confounding factors is responsible for the observed variability in K_{sat} measured in the recently placed and highly disturbed reclamation materials. For example, most of these materials were unsaturated when placed during the construction of the watershed in 2012. Since that time, material settling and the initial saturation of the watershed likely contributed to the transient nature of the hydrophysical properties observed, in addition to the other mechanisms (pore dilation, fines flushing) previously discussed. Thus, it remains unclear at this point if the systematic increase in K_{sat} is solely due to the bail tests being conducted sequentially over time at a location, or if the increase is a reflection of the temporal changes to the material properties caused by their recent placement and largely disturbed soil structure. Continued monitoring over the following few years is necessary to evaluate these changes and determine the stabilized K_{sat} for the materials. However, quantifying the representativeness of point measurements of K_{sat} beyond the extent of the near-well zone of influence in characterizing the hydrophysical properties of highly disturbed, transient reclamation materials will remain a challenge. Moreover, characterization of the extent of spatial variability in constructed ecosystems presents an additional challenge. For example, measurements of K_{sat} conducted at 63 locations throughout the fen in 2014 indicated that the shallow (50 cm) placed peat K_{sat} varied by over an order of magnitude spatially within the fen (data not shown). These spatially intensive measurements resulted in an average K_{sat} that was three times less than the 50 cm K_{sat} measured within the nests of piezometers that comprised the routine monitoring points (i.e., nests in Figure 5-1). As was hypothesized earlier, perhaps this could be an artifact of inadequate development of the piezometers used for the spatially intensive measurements compared to the 2014 K_{sat} data at the routine monitoring points, which had been developed more extensively. Indeed, the magnitude of spatial heterogeneity of highly disturbed reclamation materials is less than encountered in natural, undisturbed landscapes; however it appears to be substantial nonetheless.

5.5.4 Groundwater recharge to the upland aquifer

The isotopic signature in the upland became more depleted over the study period (Figure 5-9), which represented a shift towards the isotopic signature of snow rather than rainfall (Figure 5-14). However, recharge of snowmelt water to the constructed aquifer was presumed to be largely constrained due to frozen soils with a low infiltration capacity (discussed in Chapter three) and the timing of substantial increases in the upland water table level coincided with early-season precipitation events instead of the spring freshet (e.g., late May / early June in both 2013 and 2014; Figure 5-9). Thus, these early summer precipitation events appear to comprise the majority of annual recharge to the constructed aquifer instead of recharge during the snowmelt period. Consequently, the water table and isotope data provide conflicting information with respect to the source of the water that recharged the upland aquifer. One possible explanation for this phenomenon is that the movement of water from the unsaturated zone to the saturated zone takes place, at least in part, in layered form (i.e., 'piston flow' recharge; Zimmermann *et al.*, 1967). Thus, it is possible that some snowmelt water percolated and re-froze in the soils in the unsaturated zone. Upon thawing of the soils, the water of snowmelt origin moved downwards during the subsequent early-season precipitation events and contributed to groundwater recharge within the upland. This trend towards an isotopically depleted signature of upland groundwater was the most apparent nearest to the peat-lined basin, which is a prominent recharge feature in the upland (discussed below) and is an area where snowmelt runoff water accumulates during the spring freshet. Subsurface measurement of soil water content was not available during the 2013 snowmelt period for verification; however, measurements from 2014 indicated a strong response in the soil water content throughout the upland during the snowmelt period but only a slight response in the water table (~10 cm rise; data not shown). Hence, it appears that snowmelt waters recharged soil water storage in the unsaturated zone during this time.

5.5.5 LFH soil-capping layer

Since K_{sat} can increase within near-surface reclamation soil covers following freeze thaw cycling (Meiers *et al.*, 2011), with vegetation establishment (Loch and Orange, 1997) and the development of secondary porosity (i.e., macropores; Guebert and Gardner, 2001), the slight increase in f in the LFH soil-capping layer between 2013 (41 mm hr^{-1}) and $f_{between}$ in 2014 (68 mm hr^{-1}) can likely be attributed to this type of soil evolution following placement. Based on the observed increase, albeit over a short period of only two years, it is likely that the LFH soil capping layer will continue to evolve in a favourable manner (i.e., increasing f and K_{sat}) over the next few years, as was observed within the mine reclamation materials in the aforementioned studies. In addition, the process of surface tilling resulted in a nearly two-fold increase in the surface infiltration rate of the LFH reclamation material within the created furrows. The magnitude of this increase is apparent when comparing f_{furrow} (128 mm hr^{-1}) to $f_{between}$ (68 mm hr^{-1}; Figure 5-3). This is especially relevant because the furrows detained surface water, which provided more time for this water to infiltrate. The difference between f_{furrow} and $f_{between}$ is solely an artifact of changes caused by the tilling of the near-surface soil, since inter-year variations in soil hydrophysical properties are avoided in this comparison. Thus, the inter-year increase observed in the grouped f data that from 2013 to 2014 (Figure 5-3) was both an outcome of the remediation efforts as well as the natural evolution of soil hydrophysical properties over time.

5.5.6 Depressional features as aquifer recharge windows

The peat-lined basin feature in the upland appeared to promote recharge to the tailings sand aquifer, as the recession limb of the *VWC* drainage curve within the top of the tailings sand material had a gentler slope and, thus, took longer to return to pre-event *VWC* conditions following *P* events than measurements made beneath the LFH soil-capping layer (Figure 5-8). It should be noted that the *VWC* at 5 cm depth appears to exceed the *VWC* at 10 cm depth. This is likely an artifact of the heterogeneity associated with the peat / mineral mix reclamation material, which included pieces of fine-grained mineral sediment distributed randomly throughout the soil-capping layer. Based on the *VWC* response demonstrated at 5 cm in the peat-lined basin, it appears as though this probe was installed into a mineral sediment inclusion, which helps to explain the higher *VWC* relative to soil deeper within the soil profile.

The peat-lined basin feature was composed of a ~50 cm thick layer of peat / mineral mix soil situated within a local topographic low near the base of a hummock feature (Figure 5-1). The remainder of the upland was constructed with a topographic slope of ~2 – 3% and a variable LFH soil thickness (~30 – 45 cm). Thus, in addition to rainfall directly on the surface of the peat-lined basin, rain and snowmelt water inputs were also directed towards this depressional feature by the adjacent hummock. This resulted in the development of a transient perched water table within the peat-lined basin that persisted for approximately two days following *P* events and contributed to the prolonged recharge to the tailings sand aquifer (Figure 5-8). This indicates that depressional features represent encouraging enhanced groundwater recharge zones in constructed ecosystems and should be incorporated into the design of future surficial landforms in portions of the landscape where recharge into constructed aquifers is desired. However, these features should be designed to maximize deep percolation (recharge) and minimize soil water storage. Thus, the practice of placing ~50 cm thick peat / mineral mix soil-capping layers into depressional recharge features is not recommended. The recharge basins constructed in the upland of the Nikanotee Fen watershed have become silted over due to deposition of sediments eroded from the recently reclaimed 2011 slopes during intense *P* events. While the rate of sediment erosion from these slopes should be reduced over time as the soils stabilize and the vegetation community becomes established, the use of erosion control infrastructure (e.g., silt fencing) is recommended during the first several years following soil placement. Nonetheless, the efficacy of the constructed enhanced recharge basins still needs to be addressed.

5.6 Conclusions and recommendations

Evaluation of the water fluxes within the Nikanotee Fen / upland system during the first two years following construction indicated that the system design was capable of sustaining wet conditions within the fen, where the water table was typically within ±10 cm of the fen surface. Early season precipitation events appear to be important sources of annual groundwater recharge for the constructed upland aquifer, although isotopic data suggest that snowmelt water stored in the unsaturated zone could also contribute to this recharge. The infiltration capacity of the LFH reclamation soil-capping layer in the upland was variable but generally high enough to facilitate recharge to the upland aquifer. The addition of furrows (soil tilling) of the surface of the upland resulted in a doubling of the average surface infiltration capacity. Thus, it is recommended that soil tilling be incorporated into standard operating procedures to promote infiltration through near-surface reclamation soil-capping layers where ground and soil water recharge is desired.

Additionally, the soil-capping layer should be placed to the minimum thickness required for vegetation growth (erosion protection) in areas where groundwater recharge to constructed aquifers is desired, since the high storage capacity of the LFH layer constrained the recharge to the upland aquifer in the current study. Although the efficacy of the enhanced recharge zones added to the uplands has yet to be assessed, the peat-lined basin appeared to promote groundwater recharge in the upland, in part due to the development of an occasional transient perched water table. Thus, these findings suggest that surface depressional features could help to enhance groundwater recharge to upland landforms.

In spite of the lower than targeted K_{sat} of the reclamation materials used to construct both the upland aquifer (tailings sand) and underdrain layer (petroleum coke), the designed upland aquifer provided sufficient groundwater fluxes to the Nikanotee Fen to partially offset the high rates of evapotranspiration and supplement periods of atmospheric water deficit. However, the lower than targeted K_{sat} of the petroleum coke layer resulted in slight reductions in the strength of the vertical hydraulic gradient, thus magnitude of groundwater discharge, across the fen from the toe of the upland towards the discharge point. The presence of ground frost in the fen constrained early-season groundwater recharge from the upland aquifer in spite of relatively large early-season vertical hydraulic gradients. The persistence of these large gradients following the melt of the ground frost throughout the majority of the fen resulted in peak average daily groundwater recharge in the fen occurring in the mid-summer. Since water availability in the mid-summer period is often limited in the AOSR due to the synchronous peak of evapotranspiration rates and precipitation inputs, this shift in the timing of the delivery of groundwater recharge towards the mid-summer period due to the presence and persistence of ground frost is hydrologically important, since this is the time when limited atmospheric water availability can be partially offset by groundwater recharge.

The groundwater fluxes from the upland aquifer to the fen occurred almost entirely through the petroleum coke underdrain layer. Thus, designing fen systems to receive groundwater contributions vertically via subsurface layering of reclamation materials is a desirable approach. Furthermore, this relieves the challenge of incorporating a sufficiently large upland area immediately adjacent to constructed fen systems, since subsurface layering of materials with suitable hydraulic properties could facilitate the delivery of groundwater flow from throughout the reclaimed landscape. Hence, it is recommended that future reclamation efforts focus on the feasibility of designing integrated sub-surface hydrological connectivity between landforms to promote landscape-scale groundwater flow regimes. This ambitious task could be accomplished by incorporating high permeability layers that can function as groundwater conduits and convey water from areas within the landscape where less water is required and/or desired to targeted areas where wetland ecosystems or aquatic features (e.g., end-pit lakes) can be located. The findings of this study also suggest that including depressional features on the surface of constructed aquifers could help to enhance groundwater recharge in desired zones. This would contribute to increased water availability at the discharge point of groundwater conduits located elsewhere in the reclaimed landscape that can be targeted for future fen placement.

The importance of regional climatic trends will decrease in the years following construction, as the system saturates and develops the inherent resiliency of the design (i.e., large water reservoir to supplement low precipitation inputs). However, the system design has not yet been tested by a period of significant drought and it remains uncertain if it is sufficiently robust to withstand periods of climatic stress. Integrating hydrological connectivity between landforms within the reconstructed landscape, both through subsurface layering of materials with a high K_{sat} as well as aligning watersheds along a watercourse continuum, will serve to increase the overall groundwater storage water volume and residence time, thereby reducing the susceptibility of individual landforms to climatic fluctuations.

6 Summary

This thesis presented a comprehensive hydrological assessment of the constructed Nikanotee Fen watershed. It represents a pioneering contribution to peatland creation literature. The overall goal of this research was to provide a watershed-scale evaluation of the dominant hydrological processes operating within the constructed Nikanotee Fen watershed. The main challenges concerning the topic of fen peatland creation, from a hydrological perspective, were introduced and discussed in the synthesis presented in chapter two.

The snow hydrology study presented in chapter three identified that snow depth was greatest and more variable near the toe of reclaimed slopes and became progressively shallower towards the crest. Enhanced snowmelt (i.e., earlier and more rapid) was observed on slopes with established vegetation cover, which had no discernable effect on snow distribution. Recharge to reclaimed slopes and the constructed aquifer during the snowmelt period appeared to be minimal, as the presence of ground frost constrained infiltration. Accordingly, substantial surface runoff was observed from all reclaimed slopes, despite being designed to reduce runoff and increase water storage. Thus, it was concluded that snow dynamics must be included in the design of landscape-scale constructed ecosystems. This chapter also demonstrated that the snowmelt period hydrology within reclaimed landscapes is fundamentally different from that reported for natural settings, and represents one of the first studies on snow dynamics in constructed watershed systems in the post-mined oil sands landscape. The controls on snow distribution and ablation identified in this chapter, along with the determination of the fate of snowmelt water, is a meaningful contribution and advances our understanding of how these systems store and shed water during the melt period.

Chapter four evaluated the hydrological regime of the reclaimed slopes during the snow-free period. This research identified that infiltration-excess surface runoff from slopes reclaimed within the previous two to three years supplemented precipitation inputs to low-lying landforms (i.e., the designed upland – fen system) during intense rainfall events. Older reclaimed slopes (~five years old), on the other hand, exhibited higher surface infiltration rates and stored most summer precipitation events. From this, it was concluded that the hydrological role of reclaimed slopes might shift from water conveyors to water storage features in constructed watershed systems. This represents the first study to compare the controls on soil water distribution and runoff generation on two reclaimed slopes of different age in the AOSR.

The initial assessment of the hydrological functioning of the designed upland - fen system presented in chapter five revealed that the system design was capable of sustaining wet conditions within the Nikanotee Fen, where the water table was typically within ±10 cm of the surface. Comparisons between the Nikanotee Fen and regional reference fen systems (presented in Appendix 1) can provide a useful indication of the functional equivalence of the constructed fen. This demonstrated that high water tables were sustained within the Nikanotee Fen, even during periods of time when regional fens were drying. Thus, the constructed upland aquifer can provide sufficient groundwater discharge to sustain wet conditions under a moderate regional drying trend. This comparison also identified that the water table regime within the Nikanotee Fen was similar to a moderate-rich reference fen that appears to have a strong groundwater inflow component. However, natural fen peatlands in the AOSR exhibit a large range of hydrobiogeochemical characteristics, which makes the selection of regional reference systems difficult.

The hydrophysical properties of the reclamation materials demonstrated considerable heterogeneity, although likely less than what is typically encountered in natural systems. However, this was complicated by the evolution of these materials over time following placement, which demonstrated increased saturated hydraulic conductivities in the second year of study.

Near-surface tilling of reclamation soil-capping layers was found to increase percolation of precipitation water. Depressional features were also identified as potential enhanced groundwater recharge zones in constructed ecosystems. Their incorporation into the design of future surficial landforms in portions of the landscape where recharge into constructed aquifers is desired is recommended. Lastly, the predominance of water fluxes to the Nikanotee Fen through a permeable underdrain layer demonstrates the potential for integrating sub-surface hydrological connectivity between landforms to promote landscape-scale groundwater flow regimes in reconstructed landscapes. As is typically the case with large-scale reclamation projects, significant challenges remain in the transition from principle to operational practice.

Based on these experiences, it appears that future landscape design plans could benefit from a change of perception in the role of peatlands in the landscape. Wetland areas can function as both a sink and source of water to the remainder of the catchment. For example, wetlands could function as a source of water to adjacent areas within the constructed watershed, even if the wetland systems are isolated from groundwater inputs. Wetland interconnectivity within the reconstructed landscape could increase water detention and storage during wet periods, which would benefit both the wetlands and the adjacent forestlands during dry periods. Hence, this connectivity appears crucial for the reestablishment of processes similar to those operating within natural Western Boreal Plain landscapes.

7 Conclusions and recommendations

Since oil sands mining operations results in different landform types, the associated reclamation approaches and performance objectives vary. These landform types have different groundwater design aspects; including those that are composed of low-permeability materials designed to have low net percolation (e.g., reclaimed overburden slopes) and those constructed from high-permeability materials that will have high net percolation (e.g., tailings sand 'beaches'). Based on the findings of this research, it is possible to engineer the post-mining landscape in a manner that is suitable to sustain wet conditions within a constructed fen system. The two years of this study represent periods with slightly lower (11% lower, 2014) and slightly higher (14% higher, 2013) precipitation than the long-term climatic average for the AOSR. Thus, although not yet tested by a period of significant drought, it appears that fen ecosystems can be integrated into the reclaimed landscape. Surface and groundwater contributions from adjacent landforms can provide water inputs that will help to offset periodic climatic water deficits. However, internal control of soil moisture and water conservation mechanisms, as observed in natural peatlands in the WBP, could also help limit water lost from storage during dry periods. Future research efforts should focus on addressing the relative importance of external water inputs and internal water conservation mechanisms in constructed fen peatlands, especially during periods of drought.

Moving forward, fen construction in post-mined landscapes still faces substantial hydrological and operational challenges. For example, issues related to water quality and quantity, as outlined in chapter two, will continue to represent important factors that need to be explicitly addressed in the design of future fen creation projects. Furthermore, since the current research was conducted at the 'pilot-scale' (<0.5 km^2), applying these findings at the scale required by commercial reclamation operations (~1 to 100's of km^2) presents a considerable challenge. The constructed aquifer in the current study was capable of providing sufficient water fluxes to the fen peatland to maintain wet conditions within the fen during the snow-free period. However, at the commercial-scale, constructed fen systems will be supported, in part, by groundwater discharge from coarse-grained landforms that aren't necessarily designed for this purpose.

Recommendations made on the basis of this research, however, can help to guide the design of commercial-scale constructed fen systems. For example, this study has identified the spring freshet as an especially important time to address issues regarding water availability, since large quantities of water (i.e., approximately 25% of annual precipitation, at minimum) are released to the landscape over a relatively short period of time. Reclaimed overburden slopes, which will be prolific in mine closure landscapes, produced much surface flow during the snowmelt period. Thus, landforms that are situated near the toe of reclaimed slopes should be designed to increase the detention of surface runoff to maximize groundwater recharge during and immediately following the snowmelt period. Since water tended to aggregate in the peat-lined basin feature in the Nikanotee Fen watershed, greater detention of snowmelt water could be accomplished by including depressional features on the surface of coarse-grained landscapes where deep net percolation is desired. Also, since snow depth was greatest at changes in slope, snow would also tend to accumulate along the edges of depressional features, which would constrain the development of ground frost. Because ground frost restricted recharge during the snowmelt period, the combination of increased snow accumulation and surface detention of melt water, as well as reduced ground frost development, would maximize recharge to constructed aquifers. This would help to build groundwater reservoirs available to supplement periods of low precipitation input for constructed fen peatlands.

An improved understanding of the storage and movement of water through coarse-grained landforms in the closure landscape is an important aspect of assessing the feasibility of constructing fens on a commercial scale. It is therefore recommended that future fen construction projects, and the associated research, be undertaken at the commercial scale with a focus on operational feasibility.

The contrasting hydrological role of the reclaimed slopes at the watershed-scale also represents an important finding of this study. The surface runoff generated on the more recently reclaimed slopes provided an additional source of water for the upland-fen system and contributed to the sustained wet conditions observed in the Nikanotee Fen. Thus, these slopes could accelerate the initial recharge of constructed aquifers and fen peatlands positioned downstream in the reconstructed landscape. However, surface runoff and interflow from the older reclaimed slope was minimal during the snow-free period, which supports previous findings that these landforms typically represent efficient water storage features. Thus, their efficacy as runoff generation features could decrease substantially within several years following their construction. Accordingly, more research is required to evaluate the timing of this shift in the hydrological regime of reclaimed slopes and to evaluate if these findings are universally applicable for reclaimed slopes throughout the AOSR. Quantification of the range of variation between overburden slopes reclaimed following common industry-wide guidelines would provide a better understanding of their long-term hydrological role in the mine closure landscape.

Finally, the assessment of the success of constructed fen systems should be a reflection of the ability to correctly and accurately predict the influence of external forcings (e.g., climate) on the processes operating within a newly constructed system. Over the first two years after construction, the Nikanotee Fen exhibited a hydrologic regime (i.e., high water table position) that was similar to what was predicted in the original design. This indicates that the designed watershed is capable of sustaining a fen ecosystem. However, longer time periods will reduce uncertainty in the assessment of the system's successional pathway.

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A.1 Appendix 1: Comparison to regional systems

Although the development of the conceptual model for the Nikanotee Fen was guided largely by numerical modelling, it was also supported by experience in natural WBP fen ecosystems. However, research on natural fens in this setting has demonstrated that these ecosystems vary over a considerable range, with respect to both their hydrological interactions with the surrounding landscape (Ferone and Devito, 2004; Smerdon *et al.*, 2005; Smerdon *et al.*, 2008) and biogeochemical character (Chee and Vitt, 1989; Vitt and Chee, 1990) under regional climatic controls. Thus, selection of a particular fen, or series of fens, to be used as regional reference systems against which the hydrological performance of the Nikanotee Fen can be compared, is fraught with uncertainty.

However, the goal of selecting reference fens for the current study was to target natural fens of contrasting hydrological and biogeochemical character and landscape position, with the intention of encompassing, as best as possible, a broad range of regional fen ecosystems. This approach will help to minimize the uncertainty associated with selecting only a few reference systems in a regional landscape composed of a mosaic of fen peatland types with a broad range of hydrobiogeochemical conditions and diverse vegetation community compositions.

The reference fens selected included a poor fen (Pauciflora Fen, ~60 km south of the Nikanotee Fen; referred to as the 'poor fen'), a moderate-rich fen (Poplar Fen, ~10 km west of the Nikanotee Fen; referred to as 'moderate-rich fen') and a saline-spring fen (~30 km south of the Nikanotee Fen; referred to as 'saline fen'). The poor fen is situated within an elongated local topographic depression bordered on both sides by relatively steep hillslopes (topographic slope is towards the peatland). Vertical groundwater fluxes are predominately downwards (recharge) and constrained by the low saturated hydraulic conductivity (K_{sat}) of the underlying mineral substrate, which is fine-grained glacial till. The poor fen does, however, receive occasional lateral groundwater input from the surrounding slopes in the form of shallow subsurface flow or snow melt, although these hydrological connections are dynamic and flow reversals have been observed (unpublished data). The landscape setting surrounding the moderate-rich fen is more subdued, with gentle topographic slopes at the upland-fen boundaries and several undulating upland-fen sequences that divide the fen into distinct elongated sections in the headwaters of the system. The moderate-rich fen is typically underlain and surrounded by sandy silt mineral soils, and, accordingly, appears to function as a regional groundwater discharge feature (Elmes, unpublished data). Lastly, the topography surrounding the saline fen is comparatively flat, and the system is bordered by non-saline forested bog and/or fen peatlands (Wells and Price, 2015). Vertical groundwater discharge to the saline fen is largely constrained by the low K_{sat} of the underlying mineral substrate; however, the actual input of deep groundwater to the saline fen could be higher, owing to the potential contribution from discharge windows that were not accounted for in the groundwater flux analyses (Wells and Price, 2015). Lateral exchanges between the saline fen and the adjacent wetlands are inconsistent but typically small (Wells and Price, 2015). Thus, the reference fens can be organized in order of the relative importance and magnitude of groundwater discharge into the fen, from greatest to least, as: moderate-rich fen > saline fen > poor fen.

Seasonal patterns of water table dynamics within wetland ecosystems (i.e., the hydroperiod) convey an integration of the influence of the hydrogeological setting, watershed storage properties and water budget components. Accordingly, a comparison of water table dynamics between the Nikanotee Fen and the reference fens can provide valuable insight into the hydrological functioning of the constructed fen system relative to that of the relatively undisturbed reference fen ecosystems under a similar range of regional climatic variations.

This comparison revealed that the Nikanotee Fen typically exhibited a larger range in water table fluctuation than the reference fen systems, especially during the first half of the summer in 2014 (Figure A-1). This is likely a reflection of the extent of the spatial variability of the topography of the surface of the fen, since the absolute water table elevation was comparatively flat. The poor and saline fens demonstrated a clear drying trend and a substantial decline in water table position from June to August. Groundwater discharge is likely small in these reference fens, as it is mostly constrained to vertical discharge windows or occasional horizontal inputs. This drying trend was most extreme at the saline fen, which received the least amount of precipitation over the course of the study period (Figure A-1). Interestingly, the water table dynamics of the Nikanotee Fen were most similar to those demonstrated by the moderate-rich fen, which is the reference fen that appears to have the strongest groundwater discharge component (Elmes, unpublished data). In both the Nikanotee Fen and the moderate-rich fen, the median water table position remained at the surface of the fen in August. These trends in water table dynamics generally support the previous qualification of the relative importance of groundwater discharge at each of the reference fens. However, higher precipitation inputs at the poor fen (253 mm) relative to the saline fen (164 mm) likely helped to offset the seasonal decline of the water table. Frequency analyses revealed that the water table position was within ±10 cm of the surface of the Nikanotee Fen for 62% of the measurements made in 2014. This compares to 82, 79 and 50% of measurements made within the moderate-rich, poor and saline fens, respectively (Figure A-2).

Thus, although the water table position within the Nikanotee Fen tended to demonstrate a wider range (relative to the fen surface) in a given month than the reference fens, it did not undergo the same seasonal drying trend that was observed at the poor and saline fens. This indicates that the groundwater discharge received in the Nikanotee Fen was sufficient to offset regional climatic drying, at least on a seasonal basis. The water table dynamics exhibited by the Nikanotee Fen are most similar to the moderate-rich reference fen where groundwater discharge is likely important. Further, the similar water table positions within the moderate-rich and Nikanotee Fens in August, combined with the water table decline in the poor and saline fens, suggests that the constructed upland aquifer is able to provide sufficient groundwater discharge to sustain similar hydrological conditions within the Nikanotee Fen to those within the rich reference fen ecosystem.

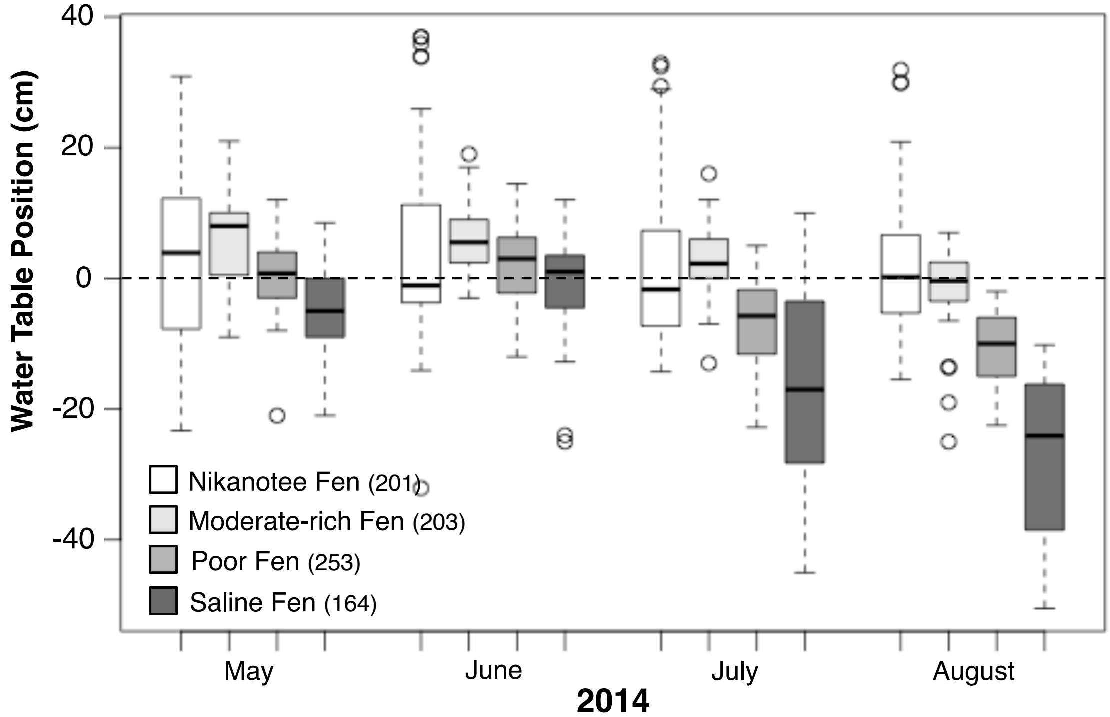

Figure A-1 – Boxplots of monthly water table position (expressed as cm relative to the ground surface; positive values = ponded water) for the Nikanotee Fen and the reference fens in 2014. The total precipitation received at each of the sites during the study period (17-May to 29-August) is shown in parentheses (mm).

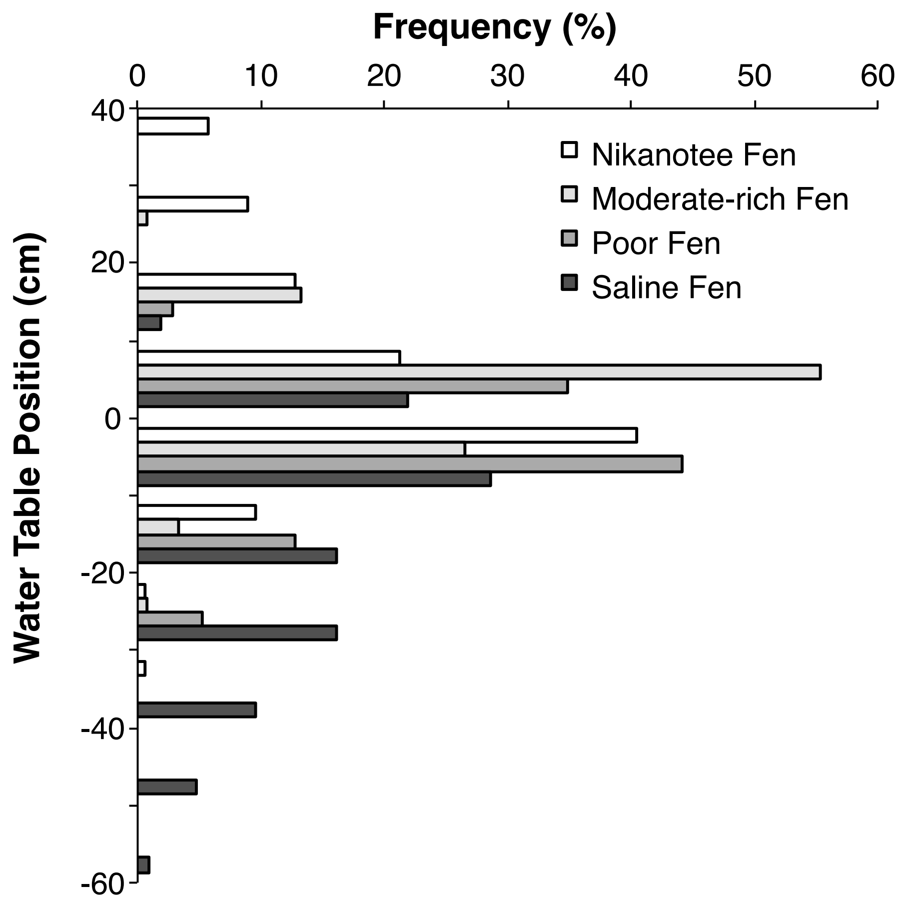

Figure A-2 – Frequency histogram for the water table position within the Nikanotee and reference fens for May - August 2014.

A.2 Appendix 2: Particle size distribution and organic matter content

Prior to particle size analyses, soil samples were oven dried to a constant mass at 80ºC. Soil samples were then homogenized and clumps were broken using a mortar and pestle. Particle size distribution was analyzed using a Horiba Partica LA-950V2 laser scattering particle size distribution analyzer. Soil samples were subjected to a 20 second ultrasonic treatment and dispersed using a 0.1% sodium hexametaphosphate solution. Particle size fractions were assigned according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998).

Determination of organic matter content was completed (following oven drying at 80ºC) using the loss on ignition procedure outlined in (Dean Jr, 1974). This appears as "LOI (%)" in the tables below. Soil samples were placed in a muffle furnace at 550ºC for a period of at least one hour. LOI (%) is expressed as the percentage of the total soil mass lost.

Table A-1 – Particle size distribution and organic matter content of soils on the 2007 slope. Depths within the upper 50 cm are peat-mineral mix soil samples and "Secondary Cap" represents soil samples from the secondary capping layer.

Slope	Site #	Depth (cm bgs)	% SAND	% SILT	% CLAY	LOI (%)
2007 Slope	1	2.5	42.3	53.3	4.5	8.9
2007 Slope	1	2.5	61.1	38.3	0.6	13.5
2007 Slope	1	10	36.0	54.7	9.3	9.4
2007 Slope	1	22.5	15.3	82.9	1.8	6.7
2007 Slope	1	45	25.9	61.9	12.2	5.8
2007 Slope	1	Secondary Cap	54.1	42.3	3.6	3.0
2007 Slope	2	2.5	51.4	47.1	1.4	9.5
2007 Slope	2	10	43.7	46.7	9.6	10.3
2007 Slope	2	10	48.1	43.1	8.9	
2007 Slope	2	22.5	48.7	49.1	2.1	6.6
2007 Slope	2	45	53.0	33.7	13.0	14.5
2007 Slope	2	45	49.1	49.9	1.0	
2007 Slope	2	Secondary Cap	39.4	50.5	10.1	2.9
2007 Slope	2	Secondary Cap	48.8	41.6	9.6	
2007 Slope	3	2.5	45.5	43.4	11.0	10.2
2007 Slope	3	2.5	53.5	41.4	5.1	
2007 Slope	3	10	55.6	41.7	2.7	11.0
2007 Slope	3	22.5	41.4	41.7	16.9	4.9
2007 Slope	3	22.5	47.5	45.0	7.5	
2007 Slope	3	45	52.8	41.3	5.9	3.2
2007 Slope	3	Secondary Cap	52.2	40.9	6.9	

Table A-2 – Particle size distribution and organic matter content of soils on the 2011 slope. Depths within the upper 50 cm are peat-mineral mix soil samples and "Secondary Cap" represents soil samples from the secondary capping layer.

Slope	Site #	Depth (cm bgs)	% SAND	% SILT	% CLAY	LOI (%)
2011 Slope	1	2.5	27.7	71.6	0.7	7.9
2011 Slope	1	10	48.1	51.4	0.5	6.8
2011 Slope	1	10	34.5	64.8	0.7	
2011 Slope	1	22.5	70.3	27.8	2.0	3.3
2011 Slope	1	45	48.9	49.9	1.2	10.1
2011 Slope	1	Secondary Cap	53.1	45.7	1.2	2.7
2011 Slope	2	2.5	41.5	54.8	3.7	10.7
2011 Slope	2	10	33.0	52.3	14.7	14.2
2011 Slope	2	10	14.8	67.3	18.0	
2011 Slope	2	45	42.7	52.5	4.8	9.2
2011 Slope	2	Secondary Cap	40.3	53.8	6.0	10.6
2011 Slope	3	2.5	48.3	50.9	0.9	10.9
2011 Slope	3	10	39.2	60.1	0.6	12.2
2011 Slope	3	22.5	33.1	62.0	4.9	12.1
2011 Slope	3	45	25.1	59.2	15.7	11.6
2011 Slope	3	45	17.9	62.0	20.1	
2011 Slope	3	Secondary Cap	52.9	44.6	2.5	3.3

Table A-3 – Particle size distribution and organic matter content of the LFH soil capping layer (surface soil layer) in the constructed upland.

Material	Site Name	Site #	Depth	% SAND	% SILT	% CLAY	LOI (%)
LFH	350	1	2.5	34.5	48.3	17.2	4.7
LFH	350	1	15	59.1	38.8	2.1	
LFH	350	2	2.5	51.2	44.8	4.0	4.6
LFH	350	2	15	50.8	41.3	7.9	3.6
LFH	350	2	2.5	59.2	38.2	2.2	
LFH	350	3	2.5	51.7	46.4	1.9	4.3
LFH	350	3	15	52.7	44.1	3.2	4.2
LFH	350	3	15	60.1	38.0	1.9	
LFH	220	1	2.5	49.4	44.2	6.4	4.2
LFH	220	1	15	51.5	41.6	6.9	2.9
LFH	220	1	15	55.8	39.5	4.7	
LFH	220	2	2.5	37.2	51.6	11.1	4.4
LFH	220	2	2.5	53.2	43.4	3.0	
LFH	220	2	15	52.7	45.4	1.9	4.6
LFH	220	3	2.5	56.7	40.3	2.6	4.6
LFH	220	3	15	63.8	28.3	7.4	4.2
LFH	220	3	15	44.7	44.5	10.8	
LFH	130	1	2.5	49.5	43.2	7.4	4.9
LFH	130	1	15	41.8	46.6	11.6	4.6
LFH	130	1	15	59.1	37.4	3.5	4.0
LFH	130	2	2.5	60.6	36.2	3.2	4.7
LFH	130	2	15	39.7	53.9	6.3	7.6
LFH	130	2	15	55.1	39.2	3.6	4.2
LFH	130	3	2.5	56.7	40.6	2.7	4.1
LFH	130	3	2.5	49.3	44.3	6.4	4.5
LFH	130	3	15	52.0	40.4	7.7	4.0

Table A-4 – Particle size distribution and organic matter content of the tailings sand aquifer material used to construct the constructed upland. Note all samples were extracted from ~10 cm below the top of the tailings sand layer (i.e., ~10 cm below the interface of the bottom of the LFH capping soil layer and the top of the tailings sand layer). Samples with a site name of "2012" were extracted from the field during the construction phase. All other sampling was completed as outlined in the thesis.

Material	Site Name	Site #	% SAND	% SILT	% CLAY	LOI (%)
SAND	370	1	93.3	6.7	0.0	0.7
SAND	370	2	94.7	5.3	0.0	0.4
SAND	370	3	81.1	5.7	0.0	0.5
SAND	350	1	84.0	16.1	0.0	1.0
SAND	350	2	80.8	17.9	0.0	1.1
SAND	350	3	84.3	14.2	0.0	
SAND	220	1	74.0	24.6	1.4	1.4
SAND	220	1	80.0	18.5	1.5	1.4
SAND	220	1	85.7	14.2	0.1	
SAND	220	1	81.7	18.2	0.1	
SAND	220	2	88.5	5.9	0.0	
SAND	220	3	90.2	9.8	0.0	0.6
SAND	130	1	90.1	8.8	0.0	0.7
SAND	130	1	90.5	7.3	0.0	0.7
SAND	130	2	92.7	7.3	0.0	
SAND	130	2	90.8	9.2	0.0	0.8
SAND	130	2	80.8	16.2	0.5	0.6
SAND	130	3	92.3	7.7	0.0	
SAND	130	3	92.3	7.7	0.0	0.8
SAND	2012	A	93.3	6.7	0.0	0.5
SAND	2012	B	89.9	9.8	0.3	0.5
SAND	2012	C	93.1	6.9	0.0	0.6
SAND	2012	C	93.0	7.0	0.0	0.6
SAND	2012	D	94.7	5.3	0.0	0.8
SAND	2012	F	94.7	5.3	0.0	1.2