

Hydrodynamic Modelling of Delta Marsh
and
**Simplified Methods of Discharge Estimation for
Discontinuous Inland Coastal Wetlands**

By

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Abstract

This thesis details the hydrodynamic research conducted at Delta Marsh as part of the *Restoring the Tradition* marsh rehabilitation project. Research has indicated that the hydraulic and hydrologic controls on the marsh can have considerable impacts on its ecological function, but the impacts of these controls had not previously been studied. Field hydrography and two-dimensional numerical modelling (using MIKE 21) provided insight into many aspects of the physical behaviour of Delta Marsh.

Eighty five percent of the inflow to Delta Marsh from Lake Manitoba passes through Clandeboye Channel, and these discharge signals propagate as far west as Cadham Bay. Inflow to the marsh disperses quickly, and accounts for a small fraction of the water that exits the marsh during subsequent outflow. Thus, Portage Diversion water that enters the marsh through the lake can remain there even if there is a net loss in marsh volume over the season. Wind friction across Lake Manitoba has the greatest impact on short-term fluctuations in marsh volume and on the composition of marsh water, followed by the Portage Diversion and the natural inflows to Lake Manitoba. Expansions to flood diversion infrastructure will considerably impact the composition of Delta Marsh waters.

Three methods of wetland discharge estimation were developed and tested. The most promising method was the regressed slope Manning method (RSMM), which estimates two-directional channel discharge as a function of the water surface elevations at both ends of a channel. When used in conjunction with the velocity index method, the RSMM can multiply the amount of reliable discharge data collected per research dollar. Thanks to its simple formulation, the RSMM is likely applicable outside of wetland settings, as well.

Dedication

To the anonymous staffer at Oak Hammock Marsh

One morning, you rounded the corner into the cafeteria and somehow wedged your shoulder under the motion-activated hand sanitizer dispenser. It made a loud whirring noise, and you noticed. You tried to get out of the way, but it was too late; it had dispensed a handful of sanitizer directly on your shoulder. Your loud, *immediate* yelp of surprise is something that will stick with me forever. When you left the room, Greg and I laughed harder and longer than we had in ages. I think about this at least weekly, and it never fails to bring me true joy. During the toughest parts of this project, I have reminded myself that if I had not enrolled in graduate studies, I would not have witnessed that beautiful, absurd moment. You changed my life, and I didn't even learn your name. You'll never know what you've done for me. Thank you.

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1. Introduction

Delta Marsh is an immense wetland along the southern shore of Lake Manitoba, as illustrated in Figure 1:1. The role of the marsh has been: to store nutrients from fluxes to Lake Manitoba; to host a variety of fish, waterbirds, mammals, amphibians, aquatic invertebrates, and plant species; and more recently, to host recreational hunters, fishers, bird-watchers, and other outdoorspeople. Over the past half-century, Delta Marsh has steadily deteriorated in function. This has resulted in diminished water quality, increases in cyanobacterial blooms, decreases in the variety and abundance of native flora and fauna, and, consequently, less productive recreational use of the marsh.

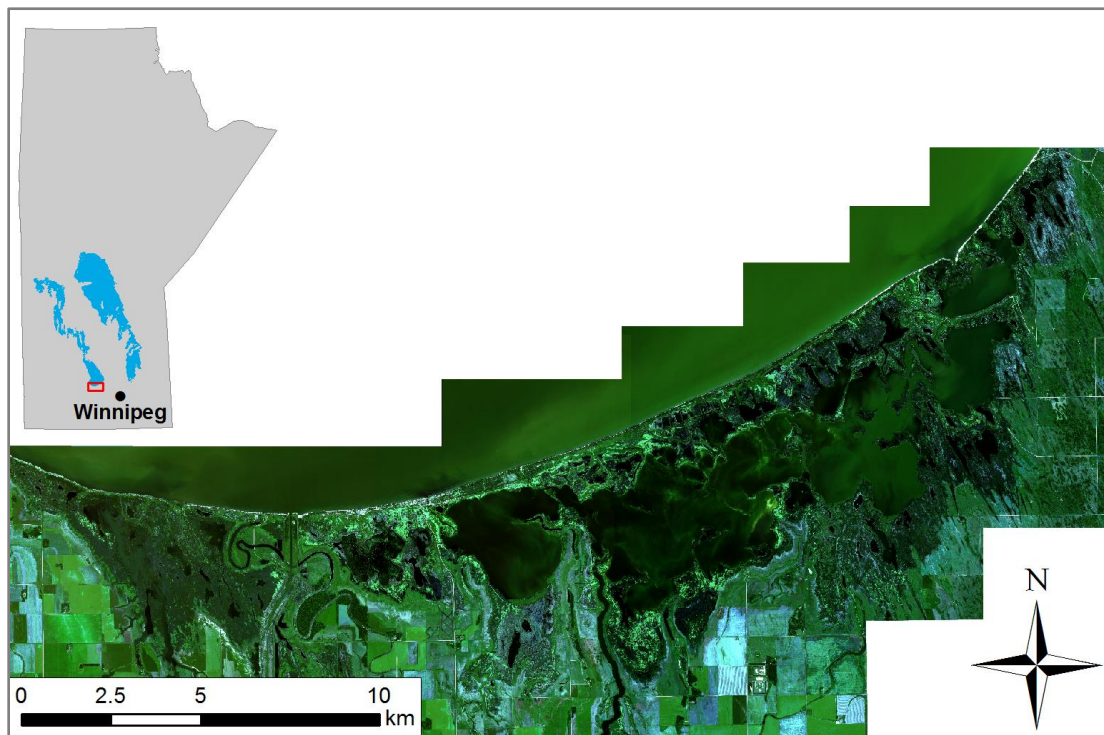


Figure 1:1 – Delta Marsh: Location Plan and Imagery (Ducks Unlimited Canada)

Over the past few decades, Ducks Unlimited Canada (DUC), the Province of Manitoba, the University of Manitoba, and other partners have been building an empirical case in favour of wetland rehabilitation at Delta Marsh. This group has been working to identify the

mechanisms behind deterioration of the marsh, and to develop appropriate mitigation measures. In 2013, this group initiated the *Delta Marsh: Restoring the Tradition* project, with the goal of restoring the ecological and anthropological traditions of Delta marsh.

In addition to active rehabilitation and response monitoring, a major component of this project is the collection of baseline knowledge for use in future planning. Despite the comprehensive records of ecological data, there is relatively little knowledge regarding the hydrodynamics of, hydrology governing, or nutrient flux within Delta Marsh. This thesis describes the two-dimensional hydrodynamic modelling of the marsh, as well as simplified methods of discharge estimation in coastal wetland environments. The hydrodynamic modelling component of this thesis is complemented by the hydrologic modelling of the watershed, as discussed by Schellenberg (in progress). Hydrologic research of the marsh will continue into the future with stable water isotope analysis by Glavonjić (in progress).

1.1. Delta Marsh: Then

Lake Manitoba was formed during the recession of Lake Agassiz over 10 000 years ago. The Portage la Prairie Alluvial Delta formed approximately 6000-7000 years ago, routing the Assiniboine River toward the southern basin of Lake Manitoba (Teller and Last 1981, Rannie, Thorleifson and Teller 1989, Last and Teller 2002). This new discharge altered the geomorphology of the area in several ways over the next few thousand years. The elevation and footprint of the lake increased, and the delta extended far into Lake Manitoba, depositing vast amounts of sediment in the southern basin (Teller and Last 1981). Roughly 4500 years ago, the Assiniboine River diverted east toward its present-day confluence with the Red River in Winnipeg, Manitoba (Last and Teller 2002).

The wave behaviour of Lake Manitoba is predominantly wind-driven (Burrows 1970). Between roughly 3500 and 2500 years ago, prevailing northwestern winds generated prevailing northwestern waves, which transported the defunct alluvial delta eastward (Teller and Last 1981, Rannie, Thorleifson and Teller 1989). These deltaic sediments formed a thin strip along a former shoreline, isolating the southern portion of the lake, creating Delta Marsh. This physical separation shielded the marsh from the wind-wave-induced turbulence experienced across the lake fetch, but still allowed water levels in the marsh to rise and fall with the lake. This calmly fluctuating hydrodynamic condition set the stage for the development of a wetland ecosystem (Batt 2000).

By the turn of the 20th century, Delta Marsh had transformed into a stable and productive wetland. It hosted a variety of waterfowl, fish and floral species. It filtered nutrients from the surrounding watershed, as well as from Lake Manitoba (Batt 2000). Note, however, that the marsh had reached this state of equilibrium over many years, adapting to slow changes in climate and geomorphology; for example, the marsh experienced inter-decadal wet-dry cycles (McAndrews, Stewart, Jr. and Bright 1967).

Previous research has been conducted in an attempt to reveal the paleoecological history of Delta Marsh. Core samples from the marsh bed were used to establish an approximate timeline of the ecological conditions in the marsh. The first macrofossils of submerged vegetation have been dated to 2400 ± 230 years old (Sproule 1972). Since then, there have been three cycles of ecologically productive and unproductive marsh states. The first two drops in habitability are likely due to extended periods of low water level (Sproule 1972). The decline in health during the 20th century, however, has been exacerbated by very rapid

and drastic anthropogenic changes to and within the marsh, the surrounding watershed, and Lake Manitoba. Due to the severity of these changes, Delta Marsh will likely continue to deteriorate without active intervention.

More recently, Delta Marsh has been used as a resource. The marsh has been the site of commercial and recreational waterfowl hunting by Manitobans and non-Manitobans alike since the end of the 19th century (Technical Committee for Development of the Delta Marsh 1968). In addition, several farms have come into and out of operation directly adjacent to the marsh. Today, the community of Delta Beach exists along the beach ridge, consisting of approximately 200 permanent and seasonal homes. Recreational use of the marsh – specifically waterfowl hunting – has suffered considerably over the past 50 years. While it may pale in comparison to the long-term threat to marsh ecology, it is the impact on hunting that has served as the primary motivator behind active marsh rehabilitation.

1.2. Delta Marsh: Now

In the past half-century, the marsh has experienced a severe decline in water quality, triggering declines in the variety, abundance, and distribution of native biota. Sediment re-suspension, predominantly driven by the invasion of common carp (*Cyprinus carpio*, hereafter referred to as carp), has increased turbidity and re-introduced bed-layer nutrients to the water column (P. H. Badiou 2005, Hertam 2010). Nutrient re-suspension and increased overland nutrient contributions have led to eutrophication, resulting in frequent and severe blooms of blue-green algae. In addition, satellite imagery shows accelerated shoreline and island erosion in recent years (Ducks Unlimited Canada 2014).

The variety and abundance of submerged vegetation have decreased significantly in the past half-century (Anderson and Jones 1976, Hertam 2010). The variety of emergent vegetation has decreased sharply, with hybrid cattail (*Typha x glauca*) consistently out-competing other species, and encroaching into shallow portions of the marsh (Shay, de Geus and Kapinga 1999). Carp have become quite abundant, and are responsible for the destruction of native fish habitat (Wrubleski, pers. comm. 2015). The variety and abundance of waterbirds have decreased sharply. For example, the breeding success of the Western Grebe has diminished noticeably since 1973 (La Porte, Koper and Leston 2014).

It is believed that the deterioration of the function of the marsh has been promoted by the invasion of carp, regulation of the Lake Manitoba water level, and nutrient-rich inflows from the surrounding agricultural land. In addition, it is difficult to assemble baseline hydrotechnical knowledge of the area, due to prairie geomorphology and the proliferation of anthropogenic changes in the last century.

1.2.1. Influence of Non-Native Common Carp

Carp were introduced to North America as a self-sustaining food source near the end of the 19th century (McCrimmon 1968). They had spread to the south end of Lake Manitoba by 1947 (Atton 1959), and have been observed to migrate annually into Delta Marsh after spring breakup since 1952 (Hachbaum and Ward 1964). Carp are responsible for triggering an ecologically threatening domino effect within the marsh. Carp are bottom-feeding (benthivorous), and disturb the marsh bed while spawning and searching for food. These disturbances re-suspend nutrient-rich sediments into the water column, increasing turbidity (Badiou and Goldsborough 2010, Hertam 2010). The combination of aggressive

benthic activity and diminished sunlight penetration due to increased turbidity causes a drastic drop in the abundance and variety of submerged vegetation (Lougheed, Crosbie and Chow-Fraser 1998, Hertam 2010). The increased water-column nutrient concentration fosters phytoplankton growth, further diminishing light penetration (Badiou and Goldsborough 2010, Hertam 2010).

Carp predominantly prey on the larvae of non-biting midges (Chironomidae) (McCrimmon 1968). Midges are a major foundation of the food web in the marsh and surrounding area (Busby and Sealy 1979), and thus their excessive consumption by carp has potentially huge impacts on the overall food web (P. H. Badiou 2005). Decreases in the abundance of submerged vegetation and alterations to the aquatic food web deter migrating waterfowl from staying at the marsh (Cahoon 1953, King and Hunt 1967). Finally, carp are rather resilient to high turbidity and low dissolved oxygen conditions, so while other species decline in abundance due to deteriorating water quality, carp become increasingly dominant (P. H. Badiou 2005).

1.2.2. Water Level Regulation of Lake Manitoba

Historically, there has been an uneasy relationship between Lake Manitoba and its coastal residents. Urgent flood and drought mitigation efforts were employed in the first half of the 20th century, including the expansion of the Fairford River in an attempt to increase discharge during flood seasons, and the construction of a simple control structure at the Fairford River outlet to promote water retention during dry seasons (The Lake Manitoba Regulation Review Advisory Committee 2003).

After a lengthy wet cycle in the mid-1950s, the provincial government constructed the Fairford River Water Control Structure (FRWCS). This was done to preserve lakefront property and protect lake-dependent economic and recreational interests (The Lake Manitoba Regulation Review Advisory Committee 2003). Since 1961, the structure has been used to maintain the lake level at a target elevation of 247.55 meters above sea level (ASL) (The Lake Manitoba Regulation Review Advisory Committee 2003). Regulation has been performed successfully with the exception of the unprecedented 2011 flood season, when the lake level rose to approximately 249 m ASL at Steep Rock (Water Survey of Canada Gauge 05LK002) – 40 cm above the previous peak recorded in the mid-1950s.

Figure 1:2 shows the Lake Manitoba water surface elevation (WSE) at Steep Rock before and after the construction of the FRWCS. Although the mean level is the same for both eras, the variability in level – the wet-dry cycle – has not been preserved. The annual mean lake level record at Steep Rock has a standard deviation of 35 cm prior to construction, compared to 11 cm or 17 cm (excluding or including 2011, respectively) after construction.

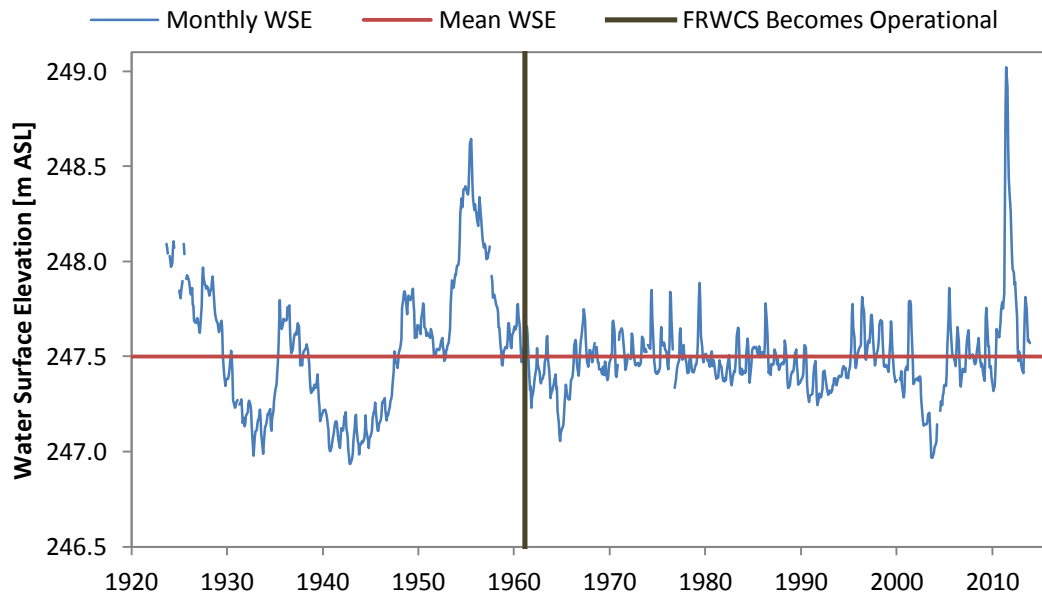


Figure 1:2 – Impact of the FRWCS on the Lake Manitoba WSE

Unfortunately, the potential negative impacts of stifling the wet-dry cycle were not investigated prior to construction of the control structure (The Lake Manitoba Regulation Review Advisory Committee 2003). Subsequent research has shown that the natural wet-dry cycle is responsible for the regulation of the abundance and composition of emergent wetland vegetation (van der Valk 2005). Section 1.3.2 describes some of the adverse effects of regulated water levels on wetland ecology in general. In 2005, the Lake Manitoba Regulation Review Advisory Committee (LMRRAC) proposed changing the operating policy of the FRWCS to allow the lake level to fluctuate between 247.05 and 247.65 meters ASL. This suggestion was accepted by the provincial government, was to be implemented in 2007, but no noticeable change in lake behaviour has been observed since. This is likely due in large part to the record volumes of water entering Lake Manitoba since 2009, but regardless, no major variation in the annual average lake level has been observed.

A decade after the construction of the FRWCS, the provincial government constructed the Portage Diversion in order to redirect Assiniboine River floodwaters away from downstream farming properties and from the Red River (The Lake Manitoba Regulation Review Advisory Committee 2003). With the exception of the 2011 flood season, increased discharge to Lake Manitoba was balanced by increased outlet discharge at the FRWCS. Despite this fact, discharge from the Portage Diversion may have considerable impact on the hydrodynamics and nutrient flux behaviour of Delta Marsh, as the diversion introduces massive amounts of water to the lake, very near to its connections with the marsh. It has been argued that the diversion essentially restores the ancient Assiniboine River flowpath. However, since this an entirely anthropogenic restoration, there is certainly a societal responsibility for the ensuing socioeconomic and environmental repercussions.

1.2.3. Nutrient Loading from the Surrounding Watershed

Agricultural intensification within the Delta Marsh Watershed has caused drastic changes in landscape and nutrient application over the region. Nutrients within the soil – either natural or added as fertilizer – will wash, primarily in dissolved phase (Sharpley, et al. 2011), toward the marsh during rainfall events or the spring freshet. The predominant native land cover of the watershed is tallgrass prairie (Sveinson 2003), which is hydraulically rough and can retain runoff for longer periods, allowing infiltration and damping the hydrograph response. Now, consider agricultural land cover; during snowmelt, a majority of the watershed is uncultivated bare soil, which results in lower hydrologic retention time, less infiltration, and thus more nutrient-rich runoff. By the time that crops have grown, spring freshet has ended. This accelerated runoff is exacerbated by the presence of surficial and tile drainage (Badiou, pers. comm. 2014).

1.2.4. Engineering Challenges: Anthropogenic Changes

Delta Marsh, its watershed, and Lake Manitoba have undergone significant anthropogenic changes over the last century. These changes have been made by government, farmers, and other private landowners, but have not been documented completely or consistently. A non-exhaustive list of these changes, their intended purposes, and ensuing engineering challenges is provided in Table 1:1. Since many of these challenges make it difficult to model the hydraulic and hydrologic behaviour of the area accurately and efficiently, they must be addressed during model setup. Note that this thesis only addresses challenges related to Delta Marsh or Lake Manitoba. Challenges related to the watershed will be addressed by Schellenberg (in progress).

Table 1:1 – Anthropogenic Changes to the Delta Marsh Area

Anthropogenic Change	Intended Purpose	Ensuing Engineering Challenges
Property development and management at Delta Marsh	<ul style="list-style-type: none"> • Residential, recreational and agricultural land use 	<ul style="list-style-type: none"> • Hindered access to the marsh
Dredging of channels within Delta Marsh	<ul style="list-style-type: none"> • Marine access 	<ul style="list-style-type: none"> • Alteration of hydrodynamics • Narrow artificial channels limit modelling efficiency
The Portage Diversion	<ul style="list-style-type: none"> • Re-direction of Assiniboine River flood waters 	<ul style="list-style-type: none"> • Bisection of the watershed area, complicating the modelling process • Potential introduction of tremendous amounts of water; may alter marsh hydrodynamics and nutrient fluxes, adding uncertainty to modelling • Difficult to quantify influence on groundwater flow • Complicated access to Delta Marsh during operation (ex. Summer 2014)
The Fairford River Water Control Structure	<ul style="list-style-type: none"> • Regulation of the Lake Manitoba water level 	<ul style="list-style-type: none"> • Current operating policy is unclear and subject to change
Land development within the Delta Watershed	<ul style="list-style-type: none"> • Agricultural, residential, and industrial land use 	<ul style="list-style-type: none"> • Alteration of runoff production and hydrologic behaviour • Dynamic, and thus difficult to catalogue across years
Drainage of local land (via surficial ditches and tile drains)	<ul style="list-style-type: none"> • Rapid drainage of spring melt and storm runoff from agricultural land 	<ul style="list-style-type: none"> • Generally poorly documented • Difficult to catalogue, even from high-resolution aerial surveys • Adds uncertainty to determination of contributing watershed area
Elevated embankments	<ul style="list-style-type: none"> • Separation of agricultural sections • base for mile roads 	<ul style="list-style-type: none"> • Disrupts natural runoff routing • Complicates hydrological modelling • Not captured well by aerial surveys
Culverts	<ul style="list-style-type: none"> • Restore natural flowpaths 	<ul style="list-style-type: none"> • Installed Irregularly, causing unnatural or incomplete flowpaths

1.2.5. Engineering Challenges: Prairie Watershed Geomorphology

The first step in any watershed study is the delineation of the drainage area contributing to discharge. In regions of high or moderate relief, the watershed boundary is often visibly distinguishable, and it confines runoff toward a single outlet. Unfortunately (from an engineering standpoint), the Delta Marsh Watershed is neither steep, nor does it flow to a single outlet.

Located on the flat Southern-Manitoban prairie, the watershed has a relief of less than 1 meter per kilometer. When observing the digital elevation model (DEM) of the watershed as provided by GeoBase, the actual change in elevation between adjacent grid-points is likely considerably smaller than the precision of the elevation measurements (Schellenberg, pers. comm. 2014). This complicates the estimation of the watershed boundary. In addition, since the watershed drains along its entire northern boundary, routing is complex and needs to extend into the marsh itself. Finally, the extents of the contributing groundwater area are unknown and difficult to identify, although this is a challenge in any watershed study.

1.3. The Relationship between Hydrodynamics and Wetland Health

The physical behaviour of water is greatly influenced by its environment. That is to say, wetland environments behave hydrodynamically differently than rivers, or even lakes. Moreover, the physics and ecology of a wetland environment are co-dependent. Delta Marsh is no exception, where there is a feedback loop between the altered hydrodynamics and the deteriorating wetland.

1.3.1. The Hydrodynamic Behaviour of Wetland Environments

The movement of water throughout a marsh is governed by the same conservation laws governing rivers and lakes. The differences in hydraulic behaviour are caused by the differences in geometry and major physical and hydrological driving forces. To illustrate, consider the differences between the Assiniboine River, Lake Manitoba, and Delta Marsh.

The Assiniboine River conveys runoff from Saskatchewan, North Dakota, and Western Manitoba to the Red River. The width and depth of the channel are negligible in comparison to the length. Water flows downstream only, propelled by the momentum of upstream discharges, and by gravitational forces pulling the water to a lower elevation (Sturm 2001). These driving forces are countered by considerable resistive shear stresses along the wetted perimeter (Sturm 2001). Changes in storage are dominated by changes in discharge, with direct precipitation and evaporation playing comparatively small roles. Due to the geometry of the river, there is no considerable fetch length across which seiching or significant wave action can occur (Resio and Vincent 1976). The longitudinal velocity dominates, and thus the flow behaviour can be approximated as one-dimensional (1D), depth- and width-averaged. Note that the tributary streams directly feeding Delta Marsh behave similarly, but have been observed to run dry or back up to stagnation.

Lake Manitoba stores water before conveying it toward Lake St. Martin via the Fairford River. The depth of the lake is small in comparison to its length and width. Point and lateral discharges along the perimeter of the lake are less dominating than in the Assiniboine River, and precipitation and evaporation have a massive impact on storage because of the large surface area to storage ratio. Although the average direction of flow is

toward the outlet, wind-induced motion can cause wave action and seiching in all directions (Resio and Vincent 1976). Thus, the driving forces are a combination of continuity- and momentum-driven forces at the points of discharge, and wind-induced shear forces across the surface (Sturm 2001). Since wind-induced motion occurs near the surface, bed roughness has little impact on the magnitude of seiching and wind-waves (Malenchak 2004). Horizontal velocity dominates, and thus the flow behaviour can be approximated as two-dimensional (2D), depth averaged.

Delta Marsh is composed of several bays connected by narrow channels, and is assumed to have hydrodynamic characteristics similar to a series of interconnected lakes. Flow is 2D, predominantly driven by discharge at the connections to Lake Manitoba. Fluxes between the marsh and the lake are two-directional, and are likely governed by seiche-induced changes in water level along the southern boundary of Lake Manitoba, as well as changes in storage of the lake (Bortoluzzi 2013). Tributary flows to the marsh can be significant during the spring freshet, but are minor during the rest of the year (barring major storm events). That being said, the seasonal variability of tributary flows is likely much higher than that of the seiche-driven flows along the northern boundary (Trebitz, Morrice and Cotter 2002, Trebitz 2006). Precipitation and evapotranspiration likely have significant impacts on storage. Wind-induced motion can occur across the bays, but will be fetch-limited and small in comparison to that experienced across Lake Manitoba. Velocity decreases drastically when flow encounters submerged vegetation (Leonard and Luther 1995), considerably reducing bed shear stress – the major driving force behind sediment re-suspension after benthic activity. Horizontal velocity dominates, and thus the flow behaviour can be approximated as 2D, depth-averaged.

Note that the complex hydrotechnical behaviours of the marsh – inflow as a function of lake level, mixing, and hydraulic retention – have been discussed conceptually, but not quantified. It is paramount to develop a hydrotechnical understanding of the area to help identify physical processes that are contributing to or against wetland deterioration.

1.3.2. The Influence of Hydrodynamics on Wetland Function

On the other hand, considerable research has been conducted in the other direction; studies at Delta Marsh and abroad have shown the influence of short- and long-term hydrodynamic phenomena on wetland function. Hydrodynamics have been observed to influence water quality, vegetative abundance and variety, and the abundance and variety of waterfowl species in wetland habitats, all of which have changed at Delta Marsh in the past half-century (Murkin, van der Valk and Clark 2000).

Nutrient removal efficiency is a function of hydraulic retention time, which, in a wetland environment, is highly variable and a function of the water level (Dierberg, et al. 2005). Higher water levels can cause short-circuiting flow throughout the marsh – water travels quickly between bays by flowing over embankments. This reduces the retention time, weakening the Total Phosphorus (TP) utilization capability of the wetland and delivering nutrient-rich water at the outlet. This phenomenon is exaggerated by the presence of relic channels and absence of vegetation within the watershed (Min and Wise 2009).

Emergent vegetation biomass is negatively related to flood depth (Waters and Shay 1992, Seabloom, van der Valk and Moloney 1998). In addition, the duration of overland inundation has considerable impact on the regeneration success of emergent vegetation

(van der Valk, Squires and Welling 1994, Nishihiro, et al. 2004). Extended periods of inundation can drown emergent vegetation, while extended periods of drought (or water level stabilization) allow invasive species to flourish, as observed with hybrid cattail at Delta Marsh (Shay, de Geus and Kapinga 1999, Batt 2000, van der Valk 2005). This, in turn, can alter the local water budget. Research at the Marsh Ecology Research Program (MERP) Cells at Delta Marsh has shown that relative evapotranspiration rates of isolated wetland cells are inversely related to the emergent vegetation biomass due to vegetative sheltering effects (Kadlec 1993).

Regarding Delta Marsh specifically, Bortoluzzi (2013) emphasized the influence of Lake Manitoba on nutrient concentrations in the marsh in two ways: nutrient concentrations across the marsh are positively correlated with the distance to the lake; also, nutrient concentrations were negatively correlated to the lake level regardless of proximity. In addition, Parks (2006) highlighted the potential influence of hydraulic connectivity on the distribution of aquatic biota; fish are limited to hydraulically connected ponds, but can migrate as fluctuating water levels alter pond connectivity within the marsh. Several hydrotechnical mechanisms have been identified as potential contributors to the deteriorating condition at Delta Marsh. It is clearly a necessity to develop robust tools for use in predicting potential changes of marsh hydrodynamics and watershed hydrology.

1.4. Delta Marsh: Restoring the Tradition

Beginning in 2013, DUC and its partners initiated the *Delta Marsh: Restoring the Tradition* project, aimed at slowing and ultimately reversing the deterioration of Delta Marsh. The goals of the project are to implement rehabilitation measures within the

marsh; to monitor the effects of those measures over time; to expand the baseline knowledge of the marsh; and to use that knowledge for the development of additional mitigation measures. The project can be divided into three informal activities, referred to in this thesis as Rehabilitation Efforts, Ecological Response Monitoring, and Baseline Knowledge and Forecasting. The work performed in this thesis is part of the third activity.

1.4.1. Rehabilitation Efforts

Since the benthic activity of carp has been identified as a key contributor to marsh deterioration, initial rehabilitation efforts have been focused on carp exclusion. DUC has been responsible for the design and construction of seven exclusion structures, while Manitoba Conservation and local land owners are responsible for their operation.

The exclusion screens are installed each spring, after native species have had the opportunity to enter the marsh. Exclusion from the marsh may induce some passive population control; by keeping carp from their ideal spawning locations, they may not reproduce as efficiently. Carp exclusion is intended to continue indefinitely. Ideally, it will be joined by other efforts, which may include hybrid cattail population control and nutrient management (Ducks Unlimited Canada 2009).

1.4.2. Ecological Response Monitoring

DUC, the Government of Manitoba, and the University of Manitoba are monitoring the response of Delta Marsh to rehabilitation (Ducks Unlimited Canada 2013). Ecological monitoring has been conducted over the past few decades, and this data will be used as the baseline to which new data will be compared. Monitoring will reveal how well the marsh is

recovering in terms of water quality and the ability to host flora and fauna. Note that the focuses and methods of monitoring are subject to change over the course of the project.

The most direct method of assessing the success of carp exclusion is regular surveying of the fish community composition. By means of gillnetting and electrofishing, the variety and abundance of different species can be monitored as rehabilitation progresses (Ducks Unlimited Canada 2013). Ideally, carp populations will cease to dominate, and community composition and abundance will approach those observed prior to carp infestation. Water quality surveying will be performed regularly across the marsh. Turbidity, light penetration, total suspended solids, temperature, and other parameters are measured regularly at 50 sites in the marsh during the open water season (Ducks Unlimited Canada 2013). Based on the benthic behaviour of carp, it is expected that turbidity will decrease and light penetration will increase during rehabilitation, promoting the regeneration of submerged vegetation. In addition, surveying will be performed to monitor changes to waterbird community composition, abundance, distribution, and feeding success; and the variety, abundance and distribution of emergent and submerged vegetation (Ducks Unlimited Canada 2013).

1.4.3. Baseline Knowledge and Forecasting

To date, the hydraulic, hydrologic, and chemical processes of the marsh and watershed have not been researched in depth. By developing an understanding of these mechanisms, researchers can assess the behavioural sensitivity of the marsh to changes to the area. This knowledge can inform future rehabilitation, or can predict the outcome of future operational or natural changes to the hydrologic system.

The engineering study of the marsh spans from 2013 to 2017. This thesis details the field-surveying program and numerical modelling performed to characterize the hydrodynamic behaviour of the marsh, based in part on field research conducted from 2013 and 2014. This research assesses the baseline hydrodynamic conditions of the marsh, and quantifies the impacts of Lake Manitoba, the Portage Diversion, and other controls. This thesis delivers a 2D hydrodynamic model of the marsh, to be used to predict the changes in water levels and flow with changes in hydrologic and climatic inputs. In addition, this research aims to develop simple, inexpensive, and indirect methods of estimating discharge into and out of coastal wetlands.

Schellenberg (in progress) addresses the hydrologic contribution to the marsh from its watershed. His research addresses the water balance of the watershed, and provides insight into the sources of runoff that reach the marsh. He delivers a representative hydrologic model, to be used to forecast the input hydrographs along the southern boundary of the marsh for a variety of conditions. Hydrologic research will continue following the conclusion of Schellenberg's research, based on stable water isotope data collected since in 2013. Glavonjić (in progress) will perform stable isotope hydrological analysis of the hydrologic system to support the water balance, nutrient-flux prediction, and hydrograph separations proposed by Schellenberg (in progress).

Finally, nutrient sampling will be performed throughout the marsh and watershed for the duration of the project. TP concentrations have been measured semi-continuously at the connections between Delta Marsh and Lake Manitoba. DUC has also measured TP

concentrations at some of the streams that convey snowmelt runoff from the watershed to the marsh. These concentrations can be paired with discharges during modelling to estimate nutrient fluxes into and out of the marsh. This data will provide a baseline estimate of how well (or how poorly) the marsh is acting as a nutrient sink.

1.5. Research Objectives

There are two main objectives of the hydrodynamic study of Delta Marsh. The first is the development of a 2D model of the marsh, to contribute to baseline knowledge and forecasting applications. The second is to develop simple and inexpensive methods of estimating wetland inflow and outflow. These numerical methods not only serve the *Restoring the Tradition* project, but may be useful to wetland hydrometrics in general.

1.5.1. Hydrodynamic Model of Delta Marsh

A multi-component numerical model of Delta Marsh will be developed for this project. This model will predict how runoff from the watershed reaches the marsh, how wind setup on Lake Manitoba influences the fluxes to and from the marsh, and how water moves once inside the marsh. This model can be used to test the hydrodynamic sensitivity of the marsh to different hydrologic controls (The Portage Diversion, natural lake inflows, climate, etc.), and can be used to predict the effectiveness of potential rehabilitation efforts. This model can be paired with estimates of nutrient concentration to predict nutrient flux into and out of the marsh. The objectives and their hypotheses are organized in Table 1:2, and will be revisited in the conclusions.

Table 1:2 – Hydrodynamic Modelling: Objectives and Hypotheses

Objective		Hypothesis
1.1	To develop a numerical model of Delta Marsh and Lake Manitoba	
1.2	To establish a baseline understanding of the water movement phenomena in the marsh	
1.3	To rank the relative hydrodynamic influences of wind set-up, the Portage Diversion, and natural lake inflows	Wind is the main governing force, followed by the Portage Diversion (during wet years), followed by natural inflows
1.4	To estimate the hydrodynamic impact of expansions to existing flood diversion infrastructure	Expansion of the diversion will accelerate spring inflow to the marsh; creation of an outlet channel will hasten drawdown
1.5	To test the hydrodynamic sensitivity of the marsh to a variety of watershed runoff scenarios (from Schellenberg)	Variability in tributary inflow will be insignificant compared to changes in marsh flux due to wind, the Portage Diversion, and natural lake inflows

1.5.2. Simplified Methods of Discharge Estimation

Common discharge estimation techniques (such as stage-discharge rating curves) are not applicable in wetland environments, so direct discharge measurement is typically required. Often, direct measurement is expensive, inaccessible or infeasible, and, at best, only provides discrete measurements. Any simplifications in equipment or required effort can yield tremendous savings in monetary or human resources. The objective of this portion of the thesis is to propose simplified estimation methods, to quantify the loss in estimation accuracy associated with each, and to identify the most balanced method.

An acoustic Doppler current profiler (ADCP) can provide highly accurate discrete discharge measurements. The velocity index method (VIM) can be used to estimate continuous discharge using a velocimeter in addition to an ADCP. This thesis introduces three new methods of estimation. The first two are the regressed slope Manning method (RSMM) and the regressed level Manning method (RLMM). Both methods estimate the geometry and friction slope of the channel using water levels. The RSMM uses data from two nearby water level gauges, while the RLMM uses only one gauge. The polynomial regression method (PRM) uses Water Survey of Canada (WSC) data to estimate discharge directly. This method attempts to capture the effects of wind setup, but does not consider channel geometry. The objectives and their hypotheses are organized in Table 1:3, and will be revisited in the conclusions.

Table 1:3 – Discharge Estimation: Objectives and Hypotheses

Objective		Hypothesis
2.1	To confirm the applicability of the VIM	The VIM is expected to work extremely well for all monitoring years
2.2	To develop and test the RSMM	The RSMM is expected to work well, and will be repeatable from year to year, given its physical basis
2.3	To develop and test the RLMM	The RLMM is expected to work moderately well, but may not be repeatable from year to year, given its vulnerability to regression error
2.4	To develop and test the PRM	The PRM will work acceptably, but will not be repeatable from year to year, given its vulnerability to regression error
2.5	To select the most balanced method	The RSMM will be the ideal method

2. Study Area

In order to study the physical behaviour of Delta Marsh, the research scope must include the driving forces from Lake Manitoba and the Delta Marsh Watershed. All three areas are studied in this thesis and by Schellenberg (in progress).

2.1. Delta Marsh

Delta Marsh is a large wetland bordering the southern edge of Lake Manitoba in south-central Manitoba. It is a discontinuous inland coastal wetland: discontinuous, in that it is not bisected by any major tributaries (not counting the Portage Diversion, which conveys water from outside of the watershed directly to Lake Manitoba); inland, in that it is non-tidal; and coastal, in that it borders (and is controlled hydraulically by) Lake Manitoba. Figure 2:1 shows the extents of the study area of the marsh, dubbed “East Marsh”. Note that this is not the entire footprint of Delta Marsh, which extends west beyond the Portage Diversion and east beyond St. Ambrose. Further instances of “Delta marsh” refer to East Marsh only.

East Marsh has an open-water footprint of 45 km². It extends west to east from Cadham Bay to Clandeboye Bay (Figure 2:1), connected to Lake Manitoba via Delta Channel (Figure 2:2, framed in red) and Clandeboye Channel (Figure 2:3, framed in red), respectively. The marsh is composed of several large bays connected by internal channels of varying width and depth. It is hypothesized that bays in the centre of the marsh are considerably more isolated from the lake than those near the eastern or western ends. On average, the bays are 1-1.5 m deep, while the channels are as deep as 3-4 m (depending on ambient water depth).

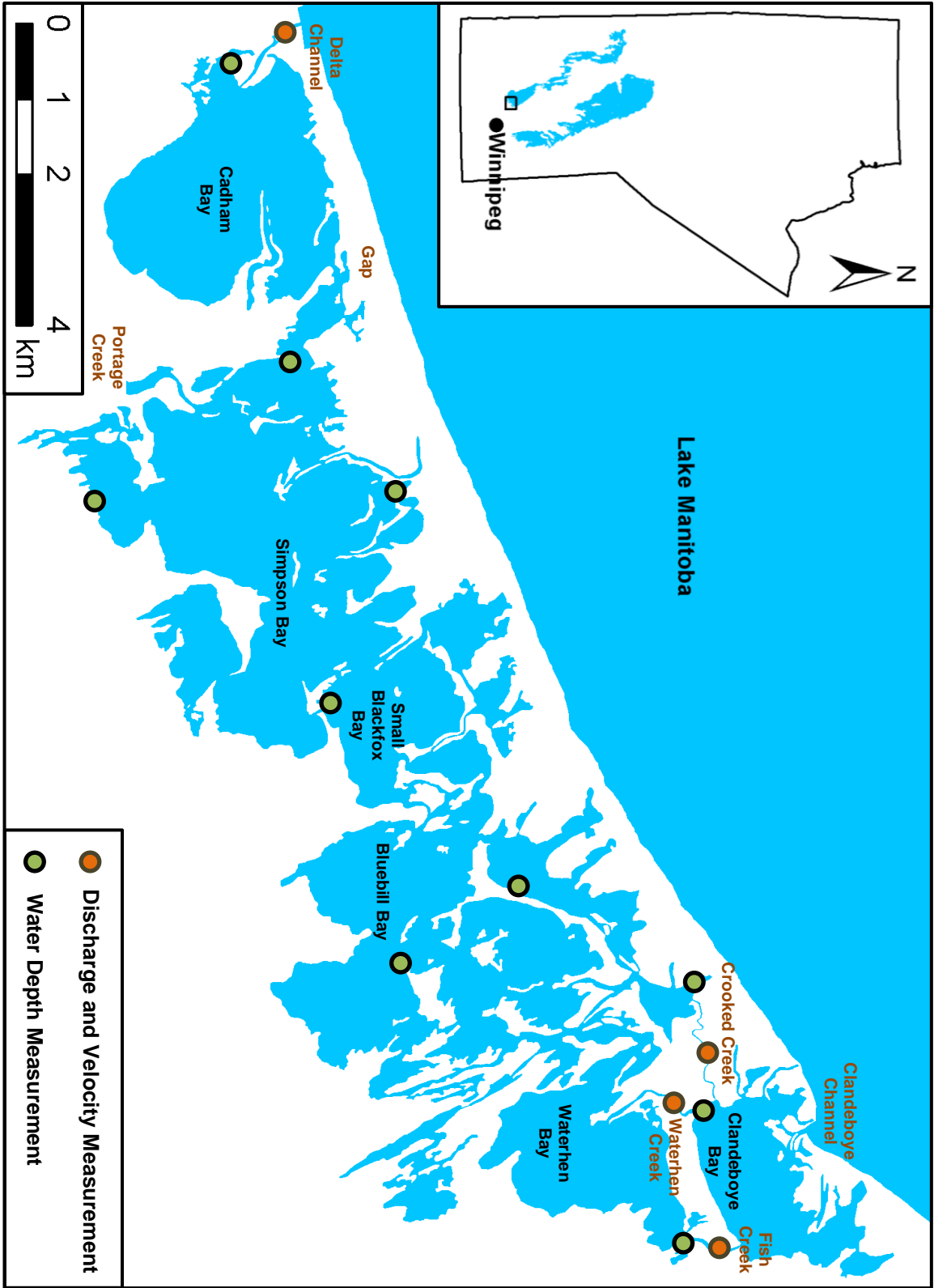


Figure 2:1 – Delta Marsh: Study Area and Relevant Locations



Figure 2:2 – Cadham Bay & Delta Channel (Ducks Unlimited Canada)

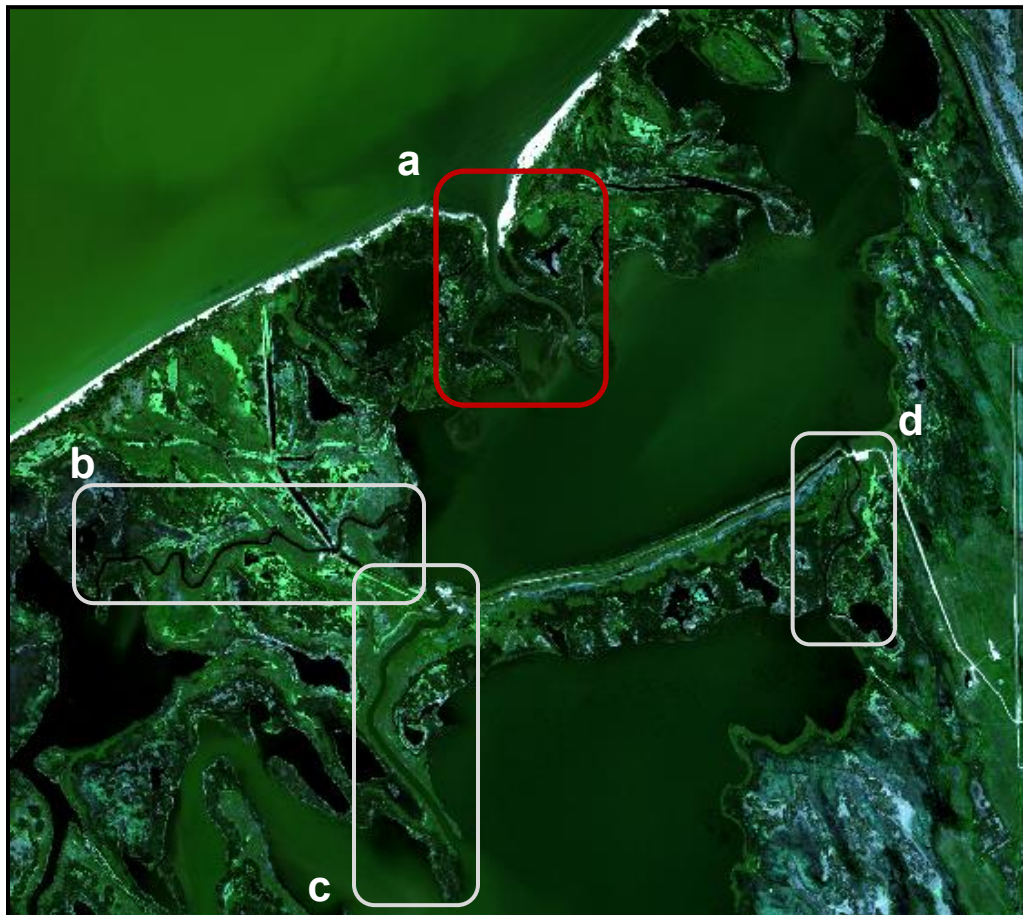


Figure 2:3 – Clandeboye Bay and Adjoining Channels (Ducks Unlimited Canada)

a) Clandeboye Channel; b) Crooked Creek; c) Waterhen Creek; d) Fish Creek

Delta Marsh gains water via overland and channel runoff from the Delta Marsh Watershed, precipitation, and groundwater recharge. It loses water via evaporation and infiltration. It gains and loses water from and to Lake Manitoba via Delta Channel and Clandeboye Channel based on wind-induced setup and changes in lake storage. Delta Marsh is bounded by its watershed to the south and Lake Manitoba to the North.

In order to quantify the effect of the lake boundary and to calibrate the numerical model, discharges into and out of the marsh were measured during the 2013 and 2014 open water seasons (described in Section 4.1.1). Ideally, velocity and discharge measurements would be taken directly at the connections to the lake. This was done easily at Delta Channel (Figure 2:2). Measurement was not performed at Clandeboye channel, for several reasons: the channel is adjacent to a public beach, and measurement equipment would potentially be invasive and at risk; Clandeboye bay is shallower than the rest of the marsh, and access from the marsh would be a challenge; Clandeboye Bay is not within the carp exclusion zone. Carp exclusion structures exist at Crooked Creek, Waterhen Creek, and Fish Creek, further limiting access to Clandeboye bay. Rather than monitoring Clandeboye Channel directly, discharge through Clandeboye Bay was estimated by measuring and summing discharges at Crooked, Waterhen, and Fish Creeks (Figure 2:3). DUC and the Province of Manitoba benefited from discharge data at their structures. This would not have been possible if measurements were taken at Clandeboye Channel only.

In addition, water levels were measured continuously across the marsh during the 2013 and 2014 open water seasons (described in Section 4.1.1). Water level measurements were used for the following purposes: to obtain baseline observations; to calibrate the numerical

model; and to assess the differences in level fluctuation between locations. This will provide insight into how well or how poorly certain bays are connected to each other. Measurements were taken at 10 locations across the marsh (Figure 2:1).

2.2. Lake Manitoba

Lake Manitoba (Figure 2:4) is Manitoba's 3rd largest, Canada's 13th largest, and the world's 33rd largest freshwater lake by surface area. The lake has an average surface area of 4624 km² but has a maximum depth of only 7 m. Lake Manitoba is considerably longer (north-south) than it is wide (east-west), and is composed of two basins that are connected through a set of narrows – aptly named The Narrows.

Lake Manitoba gains water naturally via Waterhen River (from Lake Winnipegosis), Whitemud River (from southwestern Manitoba), overland runoff from its surrounding watershed, and direct precipitation. It is also fed discontinuously by the Portage Diversion, which can account for a large portion of the inflows during Assiniboine River flood seasons (typically occurring April-July). It loses water via the Fairford River (to Lake St. Martin) and evaporation. The Lake St. Martin Emergency Channel redirects water into Big Buffalo Lake, allowing Lake Manitoba to drain more rapidly. In addition, the Province of Manitoba is planning the construction of an additional outlet channel to Lake St. Martin, which will further accelerate lake drainage (Manitoba Infrastructure and Transportation 2014). Note that lateral overland runoff and groundwater contributions have not been quantified.

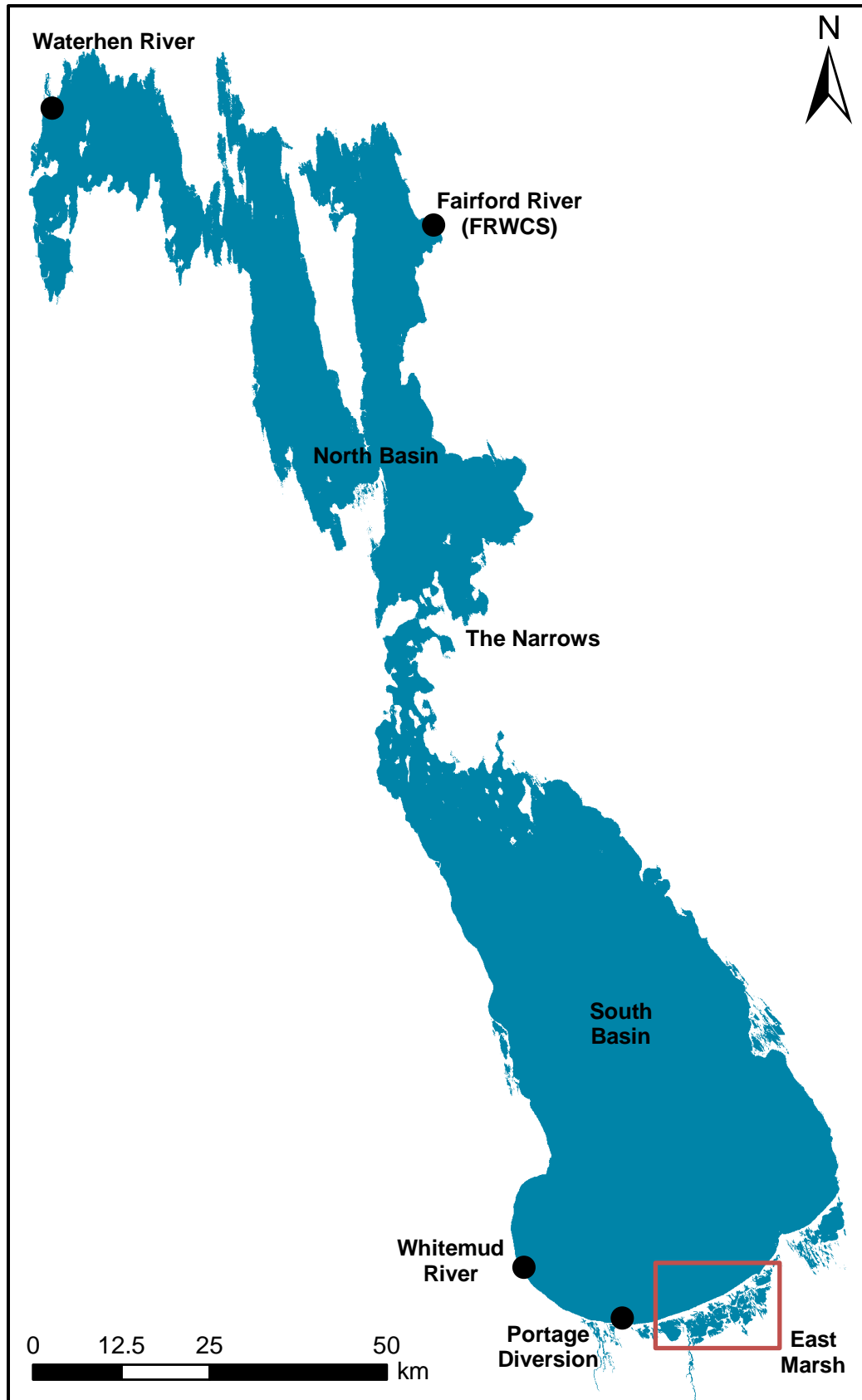


Figure 2:4 – Lake Manitoba

Under natural conditions, the lake experiences three scales of water-level fluctuation. Long-term fluctuations occur in cycles spanning tens of years caused by global climate patterns (e.g. the El Niño Southern Oscillation). Seasonal fluctuations occur annually as spring freshet (rapid inflow) and summer evaporation (gradual drawdown). Both of these scales of fluctuations have been damped in recent years by the FRWCS. Finally, the lake experiences short-term water level fluctuations in the form of wind-induced seiching (Burrows 1970). Seiching can be in the order of one to two meters, given the ample fetch length of the lake and frequency of strong winds (Malenchak 2004).

2.3. The Delta Marsh Watershed

The Delta Marsh Watershed is shown in Figure 2:5, as delineated in red by Schellenberg (in progress). It is relatively small, with an area of 558 km² (compared to 182 000 km² for the Assiniboine River Basin). The watershed has experienced significant anthropogenic change. A majority of the land is used for agriculture; land has been subdivided by roads and artificial berms; and the Portage Diversion bisects the watershed, to name a few. There is a dense stream network in the watershed, and this may lead to the assumption that there is a large amount of channelized runoff. This is countered by two points:

1. Many of the channels are relics of the Assiniboine; many are silted-in, and many terminate before reaching an outlet. They are essentially channel-shaped ponds.
2. The watershed has an extremely mild slope of < 0.1%, and a great deal of rainfall or snowmelt likely infiltrates or evaporates before reaching the marsh.

Portage Creek is regularly observed to route freshet towards the marsh, and this will be addressed in this thesis. In addition, overland runoff occurs along the southern perimeter of the marsh. The total (channel and overland) watershed contribution to the marsh water balance is difficult to quantify, and will be addressed by Schellenberg (in progress).

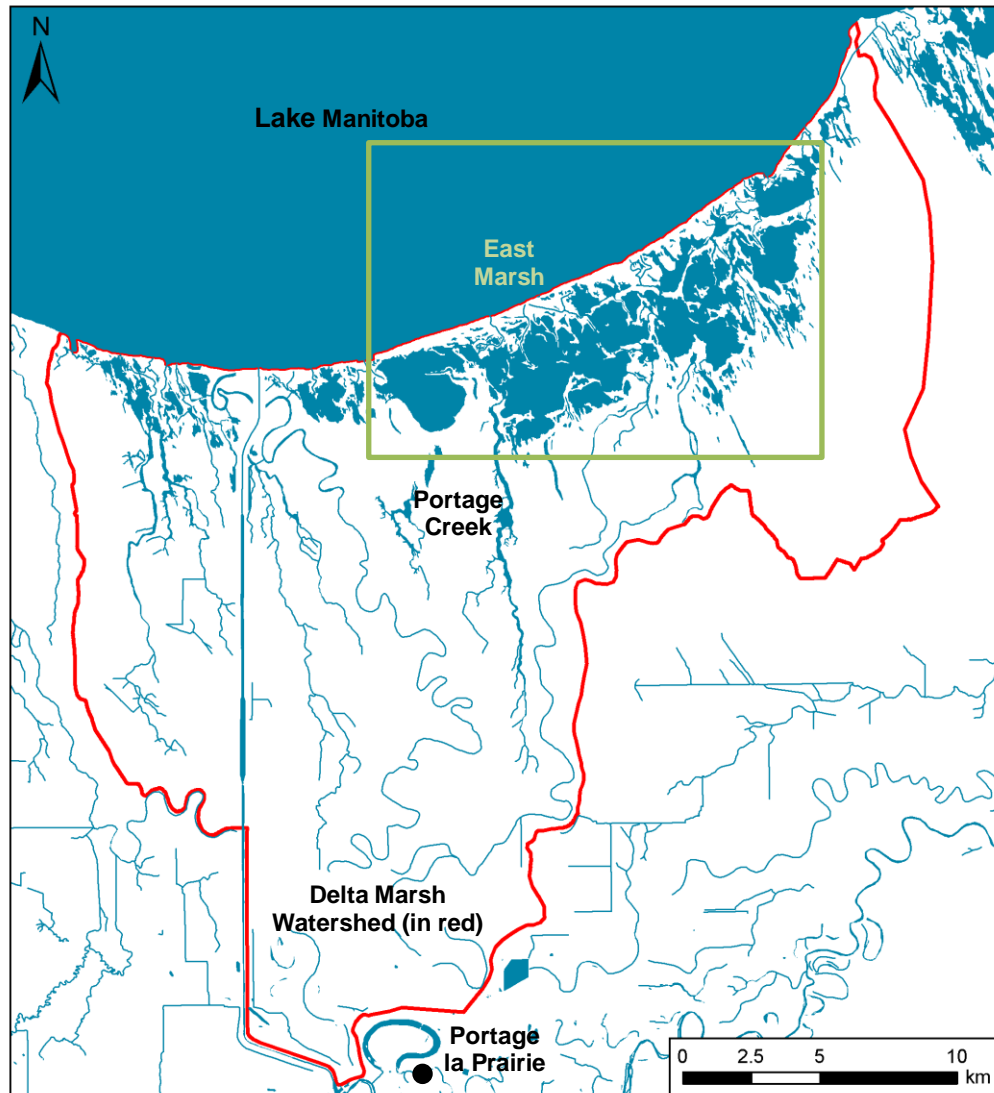


Figure 2:5 – Delta Marsh Watershed (Schellenberg, in progress)

3. Review of Engineering Tools

The first chapter of this thesis includes an ecological review of Delta Marsh, and a discussion of the relationship between wetland hydrodynamics and ecology. This chapter reviews numerical modelling and hydrography theory within the context of Delta Marsh.

3.1. Hydrodynamic Modelling

In order to assess the hydrodynamics of Delta Marsh, a numerical modelling platform must be selected that can account for and link 2D flow, watershed hydrology, and meteorology. The selection of the MIKE Platform is justified below, followed by descriptions of the relevant submodule processes.

3.1.1. Selection of Modelling Platform

Based on the modelling goals of this project, a modelling platform must be selected that can meet the following practical requirements, listed in decreasing order of importance:

1. **Must** have 2D hydrodynamic modelling capabilities
 - a. **Must** account for meteorology
 - b. **Should** have transport and particle tracking
 - c. **Should** have proven use in wetland environments
2. **Must** have hydrological modelling capabilities
3. **Must** have 1D routing capabilities
4. **Must** be able to link hydrodynamic, hydrologic, and routing models
5. **Should** be affordable
6. **Should** be supported
7. **Should** have ecological modelling capabilities

The following numerical modelling platforms are compared, and assessed against the listed requirements (as summarized in Table 3:1):

1. Hydrologic Engineering Centre (**HEC**) by the US Army Corps of Engineers
2. **River2D** by the University of Alberta
3. **MIKE** by DHI (formerly the Danish Hydraulic Institute)

Table 3:1 – Comparison of Numerical Model Capabilities

Criteria	HEC	River2D	MIKE
2D hydrodynamic modelling		✓	✓
Meteorology			✓
Transport			✓
Use in wetlands		✓	✓
Hydrologic modelling	✓		✓
Hydraulic routing	✓	✓	✓
Linkable models			✓
Affordable	✓	✓	✓
Supported			✓
Ecological modelling		✓	✓

Note that MIKE fulfils more requirements than HEC and River2D used in combination. HEC is arguably the most frequently used water resources modelling suite. The River Analysis System (HEC-RAS) is useful in 1D hydraulic routing, and the Hydrologic Modelling System (HEC-HMS) is useful in lumped mathematical watershed modelling. The popularity of these models is a result of their affordability and simplicity; HEC is free, and there is a great deal of supporting literature. HEC-RAS can be applied to streams with relative ease, and HEC-HMS allows for hydrologic modelling with limited input data. While not directly linkable, the two models can be used complementarily. The downside to

the simplicity of the HEC platform is that it is less applicable when the environment and/or modelling goals are complex; there is no 2D hydrodynamic modelling capability.

River2D is a popular, free 2D hydrodynamic model. It is often used in aquatic habitat modelling, and is thus suitable for small-scale riverine domains. It has not been used widely in large-scale limnology studies. It has not been used widely in wetland modelling, although it can account for unsteady and two-directional flow. Unfortunately, River2D cannot account for precipitation, evaporation, or wind forcing. These are the likely the primary processes governing water movement at Delta Marsh.

Consider the MIKE platform, licensed and supported by DHI (Note that “MIKE” is not an acronym). This platform has been designed for integrated environmental modelling – ideal for this research. 2D hydrodynamic modelling and tracer transport can be performed using MIKE 21 Flow Model Flexible Mesh (FM). Fully distributed, physically based hydrologic modelling can be performed using MIKE SHE (System Hydrologique European), with built-in 1D routing performed using MIKE 11. All modules can account for meteorology, and are directly linkable. The model has been used in a variety of wetland modelling scenarios, including wetland hydrodynamics (Somes, Bishop and Wong 1999, Min and Wise 2009, Karim, et al. 2012), wetland solute transport (Min and Wise 2010), and integrated wetland watershed modelling (Thompson, et al. 2004). Finally, DHI offers discounted licensing for academic research, applicable to this project. MIKE by DHI was selected for this thesis, as it meets all requirements at a low cost. The numerical methods of the hydrodynamic and routing modules are described below.

3.1.2. MIKE 21: Numerical Methods

MIKE 21 Flow Model FM (hereafter referred to as “MIKE 21”) is a robust, 2D numerical model that can be used in hydrodynamic, environmental, and sediment transport applications (DHI 2012b). MIKE 21 simulates horizontal (depth-averaged) fluid motion by iteratively solving the 2D incompressible Reynolds-averaged Navier-Stokes (RANS) equations, invoking the assumptions of Boussinesq and of hydrostatic pressure (DHI 2012b). Previous versions of 2D hydrodynamic modelling software by DHI have been based on gridded spatial discretization, while this version allows for flexible mesh generation. Only the hydrodynamic and transport submodules were used for this thesis.

The model domain is represented as a collection of non-uniform, non-overlapping triangular elements. The numerical solution method is based on cell-centred finite volume approach of the conservation of mass and momentum. As such, the 2D RANS equations are applied to solve for depth and velocity at each solution node, for each time-step. The equations for continuity (3:1) and longitudinal (3:2) / latitudinal (3:3) conservation of momentum are as follows:

$$\frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} + \frac{\partial h}{\partial t} - hS - P + E = 0 \quad (3:1)$$

$$\begin{aligned} \frac{\partial h\bar{u}}{\partial t} + \frac{\partial h\bar{u}^2}{\partial x} + \frac{\partial h\bar{u}\bar{v}}{\partial y} - f\bar{v}h + gh\frac{\partial\eta}{\partial x} + \frac{h}{\rho_0}\frac{\partial p_a}{\partial x} + \frac{gh^2}{2\rho_0}\frac{\partial\rho}{\partial x} - \frac{\tau_{sx}}{\rho_0} + \frac{\tau_{bx}}{\rho_0} \\ + \frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y}\right) - \frac{\partial hT_{xx}}{\partial x} - \frac{\partial hT_{xy}}{\partial y} - hu_s S = 0 \end{aligned} \quad (3:2)$$

$$\begin{aligned} \frac{\partial h\bar{v}}{\partial t} + \frac{\partial h\bar{u}\bar{v}}{\partial x} + \frac{\partial h\bar{v}^2}{\partial y} + f\bar{v}h + gh\frac{\partial\eta}{\partial y} + \frac{h}{\rho_0}\frac{\partial p_a}{\partial y} + \frac{gh^2}{2\rho_0}\frac{\partial\rho}{\partial y} - \frac{\tau_{sy}}{\rho_0} + \frac{\tau_{by}}{\rho_0} \\ + \frac{1}{\rho_0}\left(\frac{\partial s_{yx}}{\partial x} + \frac{\partial s_{yy}}{\partial y}\right) - \frac{\partial hT_{xy}}{\partial x} - \frac{\partial hT_{yy}}{\partial y} - hv_s S = 0 \end{aligned} \quad (3:3)$$

Where:

- x & y are the longitudinal and latitudinal Cartesian coordinates, respectively [L]
- t is the time [T]
- h is the total water depth [L]
- \bar{u} & \bar{v} are the depth-averaged velocities in the x & y directions, respectively [LT^{-1}]
- S is the magnitude of the discharge into a solution node [T^{-1}]
- P is the local precipitation rate [LT^{-1}]
- E is the local evaporation rate [LT^{-1}]
- f is the Coriolis parameter, determined internally based on geography [T^{-1}]
- g is the gravitational acceleration constant [LT^{-2}]
- η is the surface elevation [L]
- ρ_0 is the reference density of water [ML^{-3}]
- ρ is the instantaneous density of water, equal to ρ_0 throughout this thesis [ML^{-3}]
- p_a is the atmospheric pressure [$ML^{-1}T^{-2}$]
- τ_{si} is the component of the surficial wind stress in the i direction [$ML^{-1}T^{-2}$]
- τ_{bi} is the component of the bottom stress in the i direction [$ML^{-1}T^{-2}$]
- s_{ij} is component of the radiation stress tensor [$ML^{-1}T^{-2}$]
- T_{ij} is the lateral stress [L^2T^{-2}]
- u_s & v_s are the velocities at which water enters ambient water in the x & y directions, respectively [LT^{-1}]

Note that all new water added to the simulation (precipitation, boundary sources, and point sources) is considered to have no velocity, and hence, no impact on momentum.

The bottom stresses (τ_{bx} & τ_{by}) at each solution node can be calculated using the quadratic friction law, as shown for the x -direction, below:

$$\tau_{bx} = \rho_0 c_f u_b |u_b| \quad (3:4)$$

$$c_f = \frac{g}{(Mh^{1/6})^2} \quad (3:5)$$

Where:

- c_f is the bottom drag coefficient [–]
- u_b is the velocity at the bed, equal to \bar{u} in MIKE 21 [LT^{-1}]
- M is the Manning resistance coefficient; to be calibrated [$L^{1/3}T^{-1}$]

At the surface of each solution node, wind stresses (τ_{sx} & τ_{sy}) can be estimated empirically from input wind data, as shown for the x -direction, below:

$$\tau_{sx} = \rho_a c_d u_w |u_w| \quad (3:6)$$

$$c_d = \begin{cases} c_a & u_w < w_a \\ c_a + \frac{c_b - c_a}{w_b - w_a} (u_w - w_a) & w_a \leq u_w < w_b \\ c_b & u_w \geq w_b \end{cases} \quad (3:7)$$

Where:

- ρ_a is the instantaneous density of air [ML^{-3}]
- c_f is the empirical air drag coefficient (Wu 1980, Wu 1994) [–]
- u_w is the wind velocity at 10 m above the water surface [LT^{-1}]
- c_a & c_b are the lower and upper limits of the drag coefficient, respectively; to be calibrated [–]
- w_a & w_b are the velocities between which linear interpolation of the drag coefficient occurs, to be calibrated [LT^{-1}]

The lateral stresses at each solution node (T_{xx}, T_{xy}, T_{yy}) are due to viscous friction, turbulent friction, and differential advection (DHI 2012b). They can be estimated from the following horizontal eddy viscosity formulation:

$$T_{xy} = \Lambda \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) \quad (3:8)$$

$$\Lambda = c_s^2 l^2 \frac{D}{\sqrt{2}} \quad (3:9)$$

Where:

- Λ is the effective horizontal eddy viscosity (Smagorinsky 1963) [$L^2 T^{-1}$]
- c_s is the Smagorinsky Coefficient; to be calibrated [-]
- l is the characteristic length [L]
- D is the amplitude of the deformation tensor [T^{-1}]

The 2D conservation equation for transport of a given component is as follows:

$$\frac{\partial h \bar{u} \bar{C}}{\partial x} + \frac{\partial h \bar{v} \bar{C}}{\partial x} + \frac{\partial h \bar{C}}{\partial t} - h F_C + h k_p \bar{C} - h C_s S = 0 \quad (3:10)$$

Where:

- \bar{C} is the depth-averaged concentration of the scalar quantity [-]
- F_C is the horizontal diffusion term [T^{-1}]
- k_p is the linear decay rate [T^{-1}]
- C_s is the concentration of the scalar quantity at the source [-]

In this thesis, the transport module is used for source tracking only; components must behave like water, and as such, they do not decay or disperse, simplifying Equation 3:10 to:

$$\frac{\partial h \bar{u} \bar{C}}{\partial x} + \frac{\partial h \bar{v} \bar{C}}{\partial x} + \frac{\partial h \bar{C}}{\partial t} - h C_s S = 0 \quad (3:11)$$

The MIKE 21 solution method can employ one of two spatial discretization approaches. The second-order gradient reconstruction technique (Jawahar and Kamath 2000, Darwish and Moukalled 2003) is relatively computationally intensive, but it is useful in modelling flow-dominated processes. The first-order Riemann solver approach (Roe 1981) is numerically simple, but is better suited to modelling diffusion-dominated processes. In addition, there are two options for temporal integration. The second-order Runge Kutta method is relatively computationally intensive, whereas the first-order explicit Euler method is numerically simple.

Finally, the flooding and drying component curtails numerical error that arises due to a moving boundary. If the depth of water is very close to zero, the model may simulate incredibly large velocities to resolve the RANS equations. This can be avoided by adjusting the flooding/drying front for each time-step (Zhao, et al. 1994, Sleigh, et al. 1998). Each element face is classified as wet, partially dry, or dry. These classifications are separated by user-defined boundary values, and are defined as follows:

1. Wet element: the depth is greater than the “wet” boundary value; all three RANS equations are calculated
2. Partially dry element: the depth is between the “wet” and “dry” boundary values, or the depth is less than the “dry” boundary value and deep along one face; only the first RANS equation is considered (momentum is neglected)
3. Dry element: the depth is less than the “dry” boundary value; the element is temporarily excluded from calculation

3.1.3. MIKE 11: Numerical Methods

MIKE 11 is a robust, 1D numerical model that can be used in hydrodynamic, hydraulic design, environmental, sediment transport, and flood forecasting applications (DHI 2012a). MIKE 11 simulates unsteady channel flow using an implicit, finite difference solution scheme (DHI 2012a). For those who are familiar with hydraulic modelling, MIKE 11 can be described as a more inclusive and integrated HEC-RAS model; inclusive, in that it can account for meteorology, pressurized flow, flow stratification, and other considerations; and integrated, in that it is easily incorporated within a MIKE SHE hydrologic model. For the purposes of this research, MIKE 11 was required for routing overland runoff within the watershed, and as such, only the hydrodynamic submodule was used.

A channel is represented within MIKE 11 as a series of spaced cross-sections. Each cross-section is represented as a series of connected points with planar coordinates, measured transversely from an arbitrary left-bank datum, and above a fixed datum (often sea level). These cross-sections are used to solve for flow area, discharge, relative resistance, and energy loss during simulation. The hydrodynamic solution method is based on the conservation of mass and momentum, and as such, the St. Venant equations are used (DHI 2012a). This is a reasonable approach, especially for this research, given the following modelling assumptions: fully dynamic wave approximation applies; the channel slopes are mild; and flow is subcritical. The 1D St. Venant equations for continuity (Equation 3:12) and conservation of momentum (Equation 3:13) are as follows:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0 \quad (3:12)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\alpha \frac{Q^2}{A} \right) + gA \frac{\partial h}{\partial x} + \frac{gQ|Q|}{M^2 AR^{2/3}} = 0 \quad (3:13)$$

Where:

- x is the chainage [L]
- t is the time [T]
- Q is the discharge at a solution node [L^3T^{-1}]
- A is the cross-sectional area at a solution node [L^2]
- q is the zero-velocity lateral inflow at a solution node [L^2T^{-1}]
- α is the momentum distribution coefficient, defaulting to 1.0 [-]
- g is the gravitational acceleration constant [LT^{-2}]
- h is the stage above a datum at a solution node [L]
- M is the Manning resistance coefficient, a calibration term [$L^{1/3}T^{-1}$]
- R is the hydraulic radius [L]

Given initial and boundary conditions, MIKE 11 solves both equations simultaneously, using an implicit finite difference scheme developed for solving 1D depth-averaged flow regimes (Abbott and Ionescu 1967). For each computational time-step, the model calculates stage at each cross-section, and discharge between cross-sections (DHI 2012a).

As with all finite difference modelling, the accuracy and stability of a simulation are greatly influenced by the spatial and temporal discretization of the domain and period, respectively. The mode of spatial discretization is dictated by the availability and resolution of the bathymetric/topographic data; where high-resolution blanket data exist, the user can define cross-sections at will. However, if chained only cross-sectional surveys are available, the user is limited in the selection of cross-section locations. MIKE 11 allows for fixed, tabulated, and adaptive time stepping. Fixed time stepping is the most common,

as it is constant and user-defined. Tabulated time stepping is also user-defined, but changes across the simulation period. This is useful in modelling known events. Adaptive time stepping adjusts the temporal discretization internally. Since there are a variety of ways to discretize the model time and space, and that these options are often limited, it is not possible to prescribe a single best-practice approach. However, several guidelines are presented. For example, the local space-step should be reflective of the geomorphology of the area – tight turns or constrictions should be divided into greater cross-sections. In addition, the time step should be small enough to capture the propagation of a flood wave.

The initial (quasi-steady-state) backwater condition is calculated upstream from the initial stage provided at the outlet boundary, using the St. Venant equations (DHI 2012a). Boundary conditions are required at each free end of a channel (e.g. a channel that empties into another modelled channel does not require an outlet condition). Under subcritical flow conditions, upstream discharge data and downstream stage data are required. In addition, lateral inflows can be added along the channel, and are resolved to point sources at computational nodes along the channel (DHI 2012a). When used within MIKE SHE, overland runoff flowing toward the MIKE 11 channel is added as lateral inflow.

The channel bed and overbank portions of each cross-section must be assigned roughness values, using the Chézy, Manning, or Darcy-Weisbach bed resistance description. Adjusting the roughness term(s) shifts the balance of Equation 3:14; lower bed roughness increases discharge per unit depth. This can be used to calibrate the model to measured discharge and stage, or to estimate the change in flow behaviour associated with a change in bed or overbank material.

3.2. Established Methods of Discharge Measurement and Estimation

Wetland discharge quantification is necessary for a variety of scientific applications, including developing basic hydrodynamic knowledge, water quality analyses, and ecological analyses. The advantages and limitations of several existing methods of discharge measurement and estimation are discussed below. The velocity index method is the only method that is usable in wetland channels, but it is also relatively resource-intensive. This motivates the development of accurate, robust, and inexpensive discharge estimation tools, as discussed in Section 4.5.

3.2.1. Direct Discharge Measurement

Discharge measurement can be performed directly using a variety of tools, such as an acoustic Doppler current profiler (ADCP), or a handheld acoustic Doppler velocimeter (ADV). An ADCP reliably measures velocity and depth, as it is pulled across the channel, perpendicular to flow. The device automatically subdivides the cross-section into thin sub-areas, and measures the velocity through each. Figure 3:1 shows the ADCP output for a cross-section measured in Waterhen Creek on August 14, 2013. Note the visible velocity distribution across the cross-section.

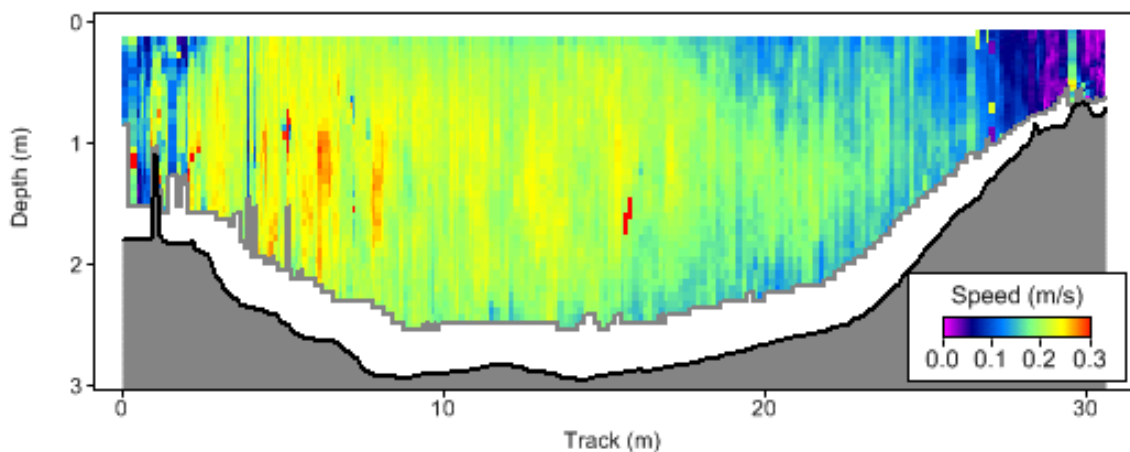


Figure 3:1 – ADCP Velocity Distribution: Waterhen Creek, 14/08/2013

The cross-sectional area of the channel is determined by summing the areas of all of the conveyances. The total discharge through the cross-section is determined by summing the discharge for each conveyance, calculated as follows:

$$Q = \sum Q_i = \sum V_i A_i \quad (3:15)$$

Where:

- Q is the discharge through a cross-section [L^3T^{-1}]
- Q_i is the discharge through the i^{th} sub-area [L^3T^{-1}]
- V_i is the measured velocity through the i^{th} sub-area [LT^{-1}]
- A_i is the measured area of the i^{th} sub-area [L^2]

ADCP measurement is not without inherent limitations. Measurement uncertainty is proportionately higher for near-stagnant flows, which occur regularly in two-directional channels. Depth and velocity measurements can be skewed or hindered by soft/moving channel beds, vegetation, and large fish. Most importantly, an ADCP can only provide discrete estimates of discharge when field crews are on site. As a result, a continuous hydrograph cannot be measured, but can be estimated using numerical tools, such as a stage-discharge rating curve.

3.2.2. Stage-Discharge Rating Curve

The stage-discharge rating curve is the most common method of discharge estimation, as it is simple to develop, relatively inexpensive to use, and easy to update. In fact, a majority of continuous discharge estimates provided by Water Survey of Canada (WSC) are derived from established rating curves. As an example, consider the development of a rating curve for the Assiniboine River at Headingley (WSC Gauge 05MJ001), illustrated in Figure 3:2

below. Instantaneous depth and discharge measurements are taken in the same quasi-uniform section of the river by the WSC, over a range of discharges. These stages and discharges are plotted against each other, and a curve is fit. From then on, stage measurements can be used to provide reliable discharge estimates. This method works at Headingley – at least in the short term – because there is a strong and relatively steady relationship between depth and discharge.

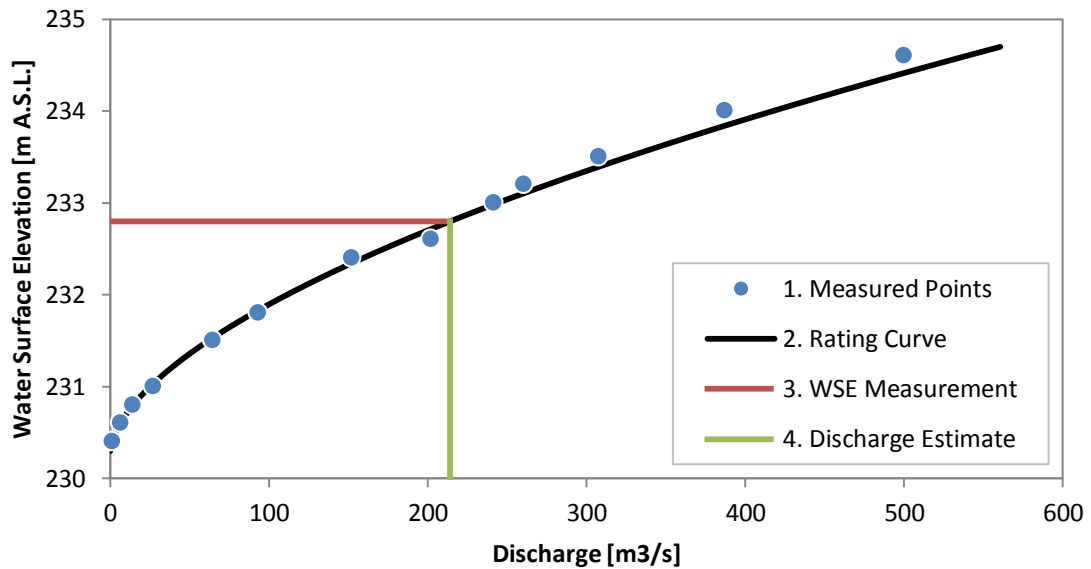


Figure 3:2 – Rating Curve for the Assiniboine River at Headingley

Note that this discussion focuses on ideal conditions only (rating curves are prone to error due to changes in bathymetry, ice formation, vegetation growth, beaver damming, etc.). Even under ideal conditions, this method does not apply for two-directional wetland flow. Figure 3:3 shows an attempt at the creation of a stage-discharge rating curve for two-directional flows through Delta Channel. It is not possible to fit a curve to the plotted points, since multiple discharges can occur at the same depth, and the same discharge can be observed across multiple depths. This outcome is reasonable, considering the nature of

wetland flow; stagnation can occur at any depth, unlike a one-directional, sloped channel like the Assiniboine.

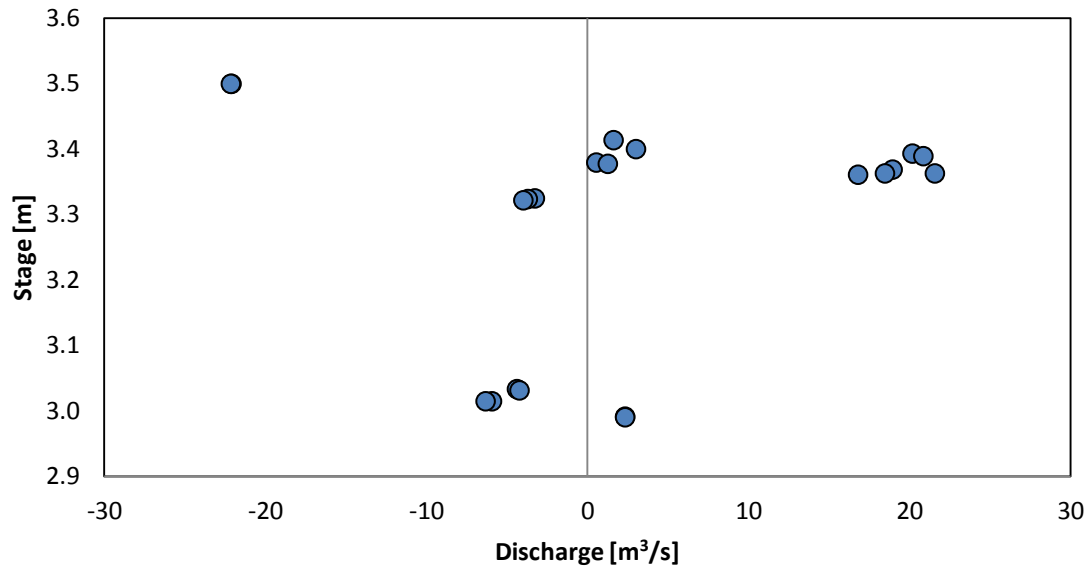


Figure 3:3 – Attempt at a Rating Curve for Delta Channel, 2013

3.2.3. The Manning Formula

The inapplicability of depth-dependent estimation tools can be further examined by deconstructing the Manning formula, shown below:

$$Q = \frac{k_n A^{5/3}}{n P^{2/3}} \sqrt{S_f} \quad (3:16)$$

Where:

- Q is the discharge through a cross-section [L^3T^{-1}]
- k_n is a unit system factor (equal to 1 for metric measurements) [-]
- n is Manning's roughness factor [$TL^{-1/3}$]
- A is the wetted cross-sectional area [L^2]
- P is the wetted perimeter of the cross-section [L]

- S_f is the friction slope, or the slope of the hydraulic grade line [–]

This formula allows for the estimation of discharge with the quantification of only four inputs. A and P are directly measurable, and can be calculated if stage-dependent relationships are established. n can be estimated, or can be used to calibrate the formula if discharge measurements exist. Under uniform flow conditions, S_f is justifiably assumed equal to the bed slope, which is measurable. Two-directional wetland flow, however, is non-uniform, and S_f is non-constant and not easily measurable. Thus, Equation 3:18 cannot be applied in a wetland channel as it is in a one-directional channel.

3.2.4. Velocity Index Method

The VIM differs from the previous methods in that it makes no assumptions of flow characteristics based on geometric characteristics (Sloat and Hull 2004). Instead of directly estimating discharge, a user estimates cross-sectional area from continuous stage measurements, and average cross-sectional velocity from the velocity above some point near the middle of the channel (dubbed the index velocity). In essence, two rating curves are calibrated and used in combination to estimate discharge, as follows:

$$\bar{V} = aV_i + b \quad (3:17)$$

$$A = cy_i + d \quad (3:18)$$

$$Q_{VIM} = \bar{V}A = (aV_i + b)(cy_i + d) \quad (3:19)$$

Where:

- \bar{V} is the average cross-sectional velocity [LT^{-1}]
- V_i is the index velocity [LT^{-1}]
- y_i is the index stage [L]
- a and c are regression coefficients [–]

- b and d are regression constants [LT^{-1}]
- Q_{VIM} is the discharge estimated from the VIM [L^3T^{-1}]

Since this method does not rely on assumptions of uniform or one-directional flow, it is applicable to a wider variety of flow conditions. It works well in environments where consistent stage-discharge relationships do not exist, such as in a non-uniform channel (Sloat and Hull 2004) or under a growing ice sheet (Morse, et al. 2010). Thus, it was hypothesized that it would also be applicable to two-directional wetland channel flow.

This method relies on continuous index velocity and stage measurements from a submersible ADV, and instantaneous discharge and area measurements from an ADCP or handheld ADV (for linear regression fitting). These tools yield reliable measurements, but become the limitation of this method; at least one ADCP is required to take instantaneous measurements at all sites, and one submersible ADV is required at each site for the entirety of the desired hydrograph period. The new methods proposed in Section 4.5 aim to reproduce VIM simulations with less expensive equipment.

4. Methodology

Field monitoring was conducted at Delta Marsh from the spring of 2013 to the autumn of 2014 in order to gather sufficient data for the fulfilment of the two thesis objectives. Methodologies of the field work, numerical modelling, and the development of discharge estimation tools are described below.

4.1. Field Monitoring Program

Continuous hydraulic monitoring and nutrient chemistry sampling was conducted during the 2013 and 2014 open water seasons. This fieldwork was performed alongside spring runoff measurement for Schellenberg (in progress), and the collection of stable water isotope samples for Glavonić (in progress). The methodologies described below are subject to change as the project progresses.

4.1.1. Hydrography

Hydraulic measurements were collected for use in the interpretation of marsh behaviour, and the calibration and validation of the numerical models. Water levels were measured across the marsh, and velocity and discharge measurements were taken at major channels. Water level measurements were taken automatically every 5 minutes at 10 sites across the marsh (Figure 2:1) using Solinst LeveLoggers (Figure 4:1a). These devices provide reliable depth measurements (± 5 mm) (Solinst 2014). The gauges were housed inside PVC pipe stands, which had been driven into the marsh bed (Figure 4:1b&c). Gauges measure total (water and atmospheric) pressure, and convert it to an equivalent depth of water. Measurements are corrected by simultaneous atmospheric pressure measurements. Depths can then be adjusted to elevations above sea level using benchmark surveys.



Figure 4:1 – LeveLogger Setup

a) Solinst LeveLogger; b) PVC pipe stand, visible from a distance; c) Close-up of pipe stand

Channel velocity measurements were taken automatically every 10 minutes using two SonTek Argonaut Shallow Water ADVs. These devices provide streamwise velocity (± 5 mm/s) and depth measurements (± 3 mm) (SonTek 2009). Each ADV was installed at the bottom-centre of a channel, and was powered by a solar-charged 12 V battery. In 2013, one ADV was installed in Delta channel for the entire season, and the other was moved between Crooked, Fish, and Waterhen Creeks (Figure 2:1). Discharges through Crooked and Fish Creeks could be reliably estimated as small fractions of the flow through Waterhen Creek. Thus, velocity (and discharge) measurement was focused to Delta Channel and Waterhen Creek beginning in 2014. Note that for all velocity and discharge measurements, at all locations, positive values denote flow toward the marsh, and negative values denote flow toward the lake.

In order to estimate discharge from the continuous velocity measurements, the velocity index method (Section 3.2.4) must be calibrated against discharge and area measurements. Discrete discharge and area measurements were obtained using a SonTek RiverSurveyor M9 ADCP. This device provides velocity (± 2 mm/s) and depth measurements (± 3 cm) (SonTek 2009), and calculates discharge automatically, as described in Section 3.2.1. ADCP measurements were conducted approximately bi-weekly at Delta Channel, Crooked Creek, Fish Creek, and Waterhen Creek in 2013, and at Delta Channel and Waterhen Creek in 2014. The ADCP was pulled along transections roughly perpendicular to flow, several times in succession (Figure 4:2). The Sontek M9 is equipped with a GPS, so deviations from the transection are accounted for during internal discharge calculations.



Figure 4:2 – Typical ADCP Operation

4.1.2. Nutrient Chemistry

Beyond collecting data for direct use in the three engineering studies, the engineering branch of the project was responsible for the collection of high-resolution nutrient data at Delta Channel and Waterhen Creek in 2014. This data will be used by DUC to assess performance of the marsh as a nutrient sink. At an elementary level, concentrations can be paired with channel discharge to estimate nutrient mass flux over time. This is introduced and discussed in section 6.1.2 of this thesis.

Hourly 50 mL water samples were collected automatically using two Teledyne ISCO Portable Samplers. ISCOs were installed nearshore, and were powered by solar-charged 12 V batteries. Twelve consecutive samples were deposited into each pre-acidified sample bottle, providing homogenized 600 mL semi-daily samples (centered around midnight and noon). Total phosphorus (TP) concentration analysis was performed by ALS Laboratories as per the “APHA 4500-P” procedure (American Public Health Association 1992).

4.2. Integrated Approach for Modelling the Delta Marsh Area

An integrated modelling methodology (Figure 4:3) was developed to capture the influences of Lake Manitoba and the Delta Marsh Watershed, and to simulate the proposed scenarios (Section 4.2.1). The original modelling approach included the following four components:

1. 2D hydrodynamic model of Delta Marsh (MIKE 21)
2. 2D hydrodynamic model of Lake Manitoba (MIKE 21)
3. Hydrologic model of the Delta Marsh Watershed (MIKE SHE)
4. 1D routing model for the Delta Marsh Watershed (MIKE 11)

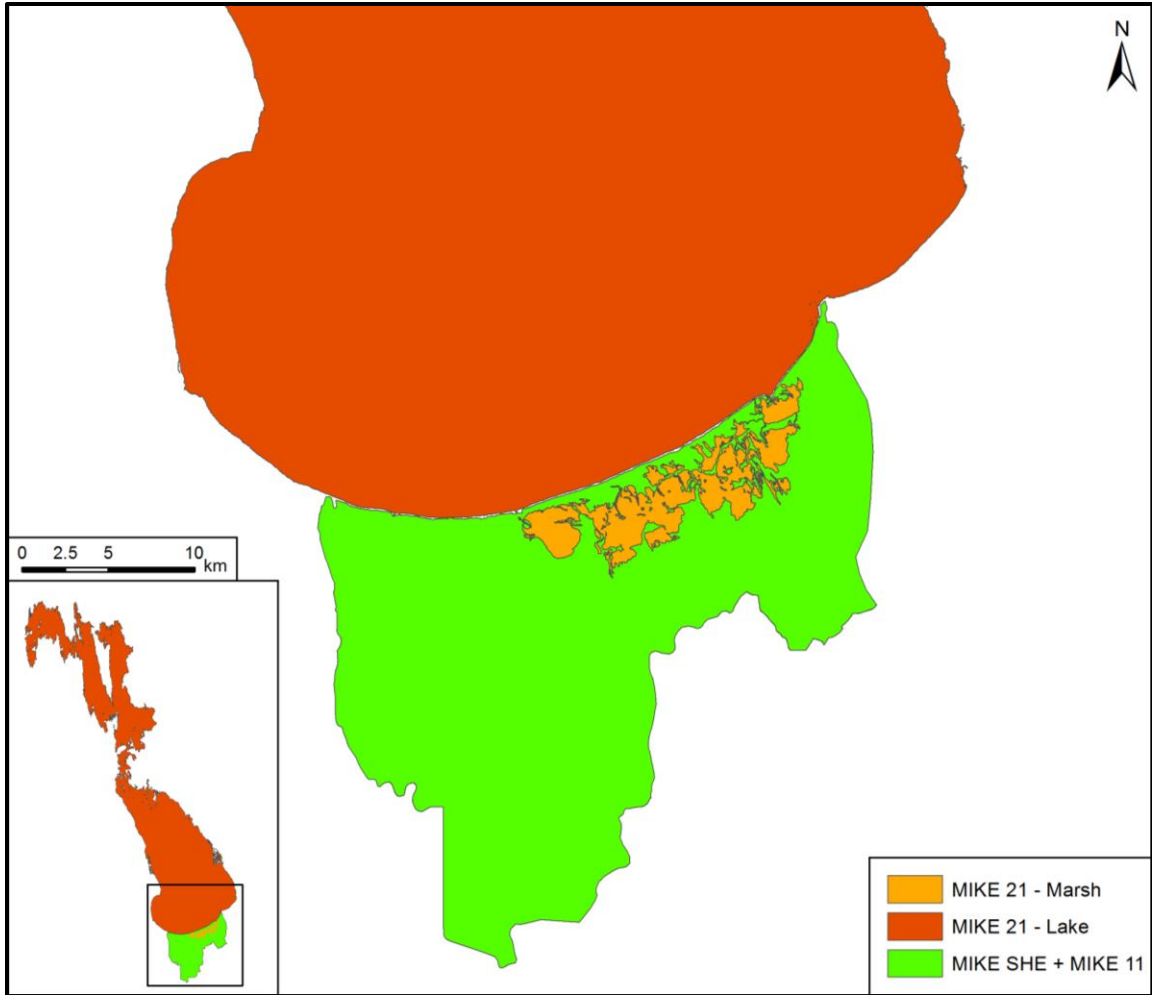


Figure 4:3 – Four-Component Modelling: Geographic View (Schellenberg)

The outputs from the marsh model (Section 4.2.2) are the focus of this thesis, and thus the spatial resolution of the marsh domain was relatively high. Conversely, the primary purpose of the lake model was to represent wind-setup along its southern boundary, and to account for changes in storage. As such, the lake domain was relatively coarse. Since the high-resolution marsh model governed runtime, the two hydrodynamic models were merged into one – reducing modelling to three components. This simplified model setup (Section 4.3), streamlined model operation, and, as an unforeseen bonus, improved model stability (Section 4.3.4).

The MIKE SHE hydrologic model was setup, calibrated, and used by Schellenberg (in progress). This model was used to estimate the different water balance components (precipitation, evapotranspiration, infiltration, overland runoff, etc.) under a variety of land use scenarios. Furthermore, this model provided overland and channel runoff as inputs to the hydrodynamic model, under the same land use scenarios. A MIKE 11 routing sub-module was implemented within the MIKE SHE model (detailed in Section 4.4).

4.2.1. Hydrodynamic Modelling Scenarios

The calibrated, integrated 2D hydrodynamic model was used to assess the relative changes in hydrodynamics (discharge, retention time, etc.) for the following scenarios:

1. Baseline conditions: reproducing observations from 2013 & 2014 field seasons; subsequent scenarios will be compared against these simulations
2. Relative impact assessment: comparing the hydrodynamic influences of major governing forces by excluding them from the model one-by-one:
 - a. Portage Diversion and natural inflows included, wind excluded
 - b. Natural inflows and wind included, Portage Diversion excluded
 - c. Portage Diversion and wind included, natural inflows excluded
3. Proposed improvements to flood diversion infrastructure: increasing the capacity of the Portage Diversion to 960 cms, and of the Lake St. Martin Outlet (at Fairford) to 210 cms (Manitoba Infrastructure and Transportation 2014)

Note that watershed contributions have been neglected from all scenarios presented in this thesis. This decision was made due to the disparity between modelling schedules. The MIKE 21 model was easier to calibrate, but was used to model many scenarios at

relatively long run-times. Conversely, the MIKE SHE model was more difficult to set up and calibrate, but fewer scenario simulations were performed over a shorter period. To allow for adequate calibration of the MIKE SHE model without sacrificing valuable MIKE 21 modelling time, the decision was made to use the models separately. Since this thesis delivers a calibrated hydrodynamic model, and Schellenberg (in progress) will deliver a calibrated hydrologic model, any watershed-related scenarios can be tested by simply using the outputs from the MIKE SHE model as inputs to the MIKE 21 Model.

4.2.2. Modelling Outputs

In order to calibrate the model and to interpret the hydrodynamic behaviour of the marsh under the above scenarios, the following datasets were extracted from the model:

1. Two-directional Delta Marsh discharges (Figure 4:4):
 - a. Delta Channel (DC)
 - b. Waterhen Creek (WC)
 - c. Crooked Creek (CC)
 - d. Fish Creek (FC)
 - e. Clandeboye Channel (CB)
 - f. Portage Creek (PC)
 - g. Gap
 - h. Simpson-Bluebill (SB)
 - i. Bluebill-Waterhen (BW)
2. Two-directional Lake Manitoba discharges (Figure 4:5):
 - a. Narrows
 - b. North Basin

3. Delta Marsh water surface elevations – All 10 LeveLogger locations (Figure 2:1)
4. Lake Manitoba water surface elevations (Figure 4:5)
 - a. Westbourne (at WSC Gauge 05LL012)
 - b. Steep Rock (at WSC Gauge 05LK002)
5. Tracer concentrations across the model domain (as described in Section 4.3.11)
6. Tracer fluxes across the marsh (Figure 4:4)
 - a. Delta Channel (DC)
 - b. Clandeboye Channel (CB)
 - c. Gap
 - d. Crooked, Waterhen, and Fish Creeks (cumulative; CC, WC, FC)
 - e. Simpson-Bluebill (SB)

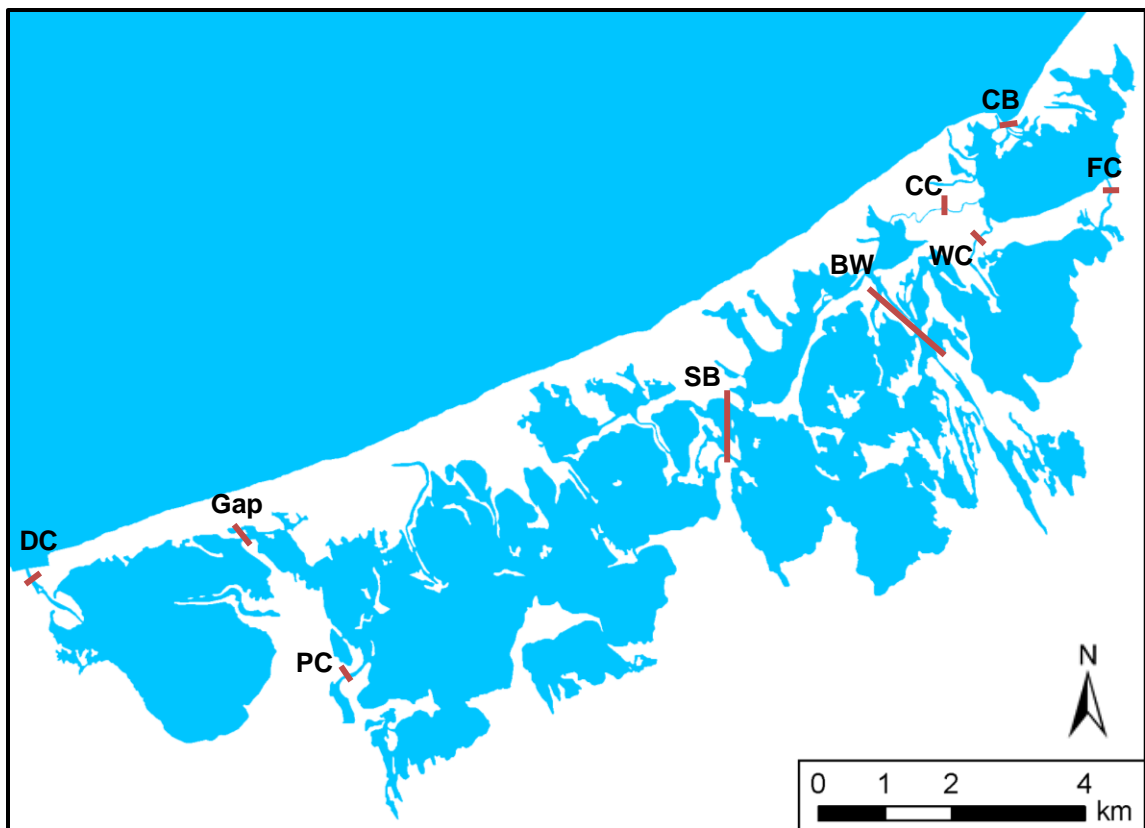


Figure 4:4 – Delta Marsh: Discharge and Tracer Flux Output Locations

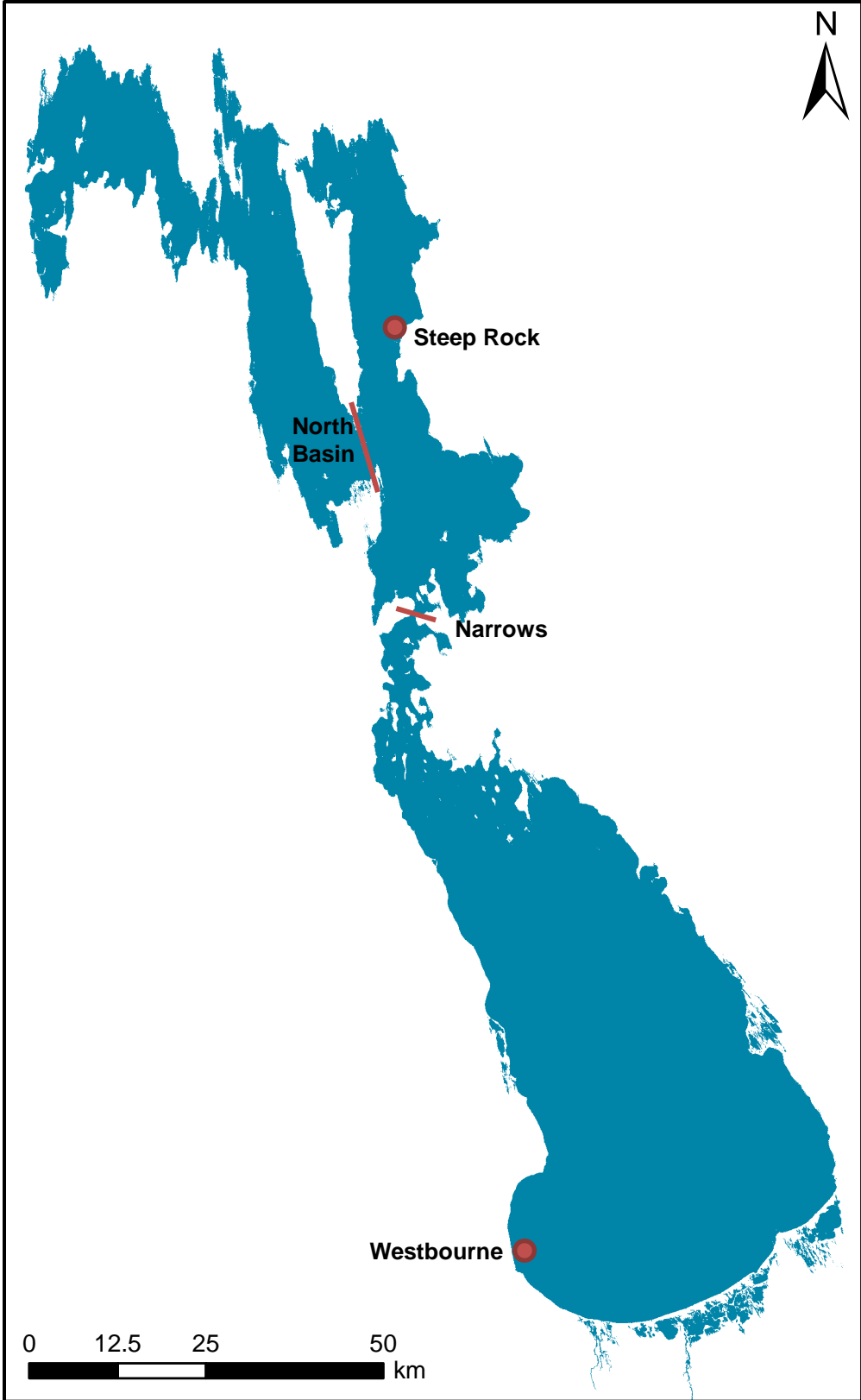


Figure 4:5 – Lake Manitoba: WSE and Discharge Output Locations

4.3. MIKE 21: Hydrodynamic Model Development

The 2D hydrodynamic and transport modules were used to model Delta Marsh and Lake Manitoba as one object. The modules are primarily physically based, thus requiring a great deal of input data. In fact, much of the effort in getting a MIKE 21 model to provide reasonable simulations is in the selection of representative data sources. Model setups are discussed below, along with justifications of choices of data sources and computation methods, where applicable. Section 5.2 discusses the calibration of the models by adjusting the precipitation, wind friction, bed resistance, and eddy viscosity controls.

4.3.1. Domain

The modelling domains of Delta Marsh and Lake Manitoba were established separately, and then merged into one (Figure 4:6). A high-resolution bathymetric mesh was developed for the marsh domain (Figure 4:7), with approximately 15 000 elements over an area of 45 km² (an average element size of 3000 m²). This mesh was generated over bathymetric data collected by the Department of Biological Sciences at the University of Manitoba (Geard 2015). A fine mesh was required to allow the model to represent narrow channel flow (as illustrated in Figure 4:8), circulation within the bays, and other small-scale processes. The mesh was refined further at channels and constrictions. Conversely, a coarse mesh was developed for the lake domain, with approximately 1650 elements over an area of 4600 km² (an average element size of approximately 3 000 000 m²). This mesh was generated over bathymetric data collected by Manitoba Water Stewardship. The purpose of the lake portion of the model was to simulate wind setup and changes in storage. Since small-scale processes were not of interest, a coarse mesh was deemed adequate.

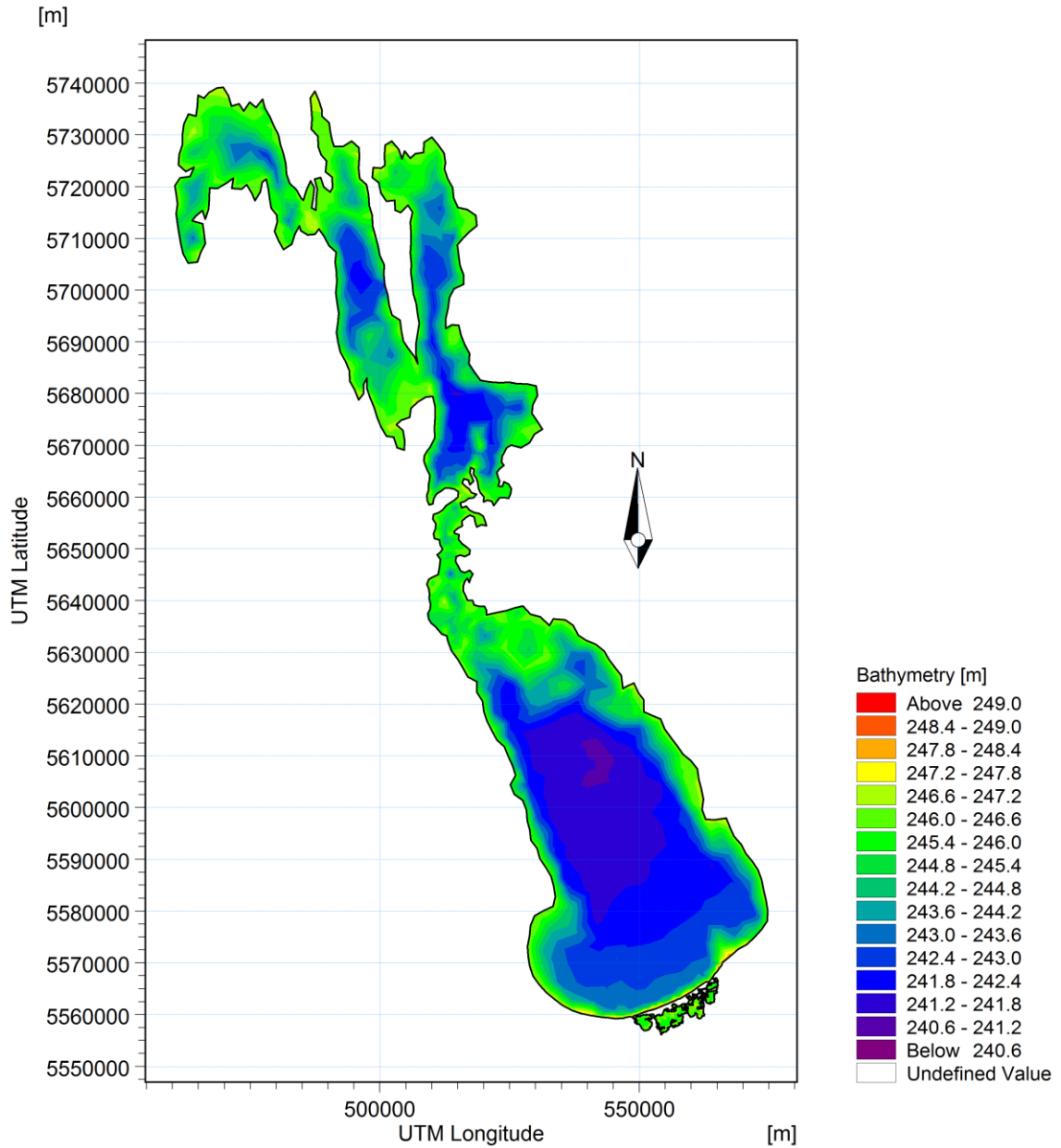


Figure 4:6 – Full Bathymetric Domain

Since Delta Marsh is a prairie wetland, its footprint can change considerably between extreme water levels (as observed during the 2011 flood season). In order to allow for these expansions and contractions, the overbank area must be included in the domain. This was not done in this study (as apparent in Figure 4:7) for three reasons: flood modelling is not the focus of this thesis; the contour data provided by DUC is lower resolution than the

bathymetry, and the model simulated erroneous flowpaths; modelling the overbank area tripled run-time. Extremely narrow channels and small bay features were also excluded, as they increased run-time and likely have little impact on marsh hydrodynamics.

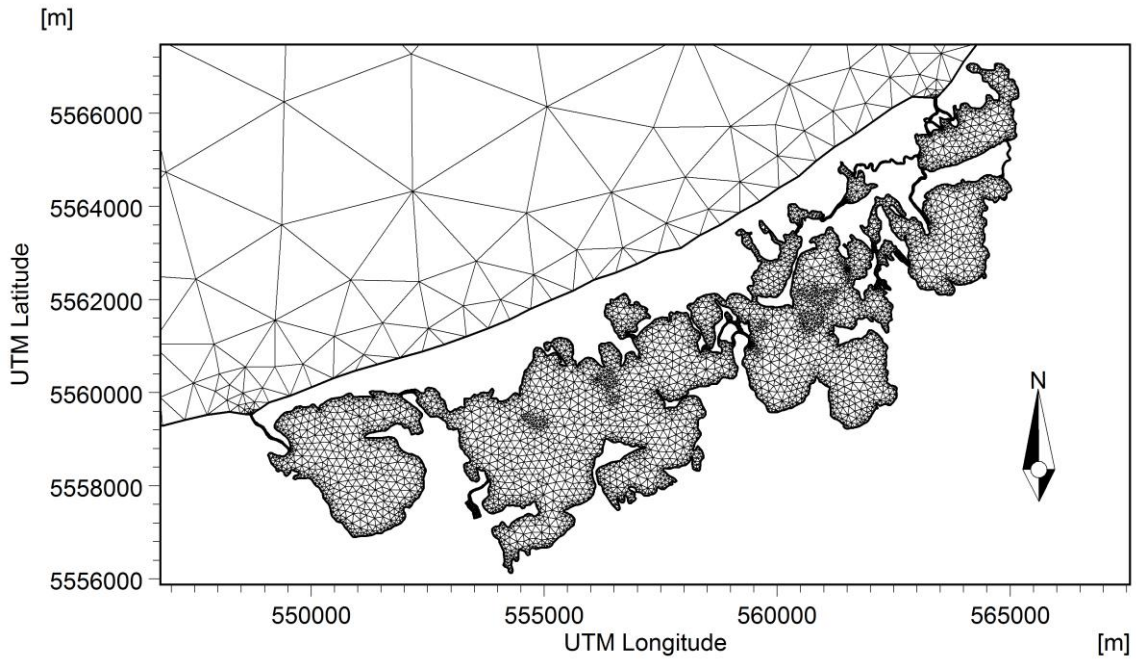


Figure 4:7 – Bathymetric Mesh: Delta Marsh and South Lake Manitoba

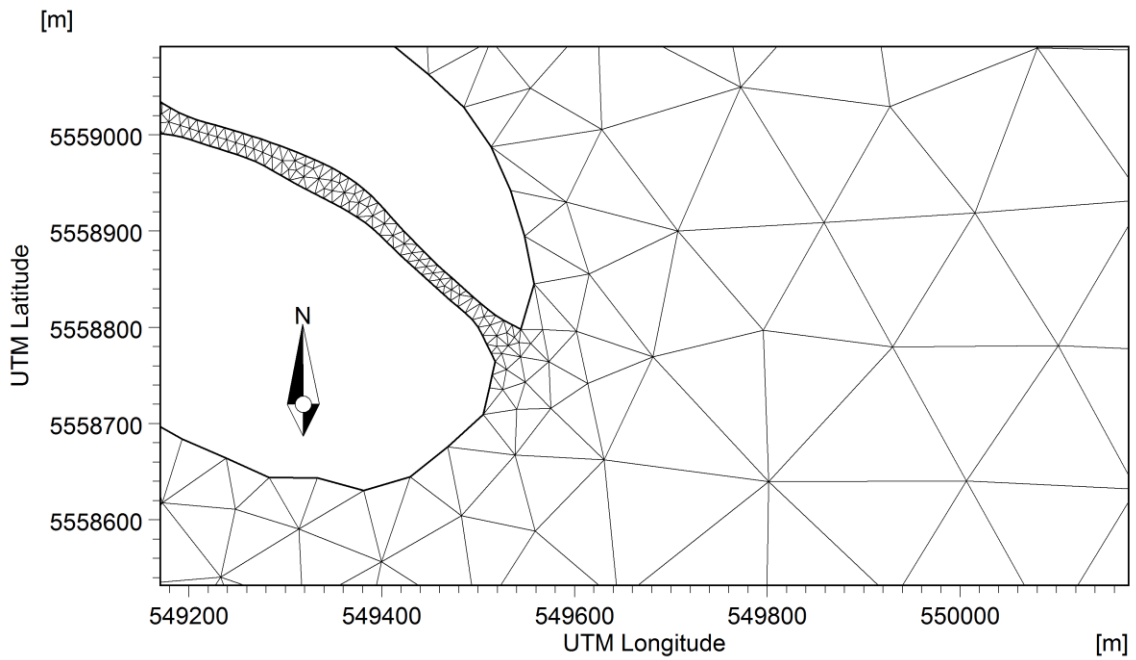


Figure 4:8 – Bathymetric Mesh: Delta Channel at Northwest Cadham Bay

Despite the coarse mesh, the geometry of the lake certainly influences its behaviour. The Narrows severely impede flux between the north and south basins; seiching along the southern edge of the north basin will not cause an immediate rise in water level at the northern edge of the south basin, or vice versa (Malenchak 2004). Figure 4:9 shows the change in simulated basin retention as the model domain becomes finer and more detailed. 24-hour, 40 km/h north winds were applied to two lake meshes. The first is quite coarse, with little detail along the boundary or at The Narrows, and consisting of uniformly sized elements. The second is more detailed, and is composed of relatively smaller elements near The Narrows. Note that the detailed mesh reasonably simulates seiching at The Narrows, while the coarse mesh allows water to pass between basins with little resistance. The model simulated WSEs at Westbourne and Steep Rock much more realistically when the finer mesh was used as the domain.

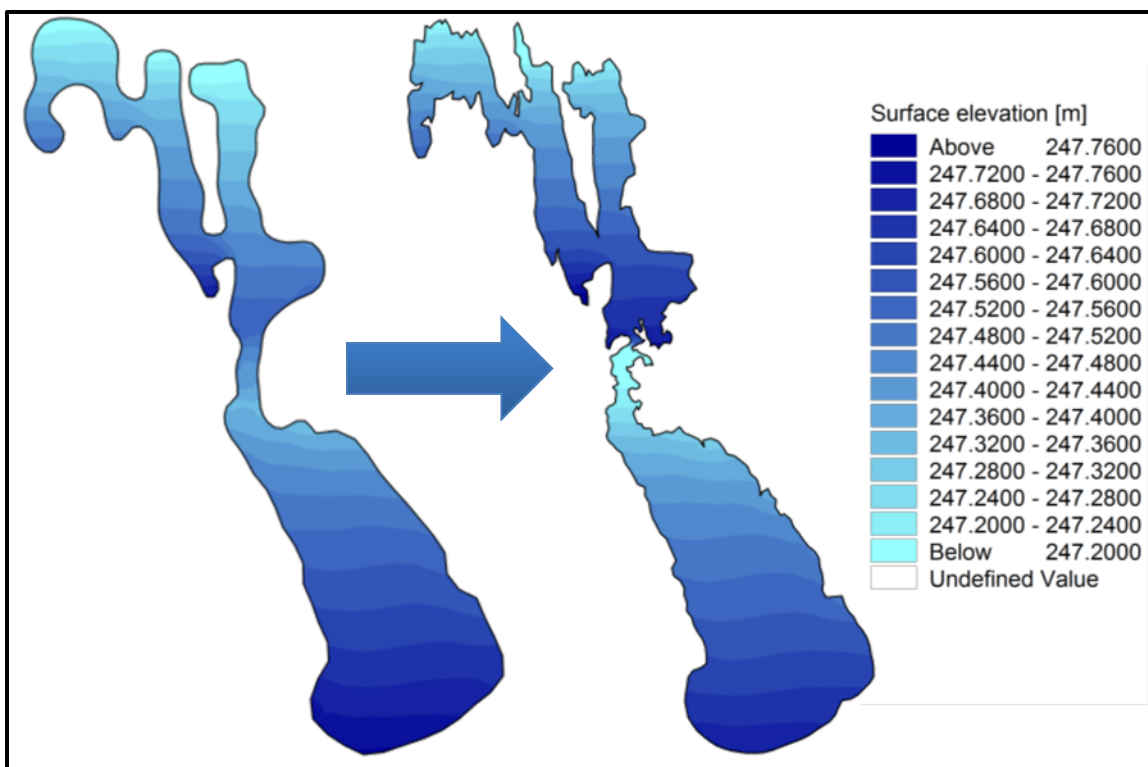


Figure 4:9 – Development of the Lake Manitoba MIKE 21 Domain

4.3.2. Time

In order to capture as much of the open water season as possible, all simulations ran from May 1 to October 31. Model spin-up begins on April 30 of the simulation year. Preliminary testing showed that spin-ups of one month, one week, three days, and one day all yielded comparable results for May 1. The output time-step was set to five minutes. This provided high-resolution output data while limiting the size of the output files. Note that this is different from the computation time-step, which is calculated internally to provide numerical stability at the smallest triangular domain element. Certain locations within the marsh required very small elements in order to keep the model stable, and this had a huge impact on run-time; a simulation over the full domain has a run time over 300 times the length of a simulation over the Lake Manitoba domain alone.

4.3.3. Solution Technique

MIKE 21 can perform high-order or low-order spatial discretization and time integration (as detailed in Section 3.1.2). The supporting literature recommends that high-order approach be selected for simulating flow-governed processes (DHI 2012c). Unfortunately, the high-order approach quadruples run time. Both methods were tested during model setup, and outputs were virtually identical. Thus, low-order discretization was selected in order to keep the calibration and simulation schedule manageable.

A critical Courant-Friedrichs-Lewy (CFL) number must be set in order to identify model instability. Instead of the theoretical value of 1.0, the threshold was set to 0.8 to account for errors in CFL number estimation (DHI 2012c). This proved useful in diagnosing geometry-related instability during domain setup.

4.3.4. Boundary Conditions

The main motivation behind combining the lake and marsh domains (other than simplifying model operation) was to eliminate instability along the marsh boundary. When the model is combined, water is free to flow between the lake and marsh. When operated separately, the marsh model requires the water level at the mouths of Delta and Clandeboye channels. These specified level boundary conditions are inherently prone to causing model instability, and the CFL numbers at the boundaries would often rise early in simulations. When combined, only land and specified discharge boundary conditions are required.

The land boundary was specified as zero normal velocity, which assumes the full-slip boundary condition. In reality, the river- or lake-bank is a no-slip boundary, but this condition cannot be assumed due to the coarse resolution of the model in the narrow channels. Numerically, a large portion of the channel would be considered no-slip, and this was observed to result in severe underestimates of channel discharge.

Two specified discharge (Dirichlet) boundaries were established at the mouths of Fairford River and Waterhen River. Daily discharge measurements were taken from the WSC gauges at “Fairford River near Fairford” (05LM001) and “Waterhen River near Waterhen” (05LH005). Data gaps were filled by means of linear interpolation. Fairford River is a point of outflow from Lake Manitoba, so all scalar discharge values were set negative, which MIKE 21 interprets as outflow. The Portage Diversion, Whitemud River, Portage Creek, and the Delta Marsh Watershed also contribute to overall storage, but these were input as point sources, as described in Section 4.3.5.

4.3.5. Sources

The mouths of the Portage Diversion and Whitemud River are relatively narrow, and thus they were included as simple (zero velocity) point sources, instead of as boundaries. Daily inflow recordings were taken from the WSC gauges at “Portage Diversion near Portage la Prairie” (05LL019) and “Whitemud River at Westbourne” (05LL002).

4.3.6. Initial Conditions

The elevation and horizontal velocity of water at each element must be defined for the first time-step (April 30, 12:00 AM). Since there are no estimates of velocity across the lake and marsh, initial velocity was set to zero across the domain. WSE measurements exist only at the following WSC gauges: “Lake Manitoba at Westbourne” (05LL012) in the south basin, and “Lake Manitoba at Steep Rock” (05LK002) in the north basin. Since there is no reliable way to estimate the instantaneous seiching conditions in both basins, the WSE across all elements was set to the average of the two measurements.

4.3.7. Wind Forcing

This is the first of several meteorological inputs to the hydrodynamic model. Since it is suspected that wind-induced setup is a major force governing marsh flux, it was imperative to select a meteorological data source that was representative of the wind experienced over Lake Manitoba (particularly the southern basin). Hourly wind magnitude and direction recordings were collected from a series of nearby Environment Canada (EC) meteorological stations and gap-filled by means of linear interpolation. The measurements were adjusted to represent wind magnitudes over the large lake and small marsh, as follows (United States Army Corps of Engineers 2003):

For winds over a long fetch (>16 km, Lake Manitoba):

$$U_w = R_L U_L \quad (4:1)$$

$$R_L = \begin{cases} -6.5(10)^{-6}U_L^3 + 9.6(10)^{-4}U_L^2 - 0.053U_L + 2.11, & U_L \leq 66.6 \frac{\text{km}}{\text{hr}} \\ 0.9, & U_L > 66.6 \frac{\text{km}}{\text{hr}} \end{cases} \quad (4:2)$$

Where:

- U_w is the magnitude of wind speed over water [km/hr]
- U_L is the magnitude of wind speed over land, measured by EC [km/hr]
- R_L is wind adjustment factor, [-] (Resio and Vincent 1976)

For winds over a short fetch (<16 km, Delta Marsh):

$$U_w = 1.2U_L \quad (4:3)$$

Adjusted data from multiple sources were tested in the model in succession until it was observed that the data from “Oak Point Marine” (504K0NM) forced seiching patterns that matched the records at the locations of both the Westbourne and Steep Rock WSC gauges.

4.3.8. Precipitation & Evaporation

In order to estimate changes in storage over the simulation period, representative estimates of precipitation and evaporation were required. Unfortunately, lateral inflow (particularly snowmelt runoff) can contribute unquantified but potentially massive volumes of water to Lake Manitoba. These volumes must be quantified if the hydrodynamic model is to be useable. This was the first step of calibration, as discussed in

section 5.2.1. Once estimates of precipitation and evaporation were made, a spatially uniform unit influx was added over the domain in order raise the level at Westbourne and Steep Rock to the corresponding WSC measurements.

Daily precipitation measurements were collected from several nearby EC stations. Hourly temperature, relative humidity, and wind magnitude measurements were collected from the same stations and linearly gap-filled. Hourly evaporation rates were estimated using the Penman method, as per Dingman (2002):

$$E = \max(E_{calc}, 0) \quad (4:4)$$

$$E_{calc} = \frac{\Delta(\phi_p + \phi_L) + \gamma K_e \rho_w \lambda_v v_a e_a^* (1 - RH)}{\rho_w \lambda_v (\Delta + \gamma)} \quad (4:5)$$

Where:

- E is the non-negative Penman-estimated evaporation rate [m/day]
- E_{calc} is the calculated Penman-estimated evaporation rate [m/day]
- Δ is the ratio of saturation vapor pressure to temperature [kPa/K]
- ϕ_p is the net shortwave radiation [MJ/m²day]
- ϕ_L is the net longwave radiation [MJ/m²day]
- γ is the psychrometric constant, equal to 0.066 [kPa/K]
- K_e is the vertical uplift efficiency coefficient [kPa⁻¹]
- ρ_w is the density of water, equal to 1000 [kg/m³]
- λ_v is the latent heat of vaporization [MJ/kg]
- v_a is the wind speed, measured by EC [m/day]
- e_a^* is the ratio of saturation vapor pressure to temperature [kPa/K]
- RH is the relative humidity, measured by EC [–]

Defined as:

$$\Delta = \frac{2508.3}{(T + 237.3)^2} e^{\left(\frac{17.3T}{T+237.3}\right)} \quad (4:6)$$

$$\phi_p = 0.0864(1 - \alpha)\phi_{so} \left(a_2 + b_2 \frac{n}{N} \right) \quad (4:7)$$

$$\phi_{so} = I_o (\sin \theta \sin \delta + \cos \theta \cos \delta \cos H) \quad (4:8)$$

$$\delta = 23.45^\circ \cos \left(\frac{360^\circ}{365} (172 - DOY) \right) \quad (4:9)$$

$$H = (t_h - 12)(15^\circ) \quad (4:10)$$

$$\phi_L = (\varepsilon_{at} - 1)\varepsilon_w \sigma (T + 273.2)^4 \quad (4:11)$$

$$\varepsilon_{at} = 1.72 \left(\frac{e_a}{T + 273.2} \right)^{1/7} (1 + 0.22C^2) \quad (4:12)$$

$$e_a = e_a^* RH \quad (4:13)$$

$$e_a^* = 0.611 e^{\frac{17.3T}{T+237.3}} \quad (4:14)$$

$$K_e = 1.69 \times 10^{-9} A_L^{-0.05} \quad (4:15)$$

$$\lambda_v = 2.50 - 0.00236T \quad (4:16)$$

Where:

- T is the air temperature, measured by EC [°C]
- α is the albedo of the water surface, equal to 0.06 [–]
- ϕ_{so} is the incident solar radiation [W/m²]
- a_2 & b_2 are the Gray (1970) constants, set to 0.25 and 0.59, respectively [–]
- $\frac{n}{N}$ is ratio of bright sunshine hours to the maximum possible hours of sunshine [–]
- I_o is the solar constant, equal to 1368 [W/m²]
- θ is latitude of the centroid of the domain, equal to 50.9 [°]
- δ is the solar declination [°]
- H is the local solar hour-angle [°]

- DOY is the Julian day of year (e.g. February 1 = 32) [day]
- t_h is the standard time (not adjusted for daylight savings) [hr]
- ε_{at} is the effective emissivity of the atmosphere [–]
- ε_w is the emissivity of water, equal to 0.97 [–]
- σ is the Stefan-Boltzmann constant, equal to 4.9×10^{-9} [MJ/m² day]
- e_a is the vapor pressure of the overlying air layer [kPa]
- C is the cloud-cover fraction [–]
- A_L is the area of Lake Manitoba, equal to 4624 [km²]

Precipitation and evaporation estimates from multiple sources were tested in the model in succession (with the adjusted Oak Point wind data). It was observed that averaged data between “Dauphin” (5040689) and “Dauphin CS” (5040681) simulated storage patterns that matched the records at the locations of both the Westbourne and Steep Rock WSC gauges for 1995 (Figure 4:10), a year that the lake received virtually no snowmelt inflow. Data from the two Dauphin sources were used again for 2013 and 2014 simulations.

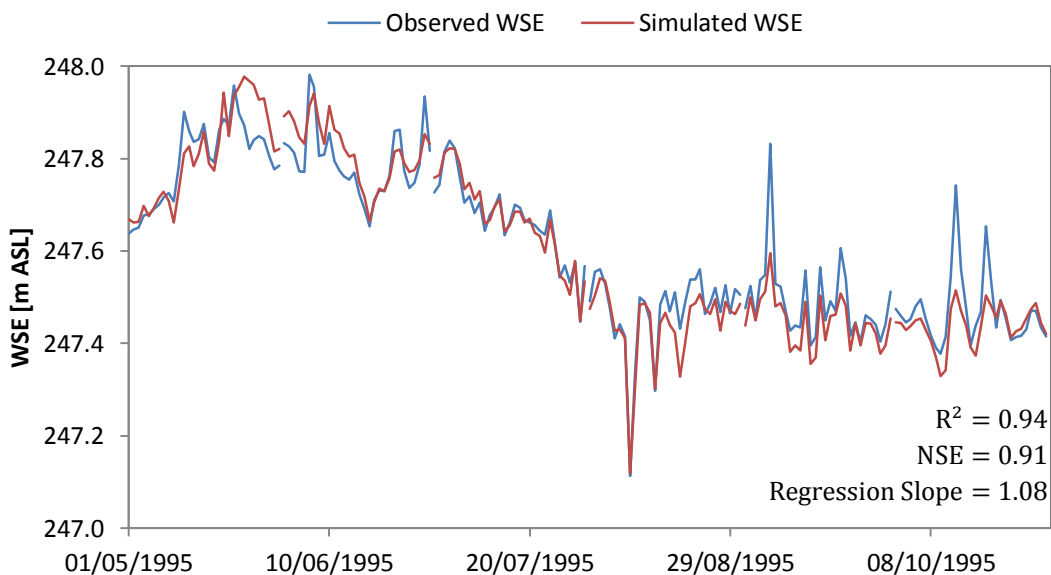


Figure 4:10 – Assessing Storage: Simulated WSE at Westbourne, 1995

Hydrologic controls like precipitation and evaporation are extremely prone to uncertainty, and can limit the accuracy and usefulness of hydrologic/hydraulic models. The spatial variability of precipitation and evaporation, precipitation gauge under-catch, and uncertainties in the Penman method are but a few of the sources of uncertainty in storage estimation. Luckily, this uncertainty can be lumped into the storage closing term, reducing the impact on the hydrodynamic model.

4.3.9. Coriolis Forcing

The Coriolis Forcing subcomponent accounts for the deflection of particles moving over the rotating surface of the Earth. Since Lake Manitoba covers a relatively large area, Coriolis forcing was considered varying in domain. This is the only required specification; calculations are performed internally based on the geography of the modelling domain.

4.3.10. Unused Hydrodynamic Subcomponents

The following hydrodynamic subcomponents were not included:

- Depth Correction: bathymetry was considered constant over the simulation period.
- Density: since vertical mixing was not considered, water density was set constant.
- Ice Coverage: ice modelling is not within the scope of this research.
- Tidal Potential: Delta Marsh is an inland (non-tidal) coastal wetland.
- Wave Radiation: wind-wave modelling is not within the scope of this research
- Structures: this subcomponent is computationally intensive and very prone to instability. Since the goal of calibration is to simulate fluxes into and out of the marsh, modelling the carp exclusion structures was not a necessity; channel flow was instead controlled by adjusting bed roughness.

4.3.11. Transport

The transport submodule can be used to simulate the advection and dispersion of contaminants or tracers across the model domain. In this thesis, it was used to track the movement of water from different sources. This allowed for deeper analysis of the marsh hydrodynamics. To illustrate, consider a common question regarding Delta Marsh:

How does the magnitude of marsh discharge increase with an increase in the capacity of the Portage Diversion?

Relying only on the results from the hydrodynamic module, an answer to this question would be limited to comparing discharges (i.e. an “x” increase in diversion capacity corresponds to a “y” increase in marsh discharge). With the transport module enabled, the questions can evolve, and the answers can have more depth:

How much of the incoming volume is water directly from the Diversion, and how much is Lake Manitoba water?

When Diversion water enters the marsh, how far does it spread before the lake and marsh begin to drain?

Does more Diversion water enter Delta Marsh through Delta Channel, which is nearer, or Waterhen Channel, which is larger?

This increased insight was a benefit to all simulation scenarios, from interpreting the baseline conditions to simulating changes in flood infrastructure capacity. Unique tracers were added to the Portage Diversion, Whitemud River, Waterhen River, and watershed sources. To make the tracers behave exactly like water, horizontal dispersion coefficients and decay rates were set to zero. Tracers were added at a constant concentration of 1 unit per cubic metre of inflow. This allowed for source-separation analysis in two ways. First, volume fluxes were calculated for each source across a transection. For example, the cumulative influx of Portage Diversion water through Delta Channel was estimated in comparison to the total cumulative discharge. Second, the simulated concentration in an element is equal to the proportion of the total volume in that element that is made up of water from a given component. For example, if the concentration of the Portage Diversion tracer at an element in Cadham bay is 0.4, that means that, for that time-step, 40% of the water in that element originated from the Portage Diversion.

4.4. MIKE 11: Routing Model Development

The 1D hydrodynamic module was used to model channelized runoff in the Delta Marsh Watershed. Recall the dense stream network throughout the watershed (Figure 2:5). It would be possible to include all of these channels in the model, but this would require:

1. A stream network joining all channels; the network would have to extend into the marsh, being fed by each watershed channel, and controlled at the lake boundaries
2. Detailed and well-spaced cross-sections along each channel and within the marsh, accounting for areas that are filled in with sediment or dense vegetation
3. Calibration of each channel to discontinuous discharge measurements

Beyond the relatively large scope, this approach introduces many potential sources of error. Recall the observations regarding these channels: many do not convey flow toward East Marsh, and many do not even have an open outlet. In fact, Portage Creek is the only watershed channel that flows into East Marsh, that is open at the outlet, and that carries any significant amount of water (Badiou, pers. comm. 2014, Schellenberg, in progress). Therefore, the adopted approach was to model Portage Creek only – all other runoff hydrographs were added to the MIKE 21 model as point sources generated directly by MIKE SHE (as described in Section 4.3.5).

Numerical runoff routing is a hydraulic approach to answering a hydrologic question. As such, the MIKE 11 model was created cooperatively. This thesis addresses the setup of the channel network and cross-sections, detailed below. The setup of the boundary conditions and routing parameters, model calibration, and model operation were performed by Schellenberg (in progress), and are not discussed here.

Cross-sections were defined on and extracted from a multi-source digital elevation model (DEM) produced for the MIKE SHE model by Schellenberg (in progress). The DEM, shown in Figure 4:11, includes high-resolution data from a recent LiDAR survey, marsh contours from DUC, and low-resolution data from GeoBase. Commentary on the formation of the DEM and on the reliability of each source is provided by Schellenberg (in progress).

Cross-sections were cut from the LiDAR and contour sources in ArcMap (Figure 4:11, Figure 4:12a). The first step in establishing the channel geometry was to trace the creek along its centreline, from the headwaters to the outlet (Figure 4:12b). Next, low flow and

zero flow extents were traced on both banks (Figure 4:12c). The levee alignments indicate the extents of flow and storage, while the overbank alignments separate the left overbank, right overbank, and channel segments of each cross-section. These alignments are estimated visually based on the DEM, and can later be adjusted at each cross-section.

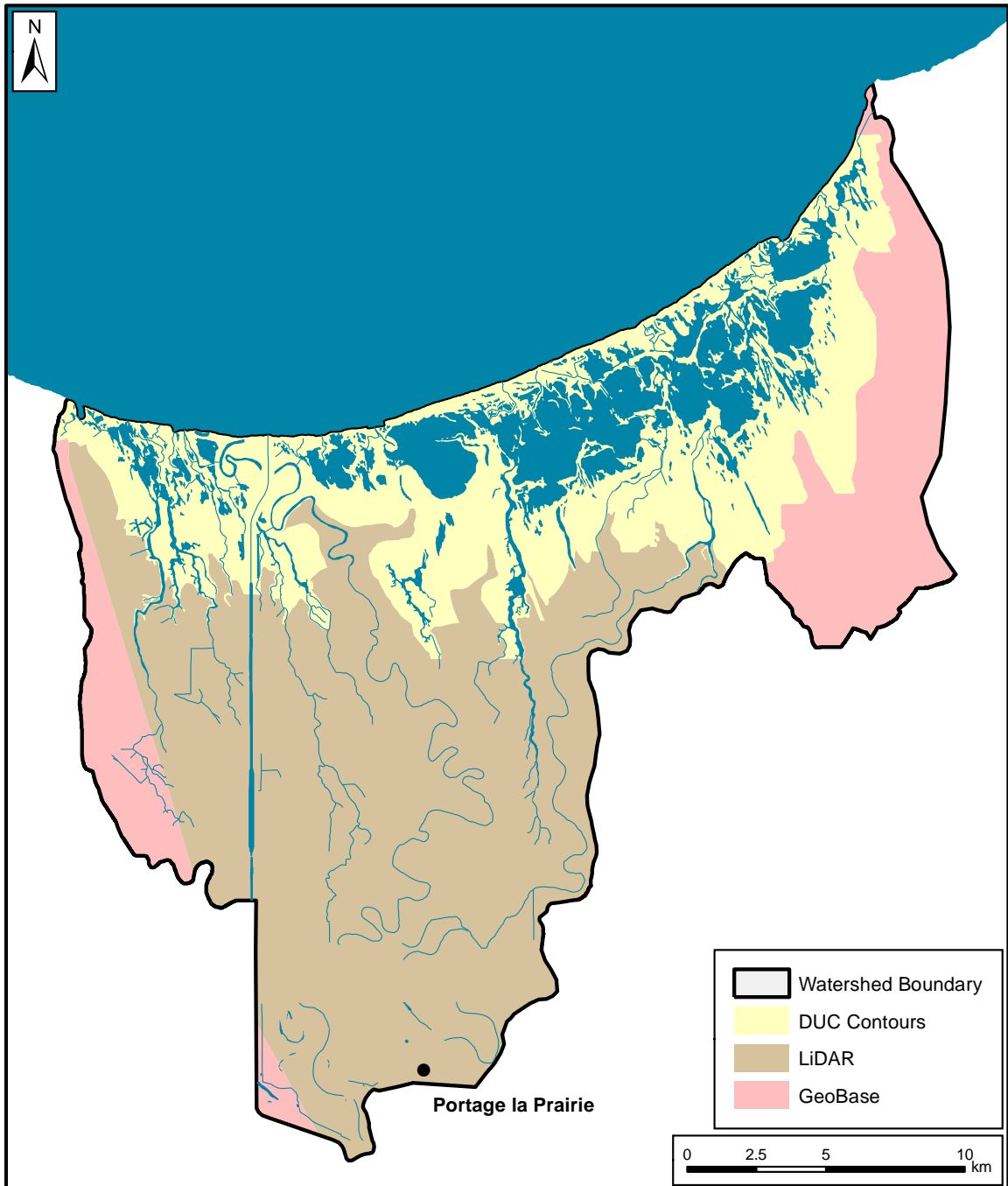


Figure 4:11 – Delta Marsh Watershed: DEM Sources (Schellenberg, in progress)

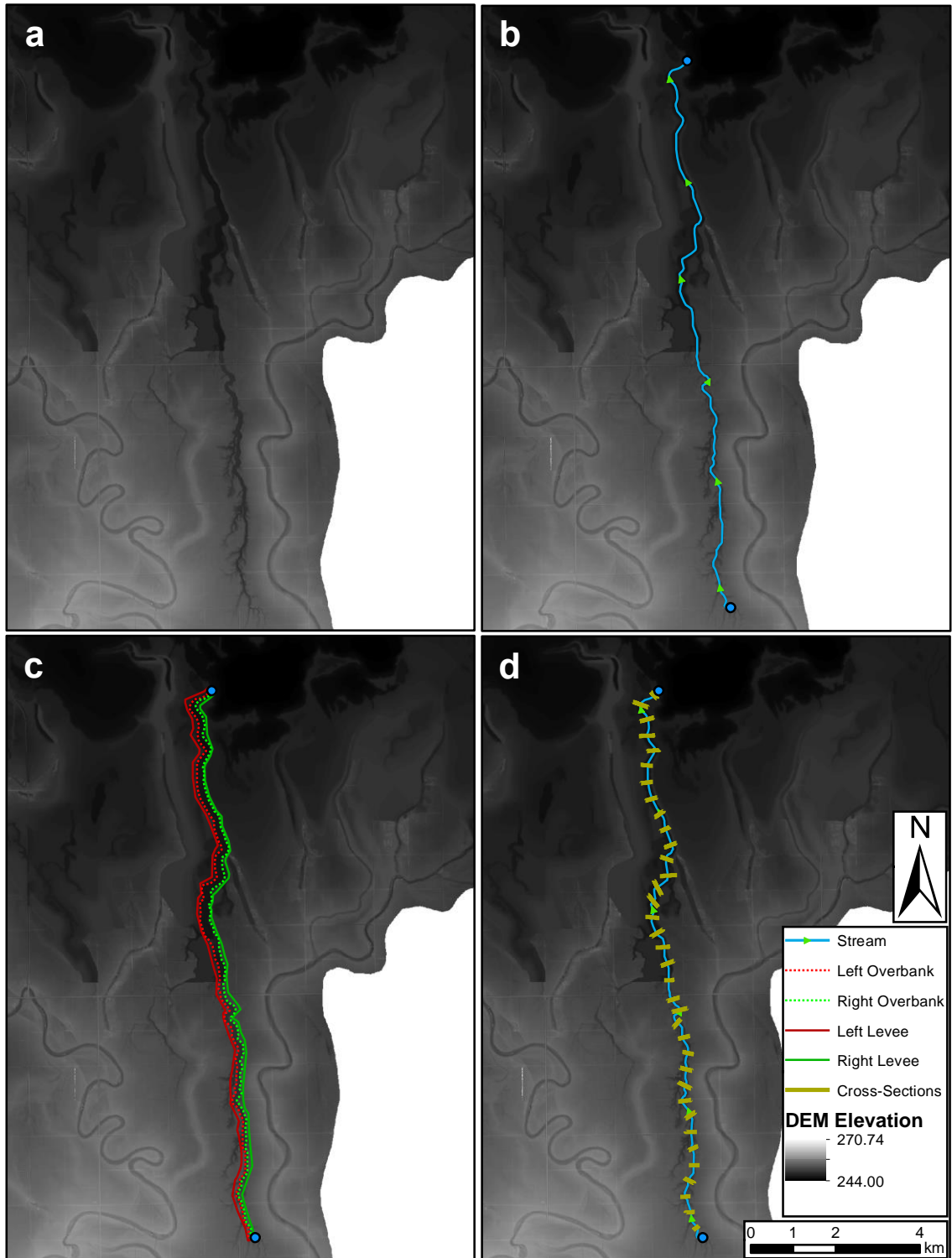


Figure 4:12 – Development of 1D Routing Network for Portage Creek

a) DEM, prior to stream delineation; b) Stream, traced along centreline; c) limits of the levees and overbanks, estimated visually; d) Cross-sections, spaced automatically, perpendicular to stream

Next, 500 m wide cross-sections were drawn automatically at a streamwise spacing of 400 m (Figure 4:12d), perpendicular to the stream. The channel and overbank chainages for each cross-section are determined automatically based on the traced stream and alignment lines. All cross-sections were clipped to the left and right levee alignments before being exported to MIKE 11. Figure 4:13 shows a typical cross-section as viewed in the MIKE 11 cross-section editor (with the downstream direction pointing into the page, by convention). The black points represent elevation points taken from the DEM during extraction, and the channel geometry is defined by the black line connecting these points. The green vertical lines represent the left and right overbank alignments. At this point, the cross-sections were handed off for inspection, calibration, and operation by Schellenberg (in progress).

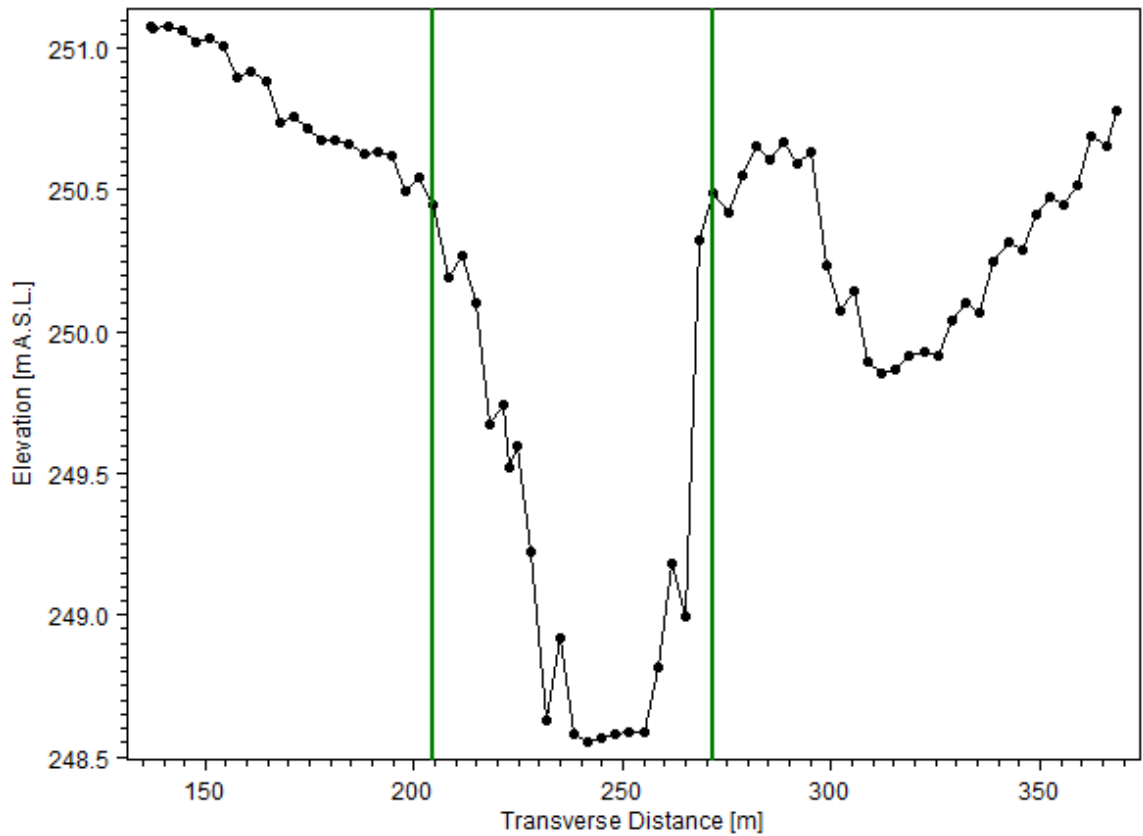


Figure 4:13 – Typical MIKE 11 Cross-Section: Portage Creek @ Chainage 1200 m

4.5. Simplified Methods of Discharge Estimation

Section 3.2 details the limitations of existing discharge measurement and estimation techniques in the context of two-directional wetland flow. At best, the velocity index method (VIM) can be used to estimate continuous discharge in a channel. This requires the use of an ADCP and a submersible ADV, which come at considerable expense. This section introduces three methods that attempt to replicate the VIM results using nearby water elevations, which can be measured at reasonably low expense. These methods are developed and tested for the first time in this thesis. If any of these methods prove useful, an ADCP and ADV can be moved between multiple channels across an open-water season, providing partial hydrographs for each site. The applicable method(s) could then be calibrated to the partial hydrograph at each channel and extrapolated to estimate complete hydrographs. Moreover, if the calibrated methods appear to work from year to year, re-calibration will not be necessary. This can considerably increase the ratio of data received to dollars spent.

The discharge through a coastal wetland channel is likely governed by wind-driven fluctuations in water level at the lake-wetland interface. This is illustrated for a general coastal wetland in Figure 4:14. Under stagnant conditions, the water surface across the domain (Figure 4:14a) is horizontal (Figure 4:14b). Thus, the friction slope through the channel (S_f) is zero, and there is no flow. If wind is applied across the surface of the lake toward the wetland, wind set-up causes water to pile up against the lakeside mouth of the channel (Figure 4:14c). This forces S_f to be positive, driving water into the wetland. If the wind direction is reversed, wind set-up causes a drawdown at the lakeside mouth of the channel (Figure 4:14d). This forces S_f to be negative, pulling water out of the wetland.

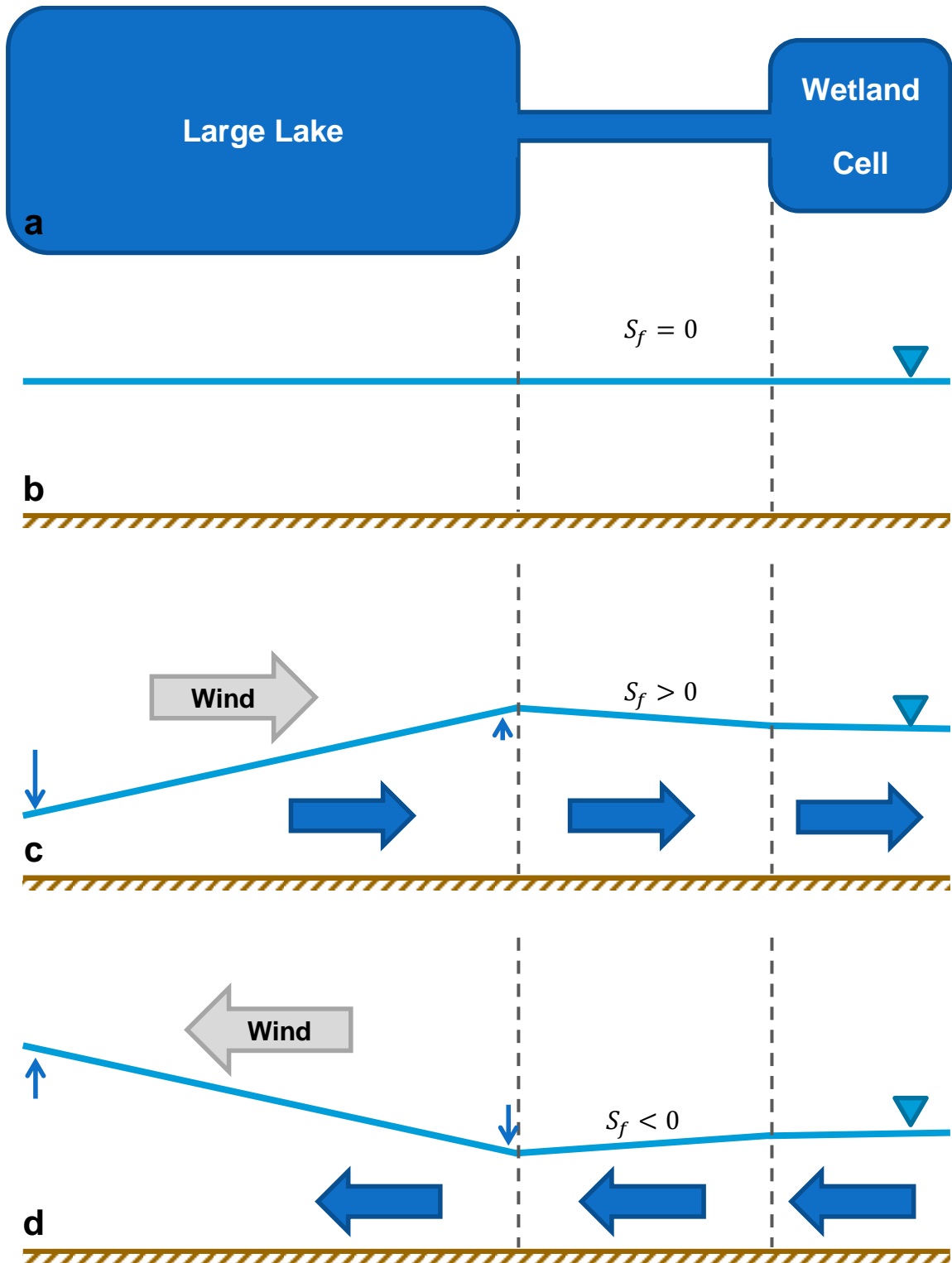


Figure 4:14 – Generalized Two-Directional Wetland Channel Flow

- a) Plan view of a large lake connected to a wetland cell; b) Profile view of stagnant water surface condition; c) Profile view of setup-inflow condition; d) Profile view of drawdown-outflow condition

In addition, changes in storage in the lake or marsh will influence S_f . For example, rapid influx to Lake Manitoba from the Portage Diversion causes a lakeside rise in water level at the marsh boundary similar to a sustained north wind. These ideas form the basis of the three proposed methods. The regressed slope Manning method (RSMM; Section 4.5.1) estimates the friction slope across a channel using measured WSEs at either end of the channel. The regressed level Manning method (RLMM; Section 4.5.2) estimates the friction slope using measured changes in WSE over time near the channel. The polynomial regression method (PRM; Section 4.5.3) estimates channel discharge directly using measured changes in WSE over time second-hand data near the channel. These methods will be tested at Delta Channel (Figure 4:15) and Waterhen Creek (Figure 4:16), where VIM discharges are required for calibration and validation of the hydrodynamic model. Table 4:1 lists the data sources used for each method.

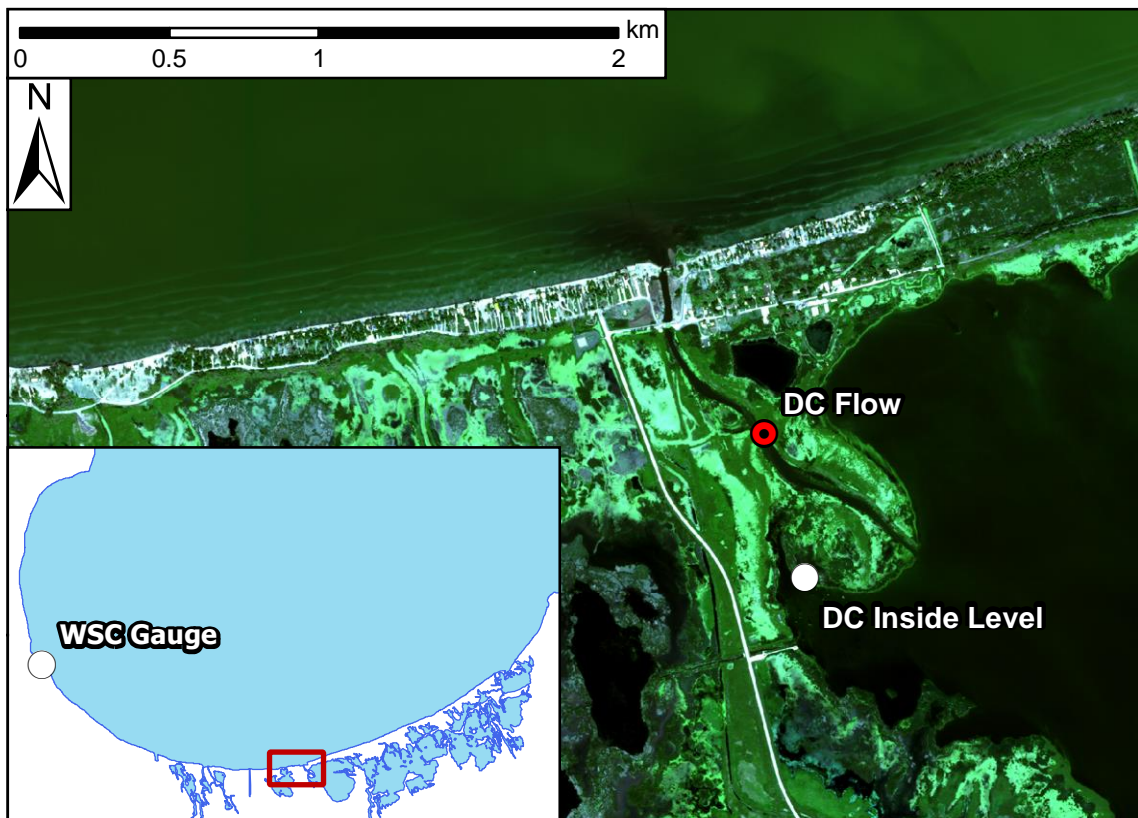


Figure 4:15 – Discharge Estimation: Delta Channel & WSC Measurement Locations

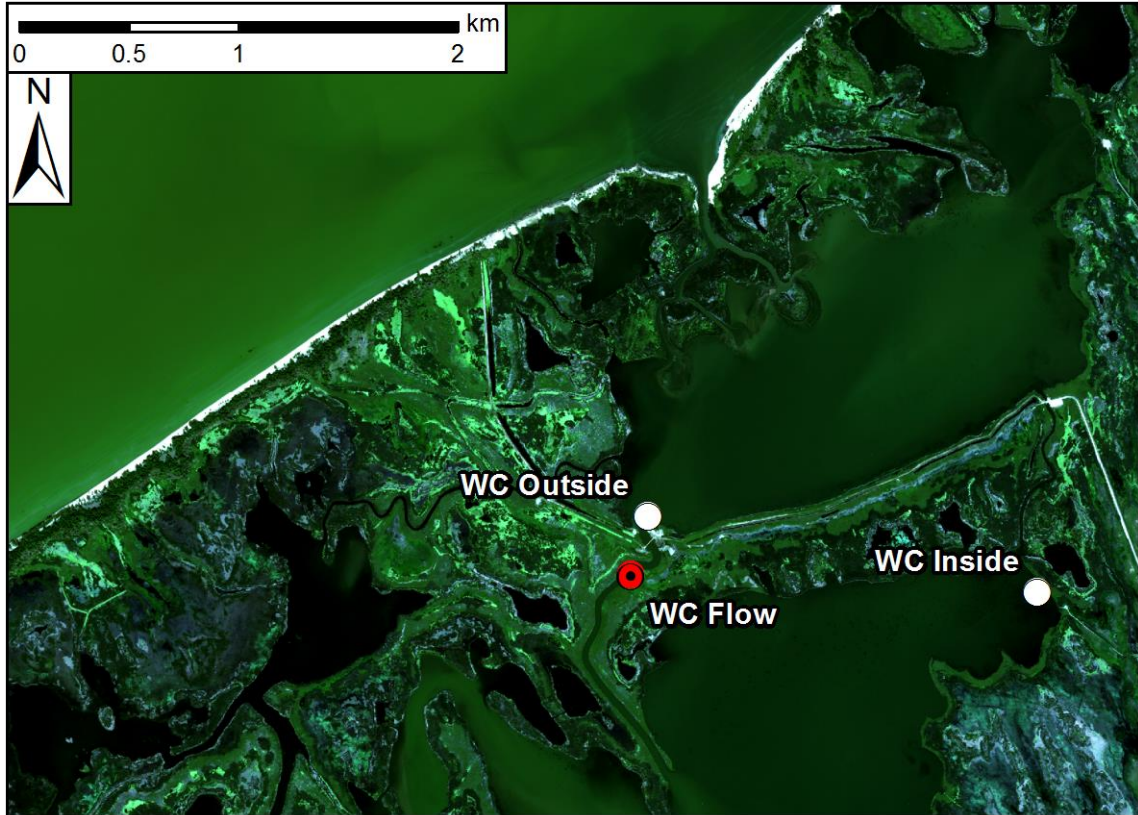


Figure 4:16 – Discharge Estimation: Waterhen Creek Measurement Locations

Table 4:1 – Discharge Estimation: Data Sources for Method Testing

Method	Location	Gauge(s) Used	
RSMM	Delta Channel	DC Inside	WSC Gauge #05LL012 ^(See Note)
	Waterhen Creek	WC Inside	WC Outside
RLMM	Delta Channel	DC Inside	
	Waterhen Creek	WC Outside	
PRM	Delta Channel	WSC Gauge #05LL012	
	Waterhen Creek		

Note that there was no gauge installed at the lakeside mouth of Delta Channel during the study period. The WSC Gauge (20 km away) was used instead.

4.5.1. Regressed Slope Manning Method (RSMM)

The Manning formula (Equation 3:2), can be simplified as follows:

$$Q = k_n \frac{A^{5/3}}{P^{2/3}} \psi \quad (4:17)$$

$$\psi = \frac{\sqrt{S_f}}{n} \quad (4:18)$$

Where:

- ψ is the uncertainty term $[L^{1/3}T^{-1}]$

Note the grouping of terms in Equation 4:17. The desired unknown (Q) is isolated. Next, the terms which are known or can be estimated are grouped; k_n is set based on the chosen unit system, while A and P can be estimated from measured depth and channel geometry, using a similar approach as the calibration of the VIM. The equation ends with the lumped uncertainty term (ψ); S_f cannot be measured directly, and is likely changing all the time, and n cannot be measured directly; it is a calibration term, and may be changing with changes in flow depth and bed condition.

If ψ can be reasonably estimated as a function of available WSE measurements, it can be combined with A and P to provide estimates of channel discharge. This can be attempted in two ways. The first approach is the regressed slope Manning method (RSMM). This method has the strongest physical basis. The first iteration of the RSMM ψ formulation was as follows:

$$\psi_t = \frac{\sqrt{S_{f,t}}}{n_t} \cong \alpha_1 \frac{\sqrt{\frac{(y_{out,t} - y_{in,t} - \beta_1)}{L}}}{(y_{in,t} - \beta_2)^{-1/3}} + \alpha_2 \psi_{t-1} - \beta_3 \quad (4:19)$$

Where:

- ψ_t is the estimated uncertainty term at time t [$L^{1/3}T^{-1}$]
- y_{out} & y_{in} are the outside and inside water levels, respectively [L]
- L is the streamwise length of the channel [L]
- α_1 is the coefficient of the estimated uncertainty term, to be calibrated [T^{-1}]
- α_2 is coefficient of the model tracking term, to be calibrated [–]
- β_1 is the slope bias correction term, to be calibrated [L]
- β_2 is the roughness bias correction term, to be calibrated [L]
- β_3 is the uncertainty bias correction term, to be calibrated [$L^{1/3}T^{-1}$]
- $\sqrt{}$ is the shorthand notation for a directional radical; the sign on the exterior of the radical is equal to the sign of the interior term (x , below). The magnitude of the radical is the root of the absolute value of the term. The full notation is as follows:

$$\sqrt{x} = \frac{x}{\sqrt{|x|}} \quad (4:20)$$

Consider the components of Equation 4:19. The numerator of first term on the right hand side represents an approximation of the $\sqrt{S_f}$ term. Note that L is a constant, and can thus be extracted from the radical and lumped into the α_1 coefficient. The denominator of the first term represents an approximation of the n value. Preliminary calibration showed that β_2 consistently converged to 0, and the model as a whole was insensitive to this term. This implies that either bed roughness does not change noticeably throughout the season, or changes in roughness are not correlated to changes in depth. Thus, the denominator term was removed. This simplified the model at no detriment to accuracy. The second term is the model tracking term. The utility in this term is that it gives insight into the

“independence” of a simulation; smaller coefficients imply less reliance on a numerical constraint, indicating confidence in the results. Finally, the β_3 term consistently converged to zero. This is likely because adequate bias correction is performed by the β_1 term. The β_3 term was removed from the equation. Thus, Equation 4:19 simplifies to its final form, as follows:

$$\psi_t = \alpha_1 \sqrt[3]{y_{out,t} - y_{in,t} - \beta_1} + \alpha_2 \psi_{t-1} \quad (4:21)$$

Where:

- α_1 is the coefficient of the estimated uncertainty term, to be calibrated $[L^{-1/6}T^{-1}]$

4.5.2. Regressed Level Manning Method (RLMM)

The second approach to estimating ψ is the regressed level Manning method (RLMM). Similarly to the RSMM, this method estimates A and P using depth and channel geometry, and lumps the unknowns. The simplification in this approach is that only one depth gauge is used to estimate ψ . Instead of estimating the instantaneous slope across the channel, the RLMM attempts to estimate ψ using changes in depth over time. Stepwise regression is used to estimate ψ using a large number of possible linear parameters, as shown in Equation 4:22, below:

$$\psi_t = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{bmatrix}^T \begin{bmatrix} x_{1,t} \\ x_{2,t} \\ \vdots \\ x_{i,n} \end{bmatrix} + \beta \quad (4:22)$$

Where:

- $\alpha_{1...n}$ are the coefficients of the RLMM parameters, to be calibrated $[L^{-2/3}T^{-1}]$
- $x_{1...n}$ are the RLMM parameters (Table 4:2) [L]
- β_1 is the RLMM intercept, to be calibrated $[L^{1/3}T^{-1}]$

These variables include the change in depth over different lengths of time, each lagged by different periods. A parameter matrix is shown in Table 4:2, with each parameter represented as a blue cell at the intersection of the level change and lag durations. Consider the 10-hour change, lagged 4 hours. When simulating ψ for August 14, 2014, at 23:00, this value would be equal to the change in level from 09:00 to 19:00 of the same day.

Table 4:2 – RLMM & PRM: Parameter Matrix

	0-hr lag	1-hr lag	2-hr lag	4-hr lag	6-hr lag
level					
1-hr change					
2-hr change					
3-hr change					
4-hr change					
5-hr change					
6-hr change					
8-hr change					
10-hr change					
12-hr change					
14-hr change					
16-hr change					
18-hr change					
20-hr change					
22-hr change					
24-hr change					
28-hr change					
32-hr change					
36-hr change					
40-hr change					
44-hr change					
48-hr change					

4.5.3. Polynomial Regression Method (PRM)

Finally, it may be possible to neglect A and P entirely. The polynomial regression method (PRM) attempts to estimate discharge directly using the same parameters as the RLMM, as shown in Equation 4:23. This is the least physically based method. However, since estimates of A and P are not required, depth measurements are not required directly at the channel. At Delta Marsh, this method used WSE data from WSC Gauge #05LL012: Lake Manitoba near Westbourne.

$$Q_t = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{bmatrix}^T \begin{bmatrix} x_{1,t} \\ x_{2,t} \\ \vdots \\ x_{n,t} \end{bmatrix} + \beta \quad (4:23)$$

Where:

- $\alpha_{1...n}$ are the coefficients of the PRM parameters, to be calibrated [L^2T^{-1}]
- $x_{1...n}$ are the PRM parameters (Table 4:2) [L]
- β_1 is the PRM intercept, to be calibrated [L^3T^{-1}]

5. Calibration

This chapter details the calibration of the 2D hydrodynamic model and the three proposed methods of discharge estimation, to measurements obtained during the 2013 field season. Accurate discharge estimates were required to calibrate the 2D model and the proposed discharge estimation methods, and were obtained using the velocity index method. The calibration and validation of the MIKE SHE and MIKE 11 models were performed by Schellenberg (in progress).

5.1. Velocity Index Method: Calibration

The velocity index method was applied to Delta Channel and Waterhen Creek for 2013 and 2014, as per the methodology described in Section 3.2.4. Recall that positive values denote flow into the marsh. The process is illustrated below for Delta Channel, 2014:

1. Collect continuous measurements of index velocity (V_i) and depth (d_i) using a submersible ADV (as described in Section 4.1.1)
2. Collect instantaneous measurements of discharge (Q_m), average velocity (\bar{V}_m), and flow area (A_m) using an ADCP (as described in Section 4.1.1)
3. Create an index-average velocity rating curve (Figure 5:1)
4. Create a depth-area rating curve (Figure 5:2)
5. Obtain estimates of \bar{V} and A across calibration period (Equations 3:19 and 3:20)
6. Multiply estimates of A and \bar{V} to obtain discharge (Q_{VIM}) (Equation 3:21)
7. Plot Q_{VIM} against Q_m and inspect; ideally, they should plot with a high coefficient of regression at a 1:1 slope (Figure 5:3)
8. If step 7 is successful, apply rating curves to entire measurement record to obtain continuous estimates of discharge (Figure 5:4)

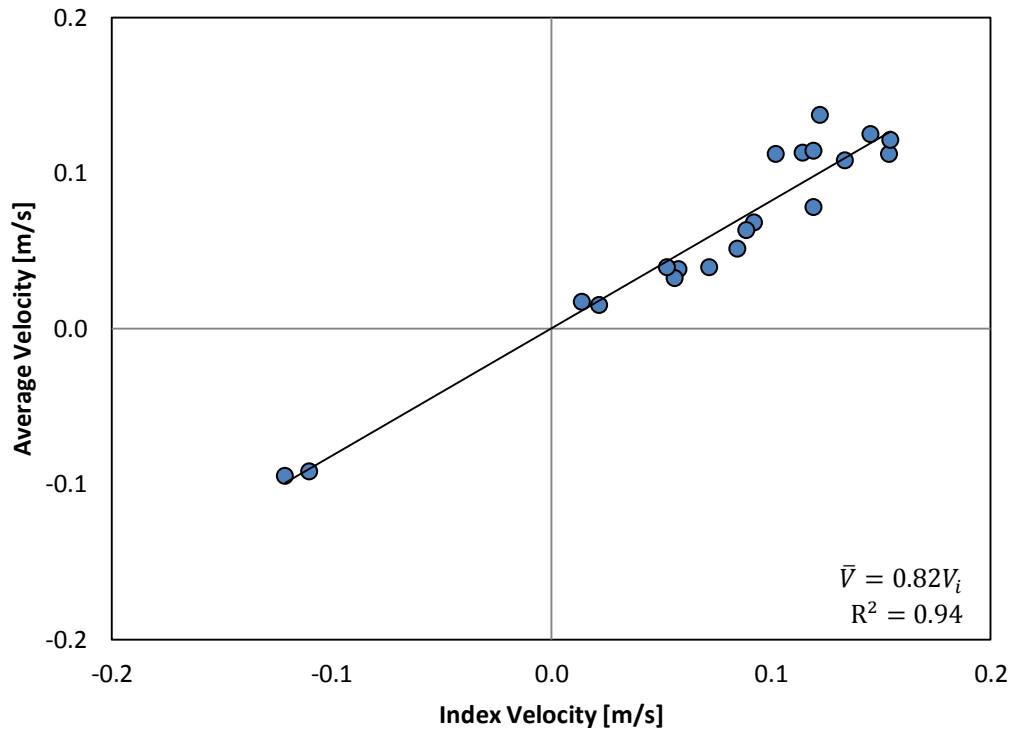


Figure 5:1 – VIM, Delta Channel 2014: Index-Average Velocity Rating Curve

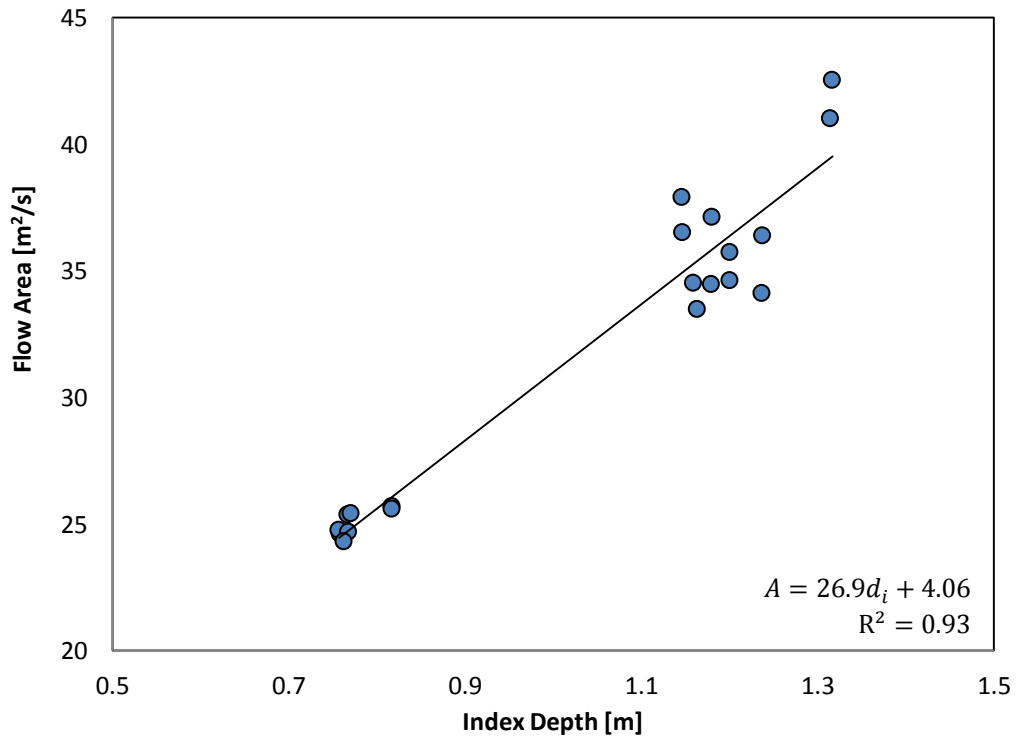


Figure 5:2 – VIM, Delta Channel 2014: Depth-Area Rating Curve

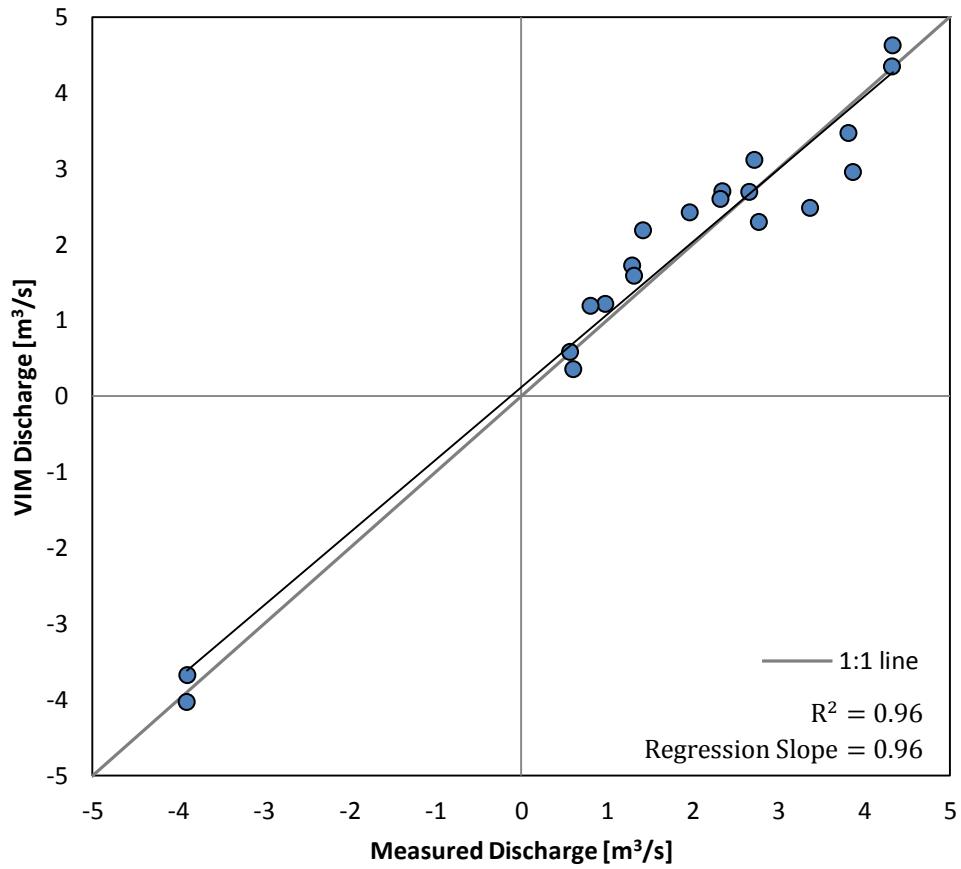


Figure 5:3 – VIM, Delta Channel 2014: Performance Plot

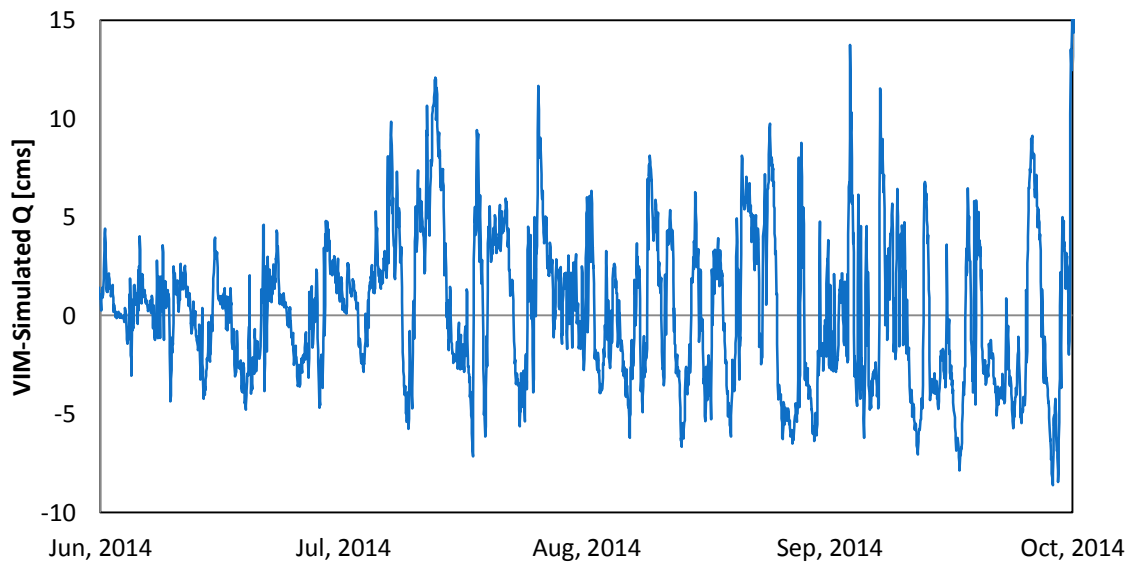


Figure 5:4 – VIM, Delta Channel 2014: Estimated Discharge Record

The VIM calibration statistics are summarized for both years at both locations in Table 4:1. The “Points” column refers to the number of measurement points used in calibration. The next two columns indicate the coefficient of determination and regression slope of the VIM discharges, respectively. For all four cases, the R^2 values are very high, and the points fall along the 1:1 line. The VIM has been successful in obtaining baseline discharges. The final column lists the ranges of the VIM discharges. Note that Waterhen Creek appears to have a considerably higher capacity than Delta Channel. Supplementary calibration results are illustrated in Appendix A.

Table 5:1 – VIM: Calibration Results

Year	Location	Points	Q: R^2	Q Slope	Q Range [m^3/s]
2013	Delta Channel	14	0.98	0.98	-5 – 15
	Waterhen Creek	11	0.99	0.99	-20 – 50
2014	Delta Channel	20	0.96	0.96	-8 – 15
	Waterhen Creek	21	0.99	0.98	-30 – 70

5.2. 2D Hydrodynamic Model: Calibration and Validation

Much of the data required for MIKE 21 is physically based and quantifiable, such as bathymetry, sources/sinks, wind, and precipitation. Most of the effort in building a working 2D model of the Delta Marsh area was directed to identifying representative data sources for these inputs (as described in 4.3). Once all physical inputs were specified, the following steps were performed:

1. The storage was adjusted to account for unquantified overland runoff to Lake Manitoba (Section 5.2.1). This was more of a correction than a calibration, as it was

done separately for 2013 and 2014. This was an appropriate solution to the overland runoff problem, since it was not adjusted beyond the baseline conditions; none of the scenarios considered changes to Lake Manitoba overland inflows.

2. The wind friction terms were adjusted to calibrate setup on the lake (Section 5.2.2).
3. The Manning roughness was adjusted to calibrate channel flow (Section 5.2.3).
4. The eddy viscosity was adjusted to calibrate channel flow (Section 5.2.4).
5. Once calibrated, the model was validated to 2014 field data (Section 5.2.5)

5.2.1. Calibrating Storage: Artificial Distributed Source

Preliminary model setup showed that for most open water simulations from 1995 to 2014, the simulated lake level began to deviate from the observed level during the spring (as illustrated in Figure 5:5a for Westbourne, 2013; Figure 5:5b for Westbourne, 2014; note the negative Nash-Sutcliffe Efficiency (NSE) scores). Deviations in storage can often be attributed to errors in the main storage terms (sources, sinks, precipitation, and evaporation), but two observations suggested otherwise. First, underestimation never continued past the summer. Second, some simulated seasons showed no deviation at all (1995; Figure 4:10). Thus, it is unlikely that these errors are the result of consistent underestimation of precipitation or inflow, or overestimations of evaporation or outflow.

Recalling the general Lake Manitoba water balance (Section 2.2), the overland and groundwater contributions from the watershed have not been quantified. Incoming snowmelt during the spring was not input to the model, and this omission seems to explain the deviation during years like 2013 and 2014. Seasons with very little snowpack and/or early snowmelt could explain accurate simulations for years such as 1995. The storage can

be corrected by adding a uniform depth of water to the domain (as artificial precipitation). Figures Figure 5:6 shows the correction of the simulated storage for 2013 and 2014. In 2013, 7.0 cm were removed (as evaporation) in mid-September. This deviation may be attributed to errors in precipitation or evaporation estimation.

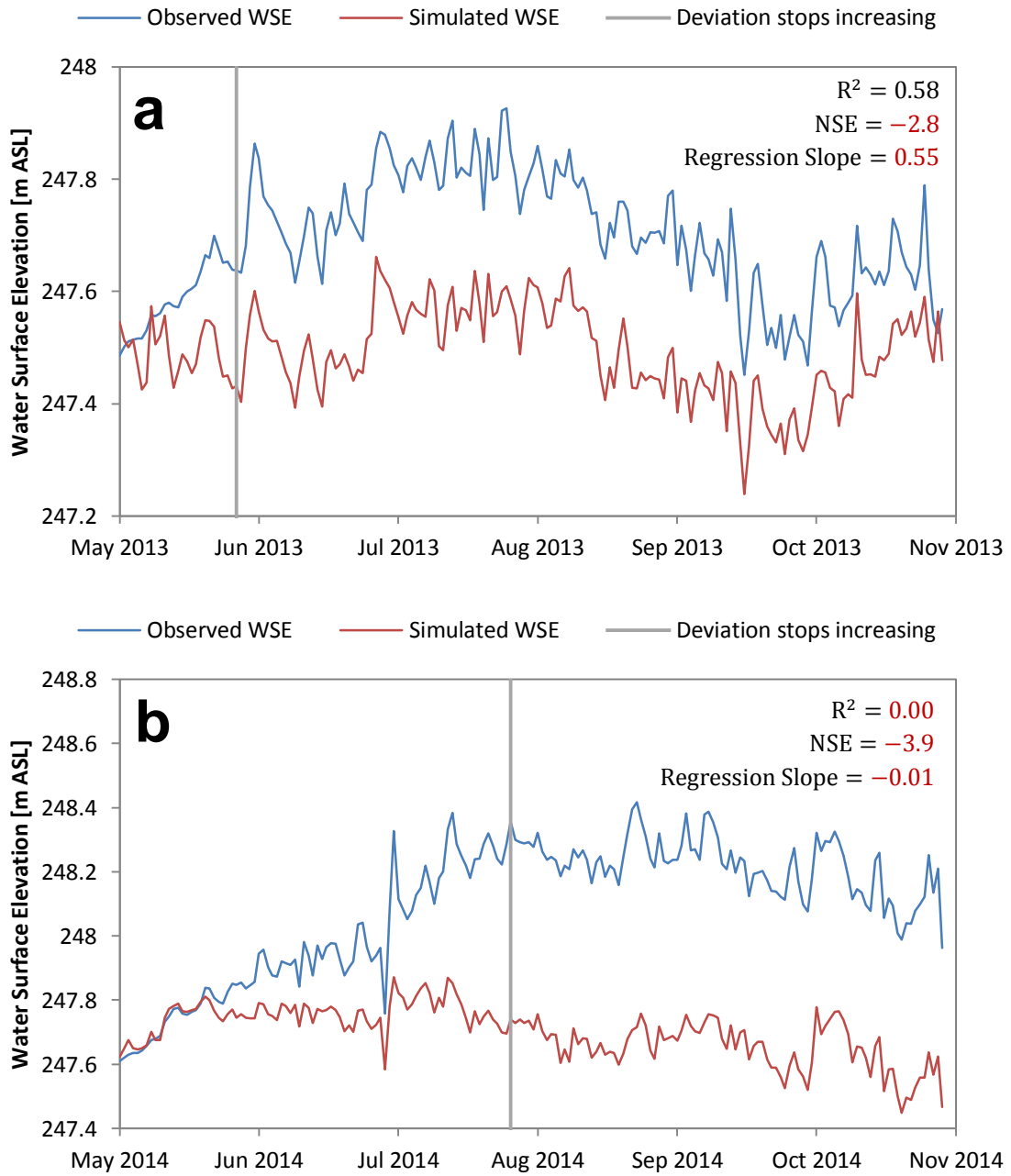


Figure 5:5 – Westbourne: Storage Deviation

a) 2013; b) 2014

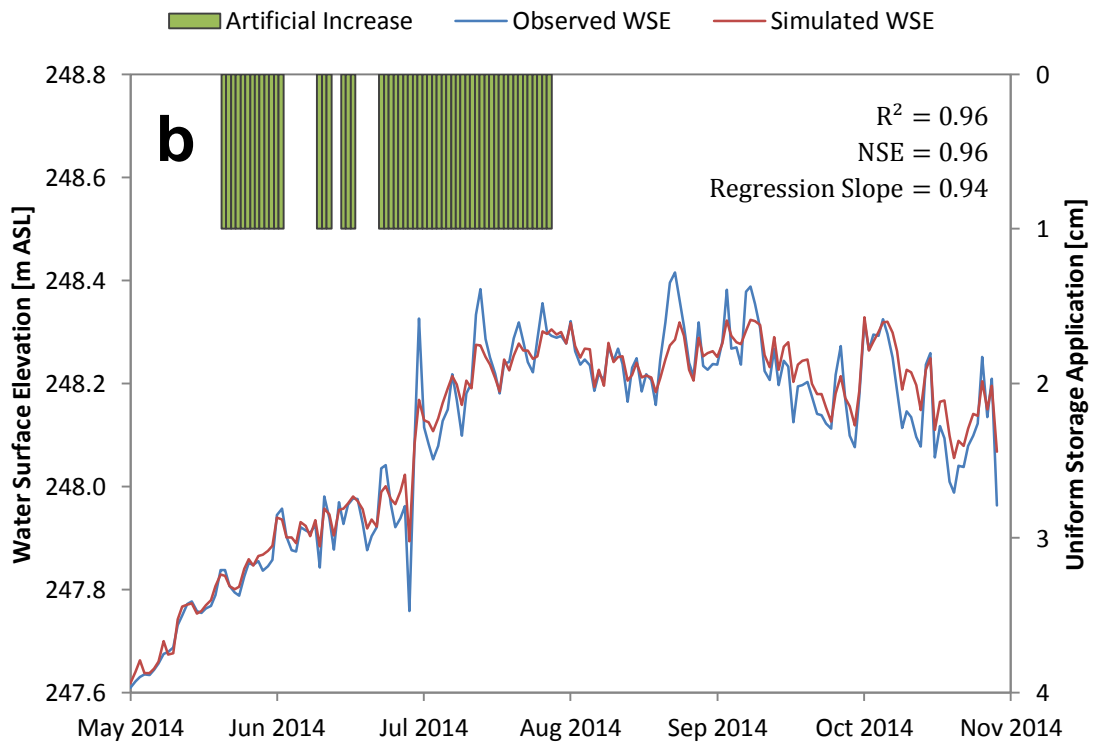
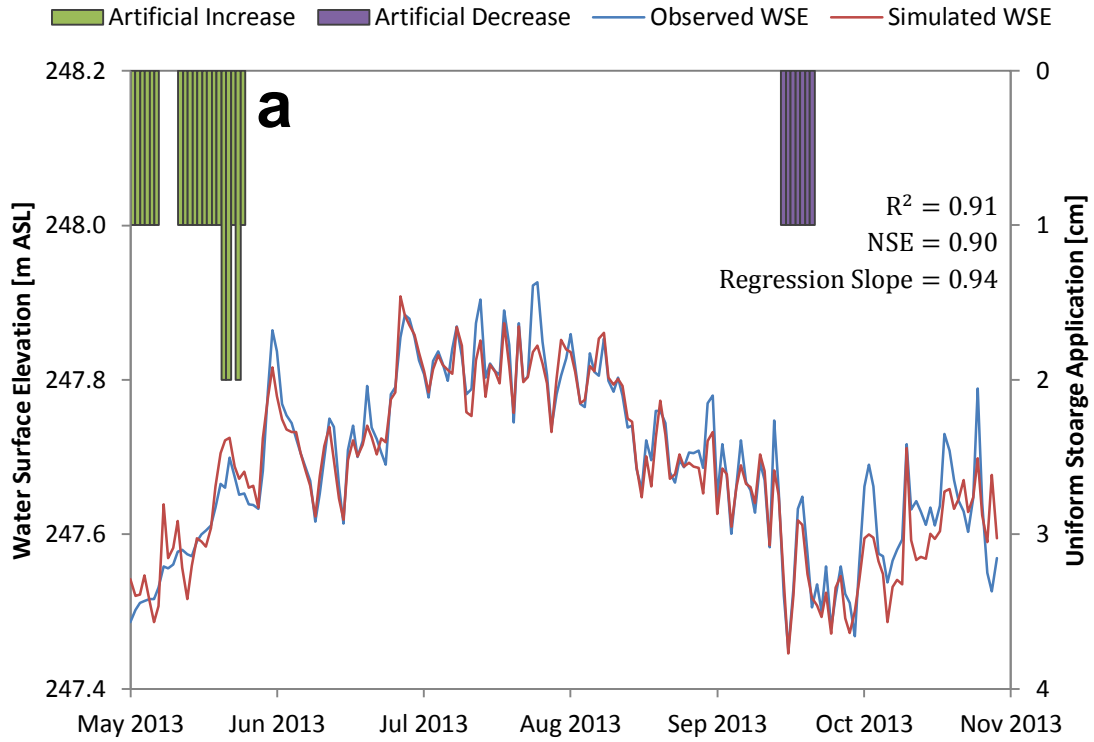


Figure 5:6 – Westbourne: Storage Correction

a) 2013; b) 2014

5.2.2. Calibrating Seiching: Wind Friction

As previously mentioned, the selection of representative data sources is the most important consideration in setting up a 2D hydrodynamic model, and can greatly simplify the calibration process. Consider the simulated WSE at Westbourne (Figure 5:6a). Prior to the calibration of wind friction, the model is already simulating the daily wind-driven fluctuations at the south end of the lake level very well ($R^2 = 0.91$). This implies that:

1. The adjusted wind data from Oak Point Marine (EC Gauge 504K0NM) is representative of the winds acting across Lake Manitoba and Delta Marsh
2. The default (suggested) wind friction values are applicable

Ranges of drag coefficient (c_f) values were tested for 2013. This was done to test the sensitivity of lake level fluctuations to wind friction, and in an attempt to find a set of c_f values that yielded a meaningful improvement in the simulation. The range of c_f values and the threshold wind speeds between which interpolation occurs (as described in Equation 3:7) can be adjusted. Alternatively, a constant c_f value can be set across all wind speeds. The statistics for four calibration attempts are summarized in Table 5:2. Note the marginal changes in statistics between simulations, illustrated in Figure 5:7.

Table 5:2 – Summary of Wind Friction Calibration Attempts

Condition	c_f Range [-]	Interpolation Range [m/s]	R^2	NSE	Notes
(1) Default	0.001255 – 0.002425	7 – 25	0.91	0.90	Performs well
(2) Damped	0.001055 – 0.002025	10 – 30	0.92	0.90	No improvement
(3) Increased	0.001455 – 0.002625	5 – 20	0.89	0.85	No improvement
(4) Constant	0.0014	N/A	0.91	0.89	No improvement

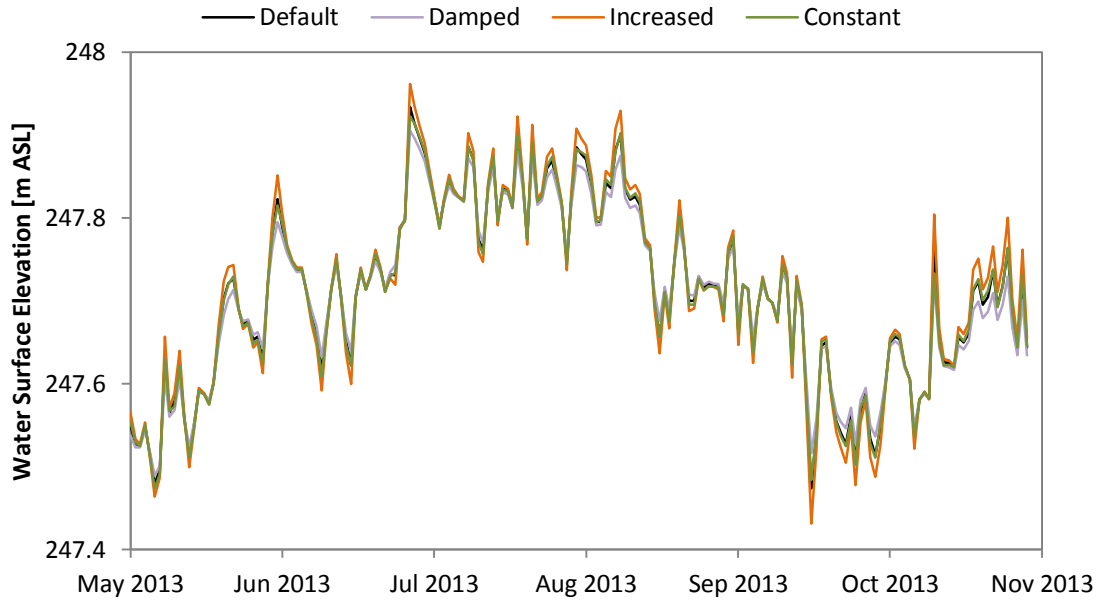


Figure 5:7 – Wind Friction Calibration: Similarity in WSE Simulations

Given the apparent insensitivity of the simulated WSE fluctuation to changes in the drag coefficients, and the strong performance of un-calibrated model, the default c_f values and interpolation range (Condition 1) were used for all simulations.

5.2.3. Calibrating Channel Flow: Bed Roughness

Wetland flux was calibrated by the adjusting the bed roughness values (Manning’s M), and the eddy viscosity coefficient, in order to simulate acceptable hourly discharges through Delta Channel and Waterhen Creek. Under the default roughness condition ($M = 32 \text{ m}^{1/3}/\text{s}$), these simulated discharges did not perform well. At Delta Channel (Figure 5:8a), the model severely overestimated mid-to-high discharges, despite the reasonable regression slope. Conversely, the model underestimated peak discharges at Waterhen Creek (Figure 5:8b). This indicated that a uniform roughness value should not be applied across the domain.

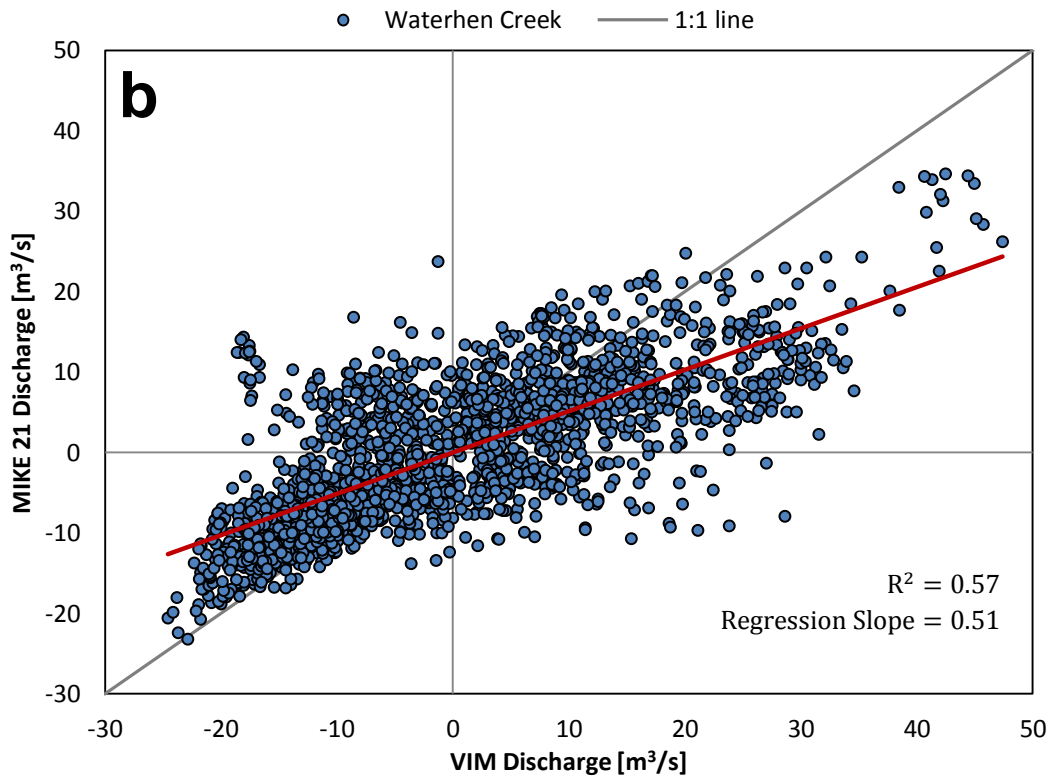
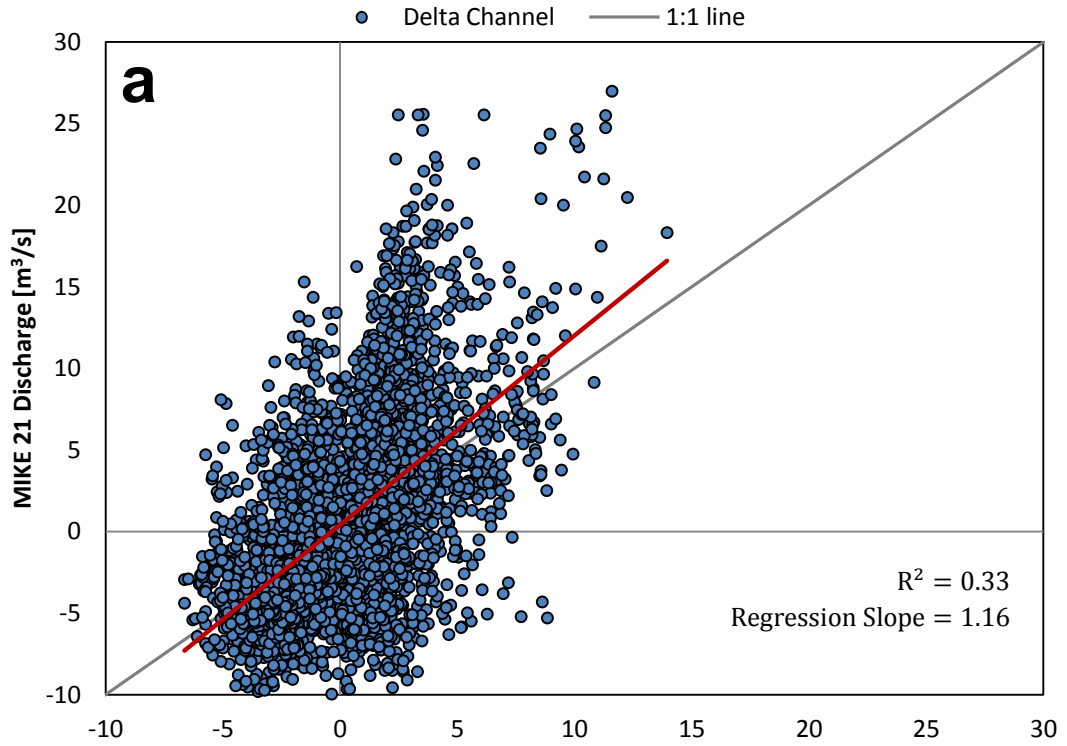


Figure 5:8 – Simulated Channel Discharge: Default Roughness

a) Delta Channel; b) Waterhen Creek

Discharge calibration was performed iteratively by adjusting M across the domain, as detailed in Table 5:3. Condition 1 shows the default performance. Condition 2 shows the performance of a much smoother uniform bed roughness. Note the increase in regression slope for Waterhen Creek. Condition 3 shows the first attempt at the application of non-uniform roughness. The regression slope did not change drastically at Waterhen Creek, possibly due to discharge limitations through Clandeboye Channel. This was addressed in Condition 4, which yielded the most acceptable statistics. Although the regression slope for Delta Channel decreased, the peak discharges were estimated more reasonably. Similarly, peaks were estimated reasonably for Waterhen Creek despite the low regression slope. Final calibration performances are shown in Figure 5:9. Figure 5:10 illustrates the discharge simulation through Waterhen Creek for September 2013.

Table 5:3 – Summary of Bed Roughness Calibration Attempts

Condition	M [$m^{1/3}/s$]	Application of Roughness	Delta Channel		Waterhen Creek	
			R^2	Q Slope	R^2	Q Slope
(1)	32	Full Domain	0.33	1.16	0.57	0.51
(2)	50	Full Domain	0.28	1.47	0.53	0.65
(3)	20	Delta Channel	0.33	0.87	0.57	0.67
	50	Waterhen Channel				
	25	Crooked Creek				
	25	Fish Creek				
	40	Elsewhere				
(4)	15	Delta Channel	0.37	0.68	0.57	0.73
	50	Waterhen Channel				
	50	Clandeboye Channel				
	20	Crooked Creek				
	20	Fish Creek				
	40	Elsewhere				

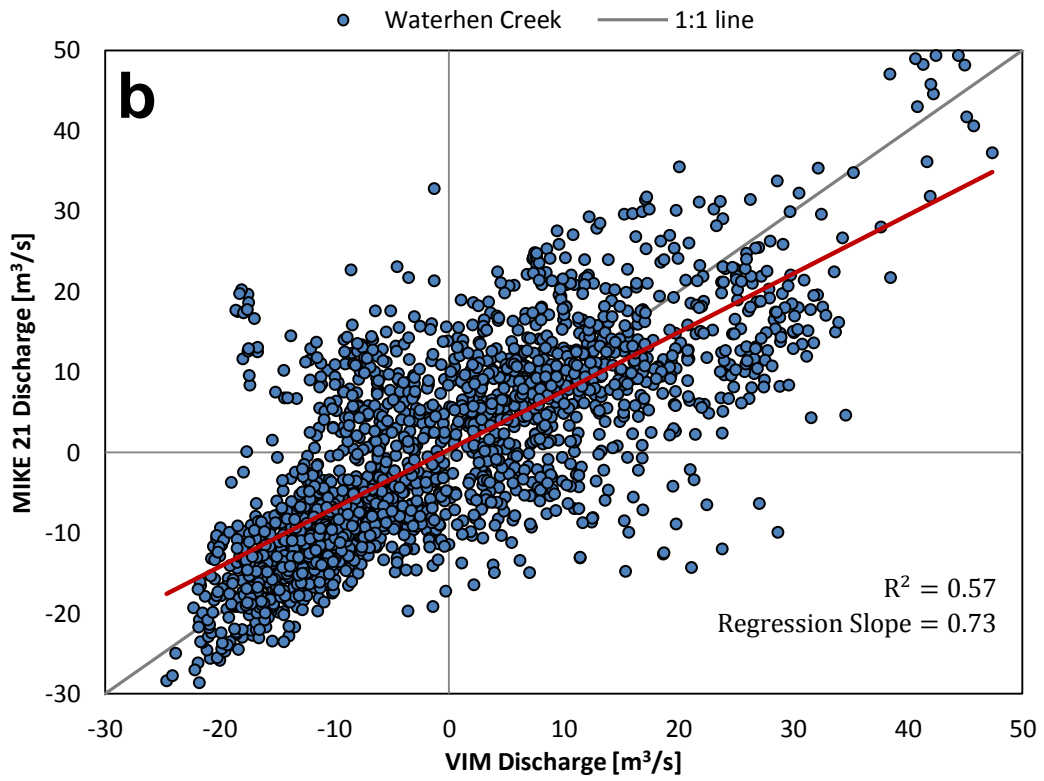
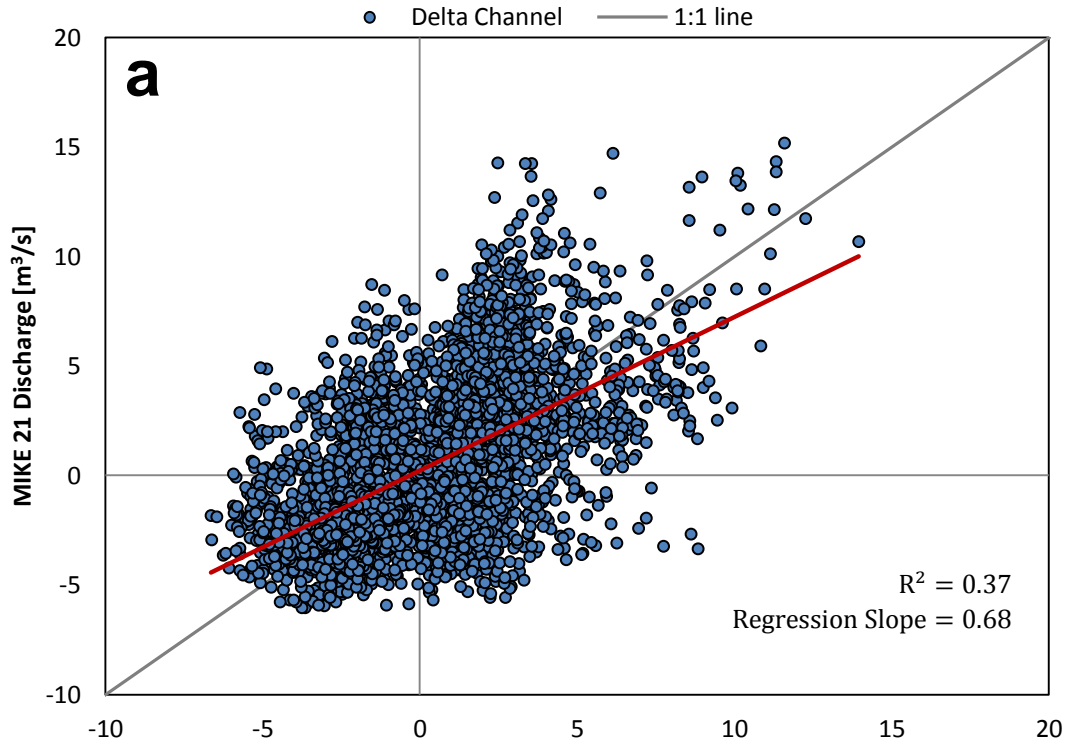


Figure 5:9 – Simulated Channel Discharge: Calibrated Roughness

a) Delta Channel; b) Waterhen Creek

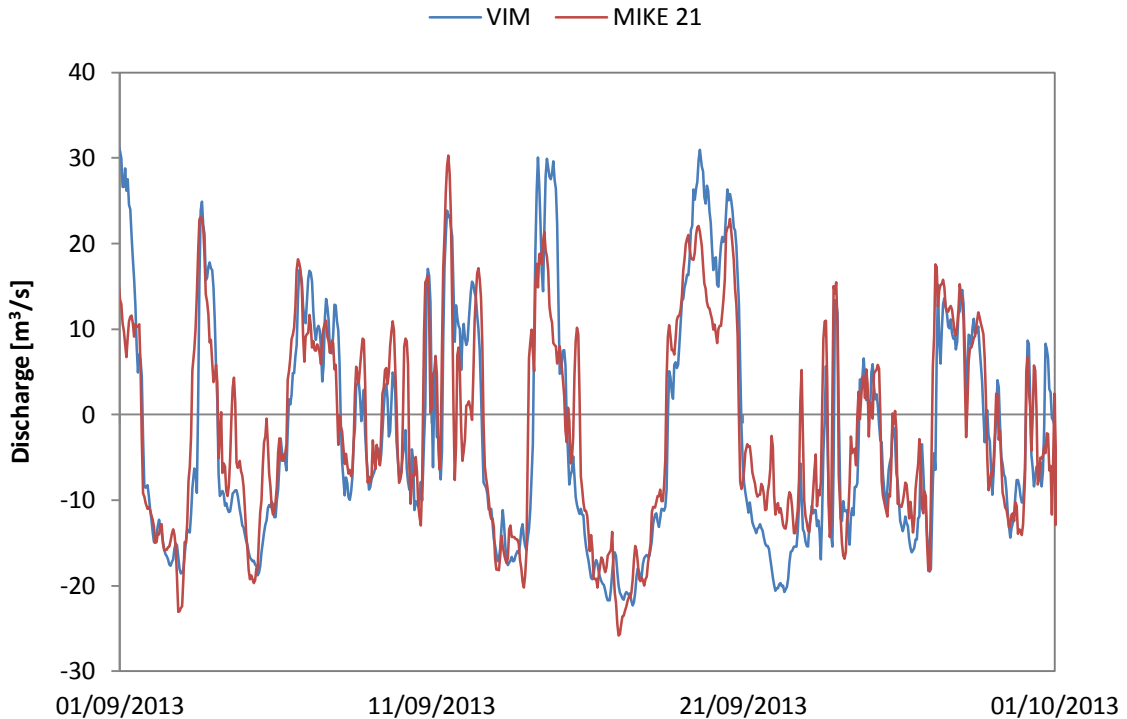


Figure 5:10 – Waterhen Creek Discharge: Calibrated Roughness, Sept. 2013

5.2.4. Calibrating Channel Flow: Eddy Viscosity

The final calibration option is the adjustment of the Smagorinsky coefficient of eddy viscosity (c_s). Similar to the calibration of wind friction, a range of c_s values were tested for 2013. This was done to test the sensitivity of channel discharge to simulated eddy viscosity, and in an attempt to find a c_s value that yielded a meaningful improvement in the simulation. The statistics for four calibration scenarios are summarized in Table 5:4. Condition 1 uses the default c_s value. Condition 2 uses the lowest recommended c_s value, as per (DHI 2012b). Condition 3 uses a c_s value much higher than the default. Condition 4 uses the highest recommended c_s value, as per (DHI 2012b). Given the apparent insensitivity of the simulated channel discharges to changes to the Smagorinsky coefficient, the default c_s value of 0.28 was adopted.

Table 5:4 – Summary of Eddy Viscosity Calibration Attempts

Condition	c_s [–]	Delta Channel		Waterhen Creek		Notes
		R ²	Q Slope	R ²	Q Slope	
(1) Default	0.28	0.37	0.68	0.57	0.73	Performs well
(2) Lowest	0.25	0.34	0.70	0.57	0.73	No improvement
(3) Higher	0.5	0.34	0.70	0.57	0.72	No improvement
(4) Highest	1.0	0.35	0.70	0.54	0.70	No improvement

5.2.5. Validation

The previous subsections describe the calibration of the MIKE 21 model to 2013 data. Validation of the model was relatively simple. Hydrologic and meteorological data from the 2014 open-water season was input to the calibrated model, and the WSE and discharge outputs were compared against 2014 data. Since storage was corrected for 2014, the simulated WSE record at Westbourne (Figure 5:6b) looks very reasonable. The high calibration statistics also demonstrate that the selected wind friction terms apply. The statistics for simulated discharge for both years are summarized in Table 5:5, and illustrated in Figure 5:11. Note that the statistics improved for Delta Channel, and are consistent from year to year for Waterhen Creek. Thus, the calibrated MIKE 21 model was validated successfully. The model is considered usable for 2013 and 2014 simulations only, and should be re-validated prior to use in subsequent years.

Table 5:5 – Summary of Validation Statistics for Channel Discharge

Year	Delta Channel		Waterhen Creek	
	R ²	Q Slope	R ²	Q Slope
2013 (Calibration)	0.37	0.68	0.57	0.73
2014 (Validation)	0.49	1.01	0.53	0.72

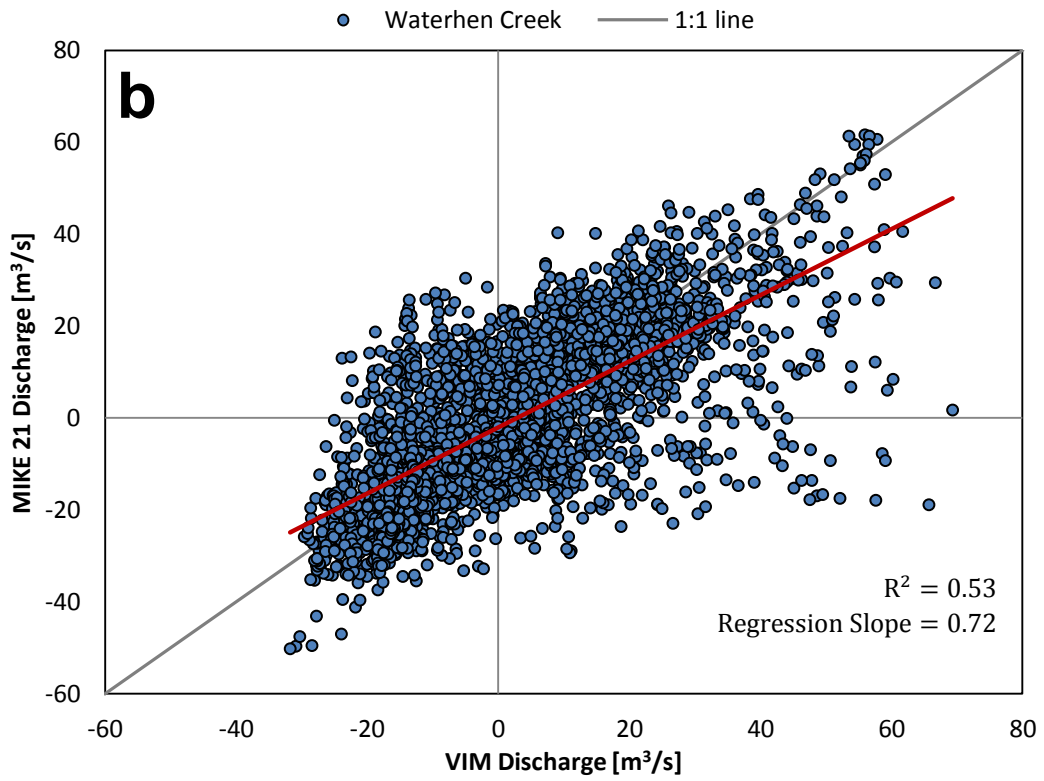
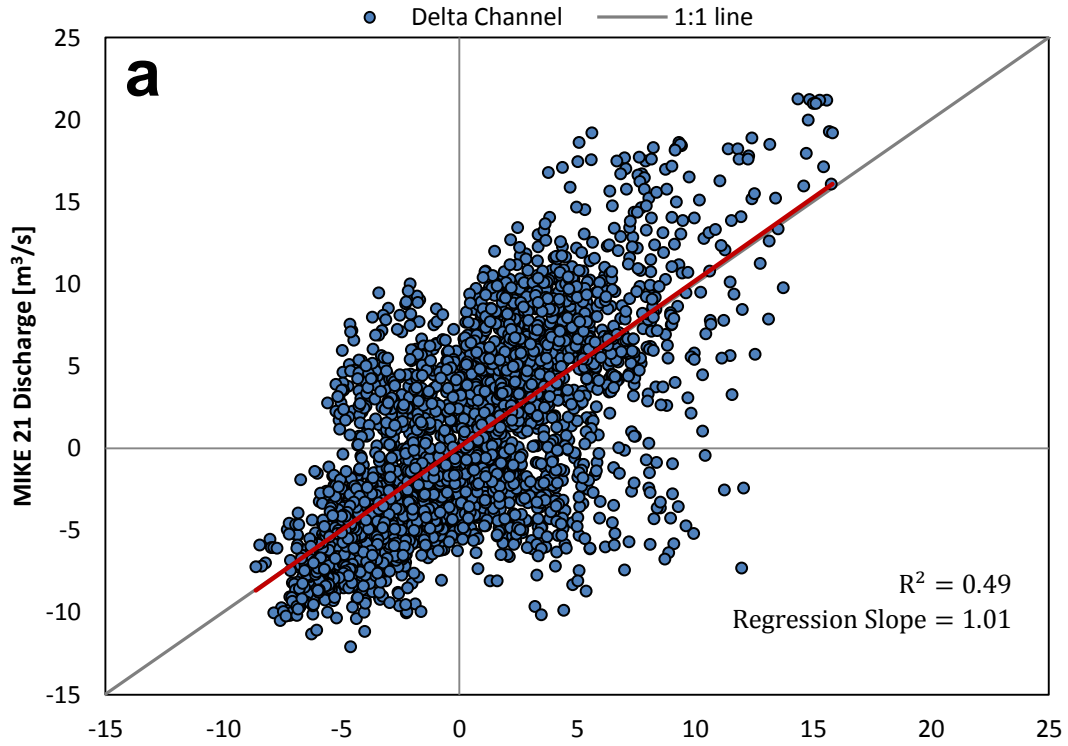


Figure 5:11 – Simulated Channel Discharge: 2014 Validation

a) Delta Channel; b) Waterhen Creek

5.3. Discharge Estimation: Calibration

The three proposed methods of discharge estimation were calibrated to 2013 VIM discharges, as described in the following sections. Note that the calibration of each method is the test of its direct applicability, and the attempted validation of each (Section 6.3) is the test of its usability across seasons and locations.

5.3.1. Regressed Slope Manning Method

The RSMM calibration method is illustrated below for Waterhen Creek, 2013:

1. Obtain a VIM discharge record (Q_{VIM}), as per Section 5.1
2. Collect continuous measurements of outside and inside water depths (y_{out} & y_{in} , respectively) using two pressure gauges (as described in Sections 4.1.1 and 4.5.1)
3. Estimate the wetted perimeter for each ADCP survey used in the VIM calibration
4. Create a depth-area rating curve, using the nearer gauge
5. Create a depth-wetted-perimeter rating curve, using the nearer gauge
6. Obtain estimates of A and P for the calibration period using these rating curves
7. Estimate ψ_{VIM} by substituting A , P , and Q_{VIM} into Equation 4:17.
8. Calibrate the RSMM calibration terms as follows (Figure 5:12a,b):
 - a. Set default values: $\alpha_1 = 1$, $\alpha_2 = \beta_1 = 0$
 - b. Plot ψ_{RSMM} against ψ_{VIM}
 - c. Adjust β_1 to force the regression line of the plot through the origin
 - d. Iteratively solve for the value of α_2 that yields the maximum R^2 value
 - e. Iteratively solve for the value of α_1 that yields the minimum RMSE value
9. Use the calibrated ψ_{RSMM} record to estimate Q_{RSMM}
10. Plot Q_{RSMM} against Q_{VIM} (Figures 5:12c and 5:13; Figure 5:14 for Delta Channel)

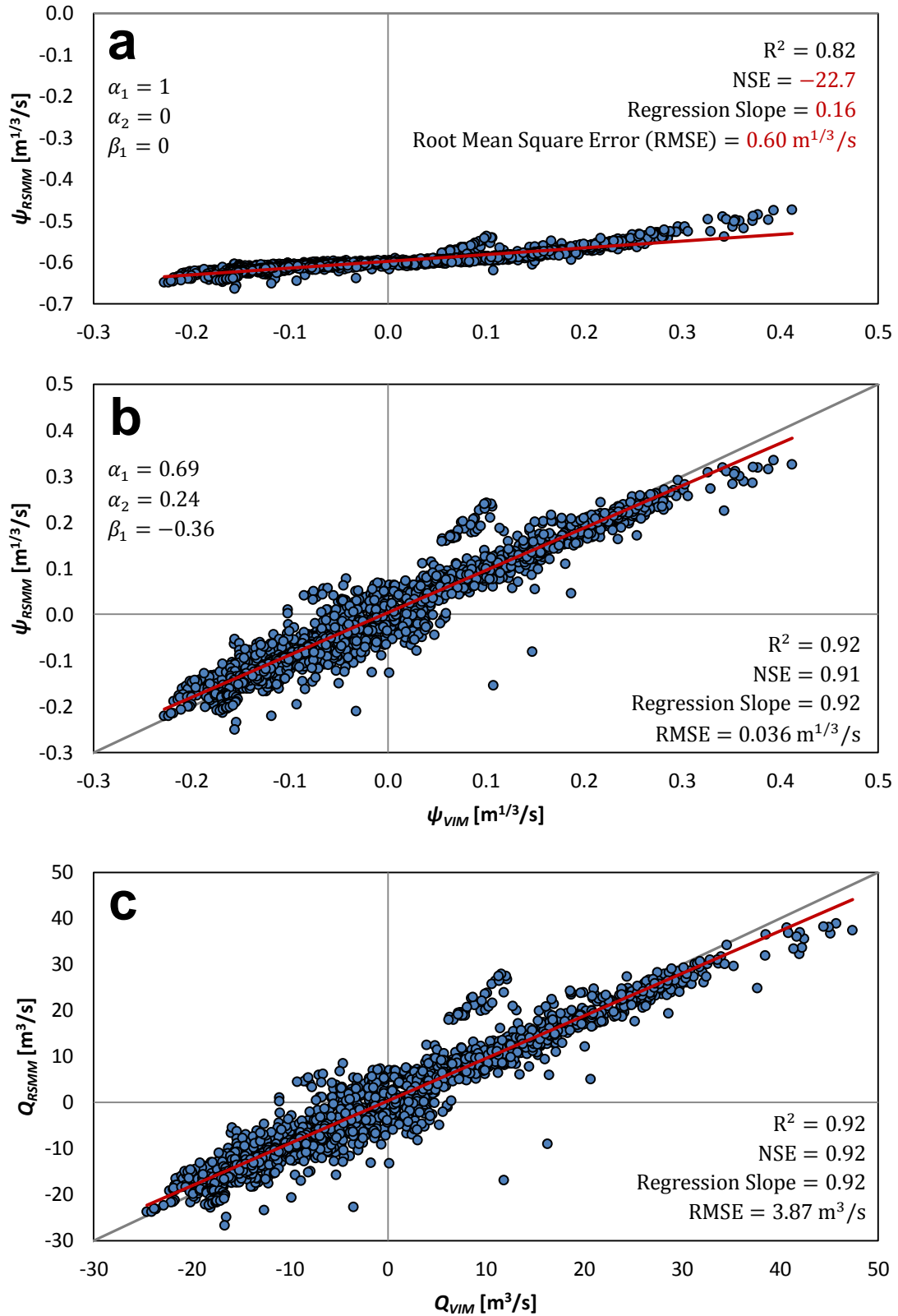


Figure 5:12 – Calibration of the RSMM Coefficients for Waterhen Creek, 2013

a) ψ : Pre-calibration; b) ψ : Post-calibration; c) Q : post-calibration

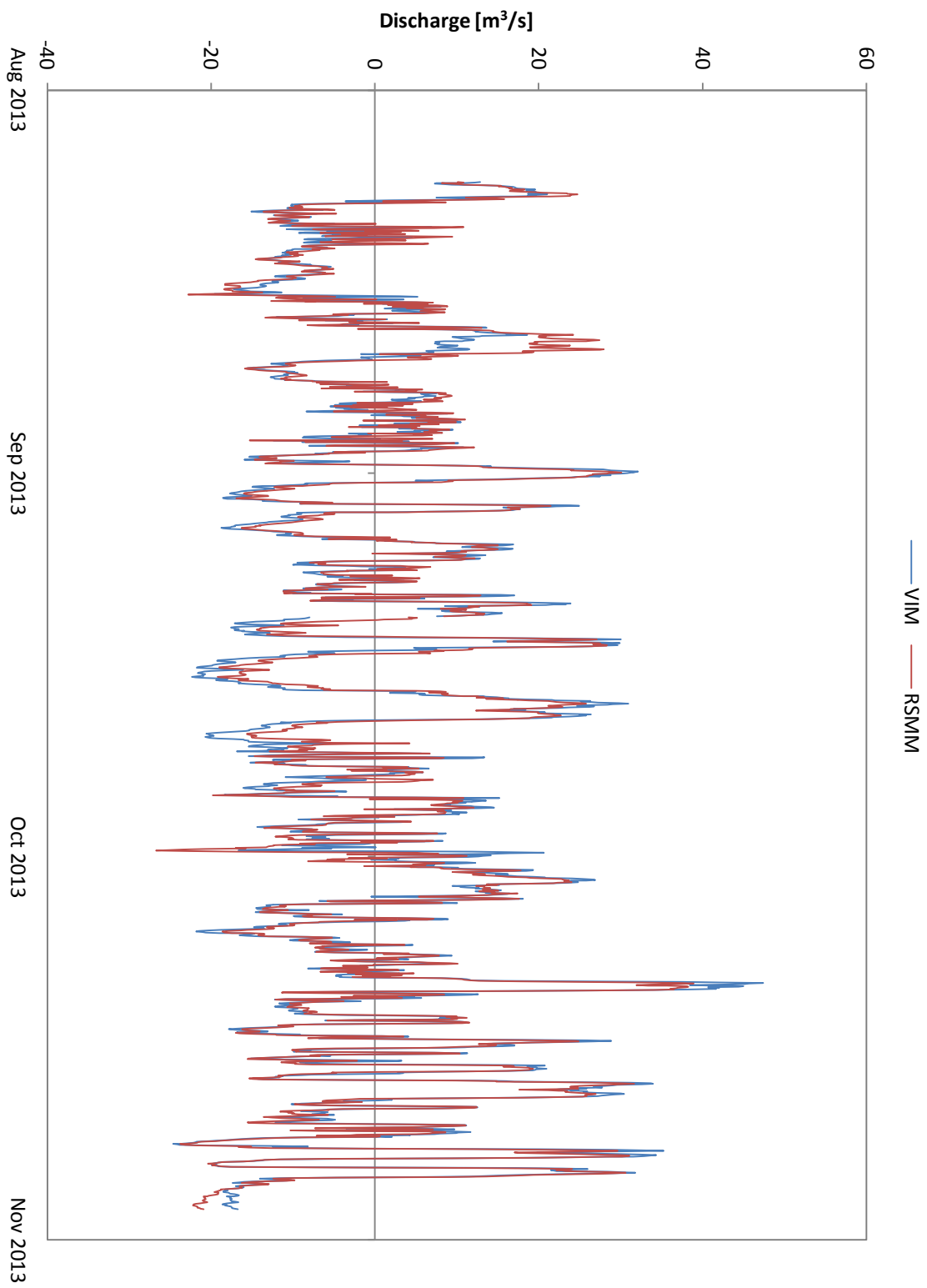


Figure 5:13 – RSMM Simulation Performance for Waterhen Creek, 2013

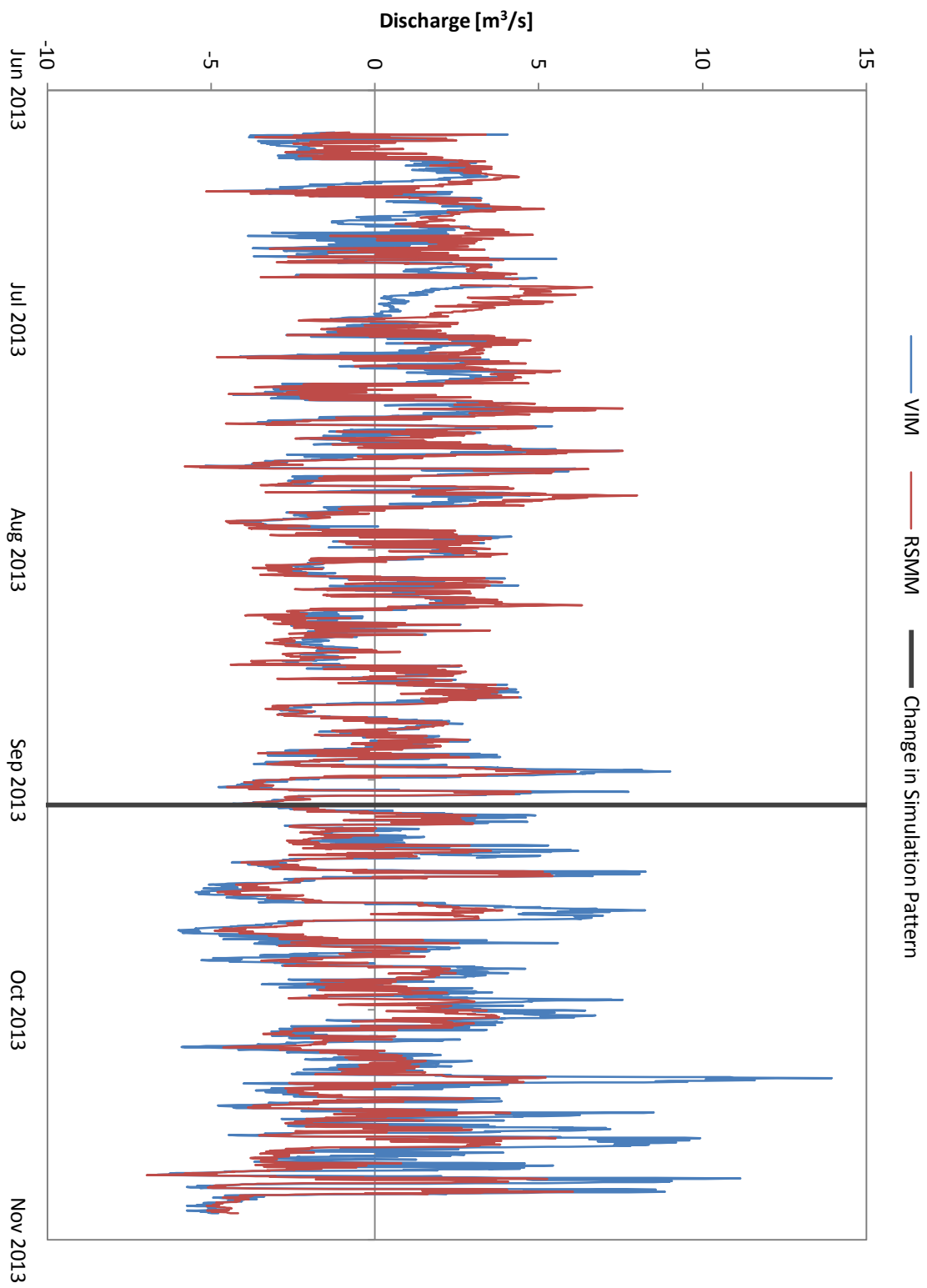


Figure 5:14 – RSM Simulation Performance for Delta Channel, 2013

Note that the calibrated ψ and Q performance plots (shown in Figures 5:10b and 5:10c, respectively) and associated statistics are almost identical, indicating that the rating curve estimates of area and wetted perimeter did not contribute much uncertainty to the estimation of discharge for this case. Also, note the success of the simulation, as illustrated in Figure 5:13. Much of the deviation between the VIM and RSMM discharges occurred at near stagnant flows, while most peak flows were been simulated reasonably well. At Delta Channel, the simulation pattern changed in September, when it began to consistently underestimate discharge. This was possibly due to the movement of the depth gauge during regular maintenance. The calibration statistics for Delta Channel and Waterhen Creek are summarized in Table 5:6. The statistics at Delta Channel may improve if depth measurements are collected directly at the lakeside mouth of Delta Channel.

Table 5:6 – RSMM Calibration Statistics, 2013

Location	R ²	NSE	R Slope	RMSE [m ³ /s]	Notes
Delta Channel	0.62	0.61	0.71	1.90	Good for Summer
Waterhen Creek	0.92	0.92	0.92	3.87	Excellent Simulation

5.3.2. Regressed Level Manning Method

The RLMM calibration method is illustrated below for Waterhen Creek, 2013:

1. Repeat Steps 1-7 of the RSMM calibration procedure using only one depth gauge
2. Create the matrix of 106 variables (shown in Table 4:2) using the same gauge
3. Use stepwise linear regression to calibrate ψ_{RLMM} (Table 5:7)
4. Use the ψ_{RLMM} record to estimate Q_{RLMM}
5. Plot Q_{RLMM} against Q_{VIM} (Figures 5:15 and 5:16, Figure 5:17 for Delta Channel)

Table 5:7 – Stepwise Calibration of the RLMM for Waterhen Creek, 2013

Step	Variable to Include	R ²	Notes
0	None	0.00	Pre-calibration
1	28-hour change, lagged 0 hours	0.53	Tremendous improvement
2	48-hour change, lagged 0 hours	0.60	Moderate improvement
3	10-hour change, lagged 0 hours	0.65	Moderate improvement
4	18-hour change, lagged 0 hours	0.66	Small improvement
5	6-hour change, lagged 4 hours	0.66	Negligible improvement
⋮	⋮	⋮	⋮
10	28-hour change, lagged 6 hours	0.68	Negligible improvement

Stepwise regression does not significantly improve the simulation of the ψ term beyond step 4. To preserve the simplicity of the method, only the first four variables were used.

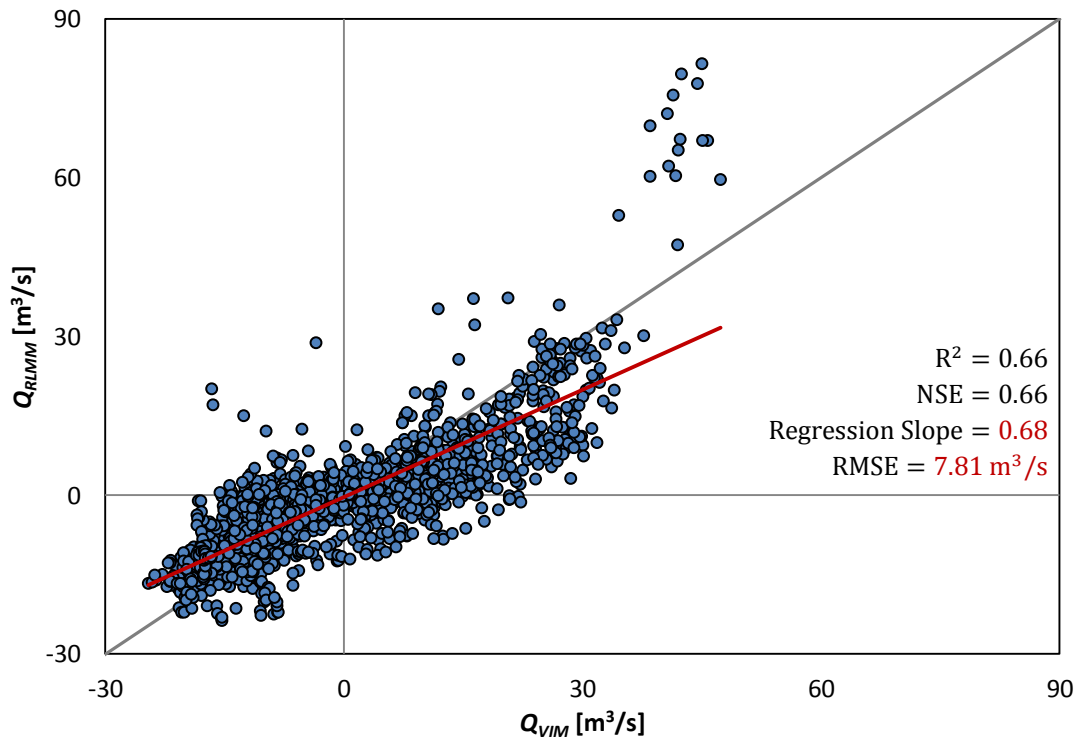


Figure 5:15 – Calibration of the RLMM for Waterhen Creek, 2013

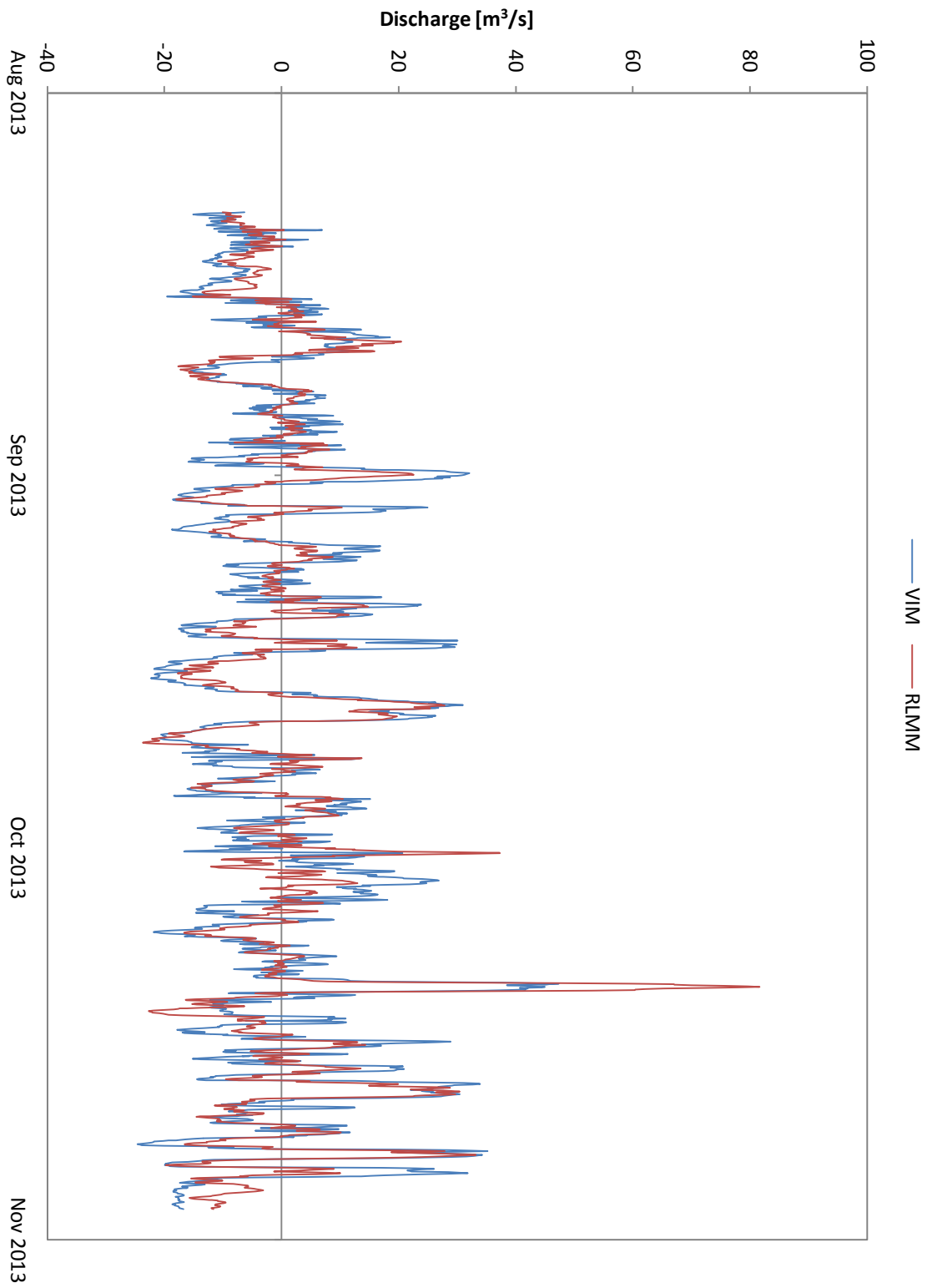


Figure 5:16 – RLMM Simulation Performance for Waterhen Creek, 2013

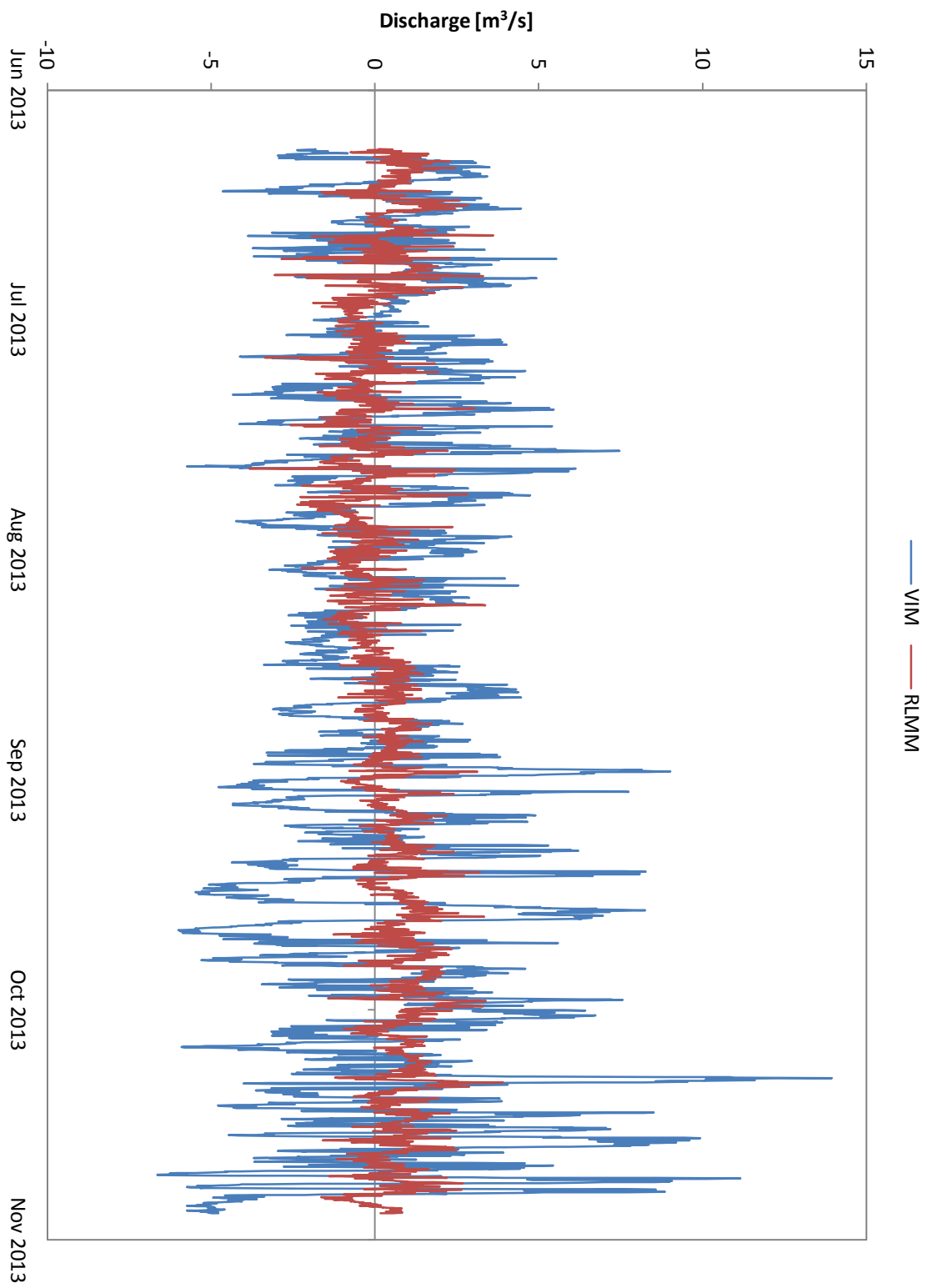


Figure 5:17 – RLMM Failure for Delta Channel, 2013

At Waterhen Creek, the RLMM simulation generally followed the shape of the observed discharge record. That being said, it did not perform as well as the RSMM. Most noticeably, this method appears to be prone to overestimating peak events, as manifest in mid-October. This gross overestimation influenced the calibration of the method across the season. The root-mean-squared-error was quite large, due to the fact that the method both over and underestimated peak events throughout the season. The calibration statistics for Delta Channel and Waterhen Creek are summarized in Table 5:8. Calibration of the RLMM was not successful at Delta Channel (as apparent in Figure 5:17). The parameter space was constructed using depth data at the nearest gauge to Delta Channel, which was on the marsh side. While data from this gauge can be useful in estimating area and wetted perimeter, it is not useful in estimating ψ . Recalling Figure 4:14, changes in friction slope across the channel may be estimated from changes in level at the lakeside channel mouth.

Table 5:8 – RLMM Calibration Statistics, 2013

Location	R²	NSE	R Slope	RMSE [m³/s]	Notes
Delta Channel	0.08	0.08	0.09	2.92	Unable to calibrate
Waterhen Creek	0.66	0.66	0.68	7.81	Acceptable

5.3.3. Polynomial Regression Method

The PRM calibration method is illustrated below for Waterhen Creek, 2013:

1. Obtain a VIM discharge record (Q_{VIM})
2. Create a matrix of variables using second-hand Water Survey of Canada data
3. Use stepwise linear regression to calibrate Q_{PRM} (Table 5:9)
4. Plot Q_{PRM} against Q_{VIM} (Figures 5:18 and 5:19, Figure 5:20 for Delta Channel)

Table 5:9 – Stepwise Calibration of the PRM for Waterhen Creek, 2013

Step	Variable to Include	R ²	Notes
0	None	0.00	Pre-calibration
1	32-hour change, lagged 1 hour	0.51	Tremendous improvement
2	48-hour change, lagged 2 hours	0.62	Moderate improvement
3	20-hour change, lagged 0 hours	0.70	Moderate improvement
4	36-hour change, lagged 2 hours	0.71	Small improvement
5	22-hour change, lagged 0 hours	0.72	Negligible improvement
⋮	⋮	⋮	⋮
19	40-hour change, lagged 6 hours	0.74	Negligible improvement

Stepwise regression does not significantly improve the simulation of Q beyond step 4. To preserve the simplicity of the method, only the first four variables were used.

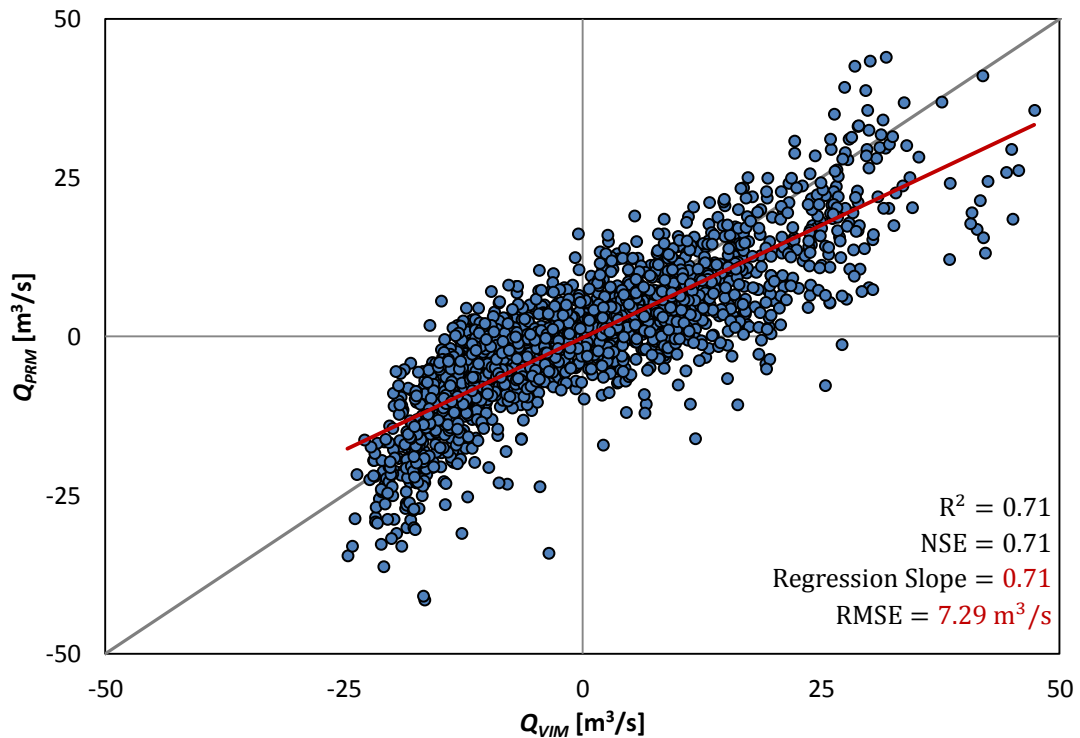


Figure 5:18 – Calibration of the PRM for Waterhen Creek, 2013

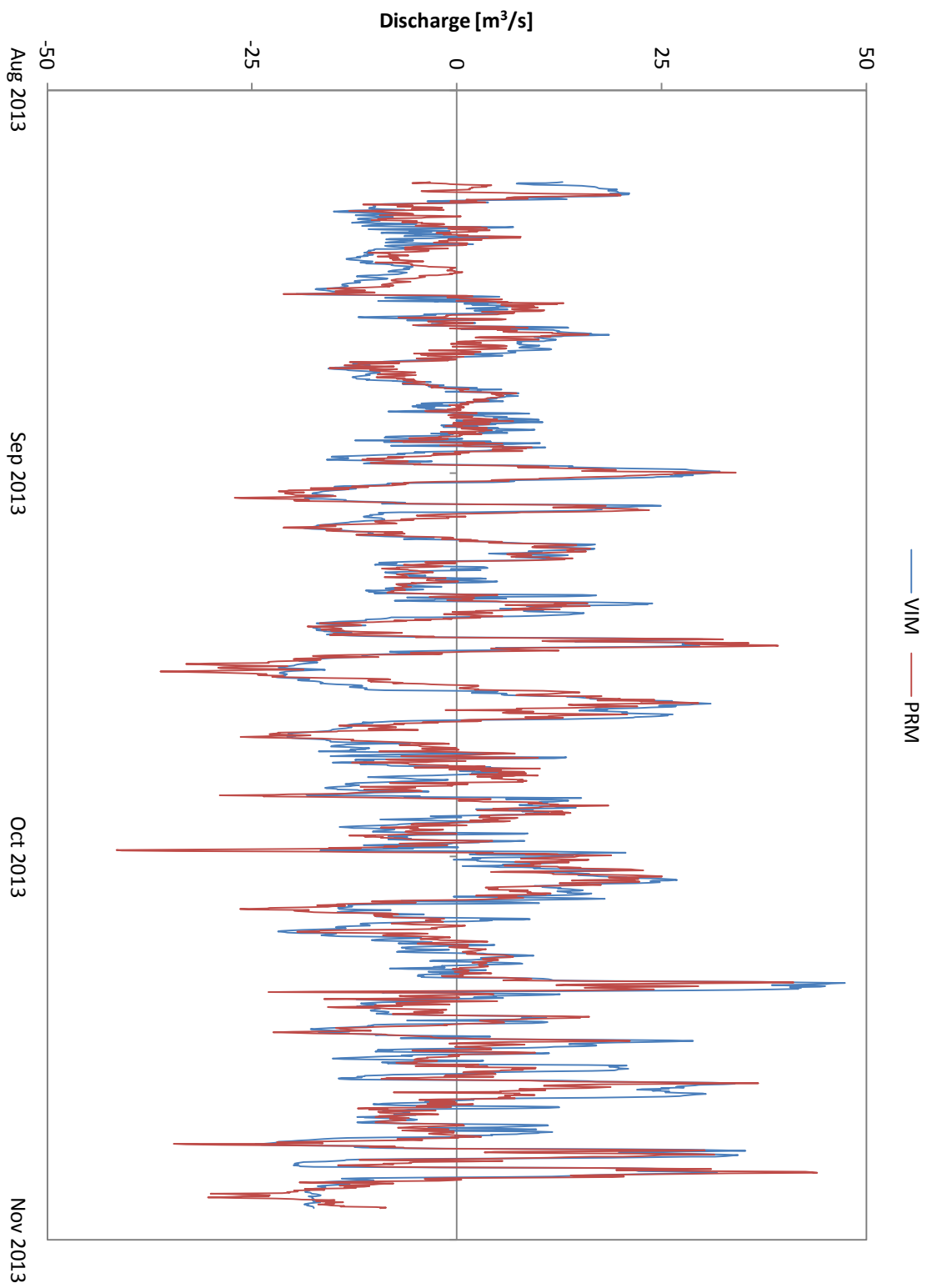


Figure 5:19 – PRM Simulation Performance for Waterhen Creek, 2013

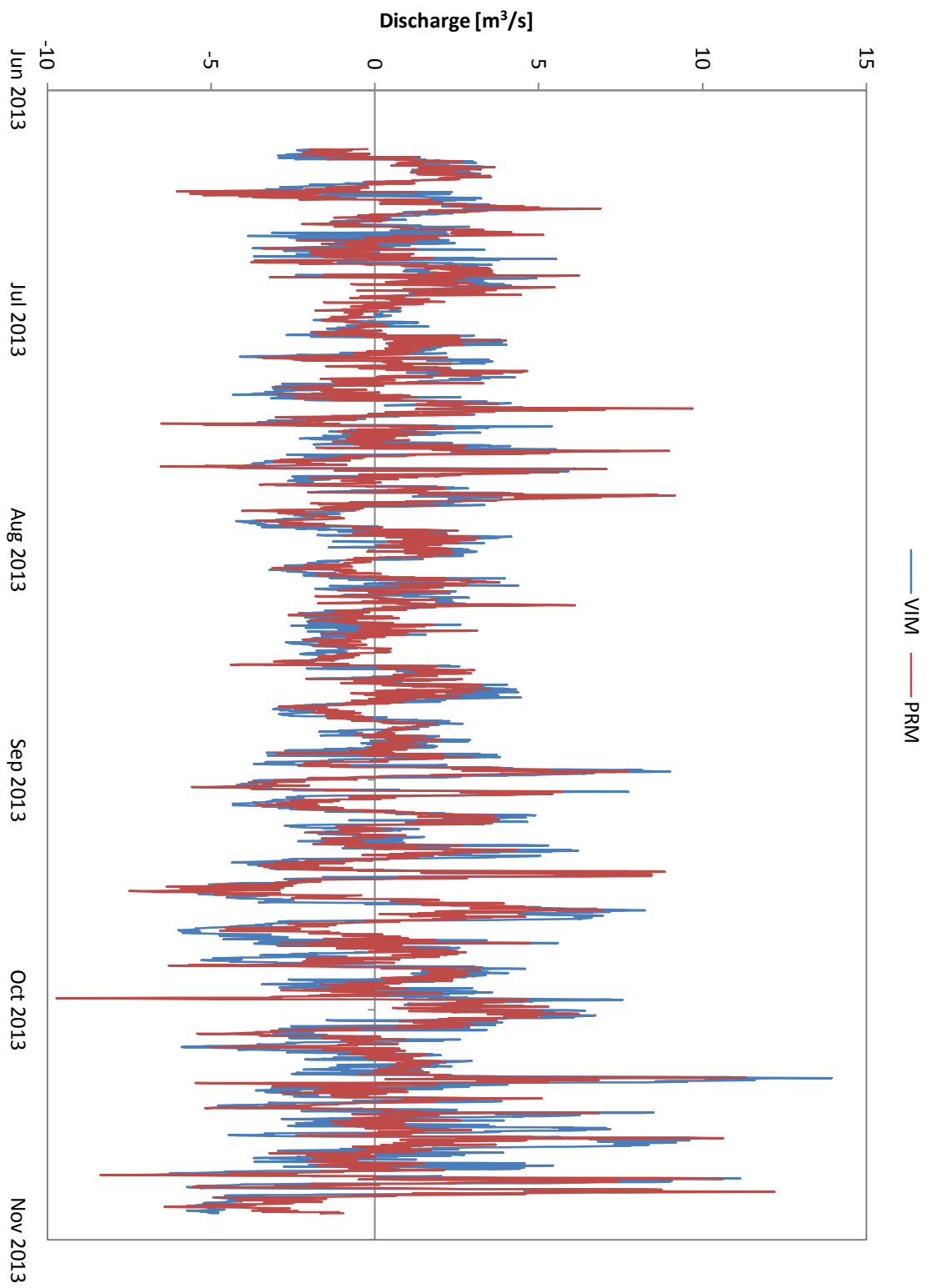


Figure 5:20 – PRM Simulation Performance for Delta Channel, 2013

At both locations, the PRM simulations generally followed the shape of the observed discharge records. However, Figure 5:19 shows the s-shaped nature of the performance scatterplot at Waterhen; the method underestimated lower flows, and overestimated higher flows. The statistics for Delta Channel and Waterhen Creek are summarized in Table 5:10. The PRM appears to rank between the RSMM and the RLMM in simulation strength. The R^2 and NSE scores were acceptable, and the RMSEs were marginally lower than those of the RLMM. There was no issue using the method at Delta Channel, since the parameter space was constructed using lakeside depths (from the WSC gauge). Recall that the PRM has the added benefit of being the most practically simple method to employ, provided that nearby second-hand depth measurements are available.

Table 5:10 – PRM Calibration Statistics, 2013

Location	R^2	NSE	R Slope	RMSE [m^3/s]	Notes
Delta Channel	0.58	0.58	0.58	1.96	Acceptable
Waterhen Creek	0.71	0.71	0.71	7.29	Acceptable

Section 6.3 addresses the validation of these three methods against 2014 data, and includes interpretations of the results, discussions of the limitations of each method, identification of the best method, and suggestions for improving the methods into the future.

6. Results

This chapter details the results of the field research, hydrodynamic modelling, and development of discharge estimation tools performed in this thesis. Interpretations of the results are discussed in this chapter, and summarized in Chapter 7.

6.1. Field Observations

In addition to providing hydrographic data necessary to the calibration and validation of the hydrodynamic model and the discharge estimation tools, field research gave early insight into the physical behaviour of the marsh. These observations confirmed several hypotheses regarding water movement throughout the marsh, and complemented results from 2D modelling (Section 6.2). Supplementary results can be found in Appendix A.

6.1.1. Hydrography

Water level measurement supported the hypothesis that WSE fluctuation decreases in amplitude into the marsh. Figure 6:1a shows the difference in WSE record between the WSC gauge at Westbourne (in Lake Manitoba) and at Clandeboye Bay. There is much less short-term fluctuation on the marsh side. Figure 6:1b shows the difference between Clandeboye Bay and Small Bluebill Bay. Peak events are severely damped on the inside. Figure 6:1c shows the difference between Small Bluebill Bay and South Claire Lake. Fluctuation is marginally damped. The average absolute changes in level at Westbourne, Clandeboye, Small Bluebill, and South Claire were 21.1, 6.4, 2.6, and 2.2 mm/hr, respectively. Thus, modelling should show rapid ebb and flow at the lake connections, with less interaction between the interior bays. Note that 5-minute-interval measurements were averaged over the hour in an attempt to diminish gauge sheltering effects.

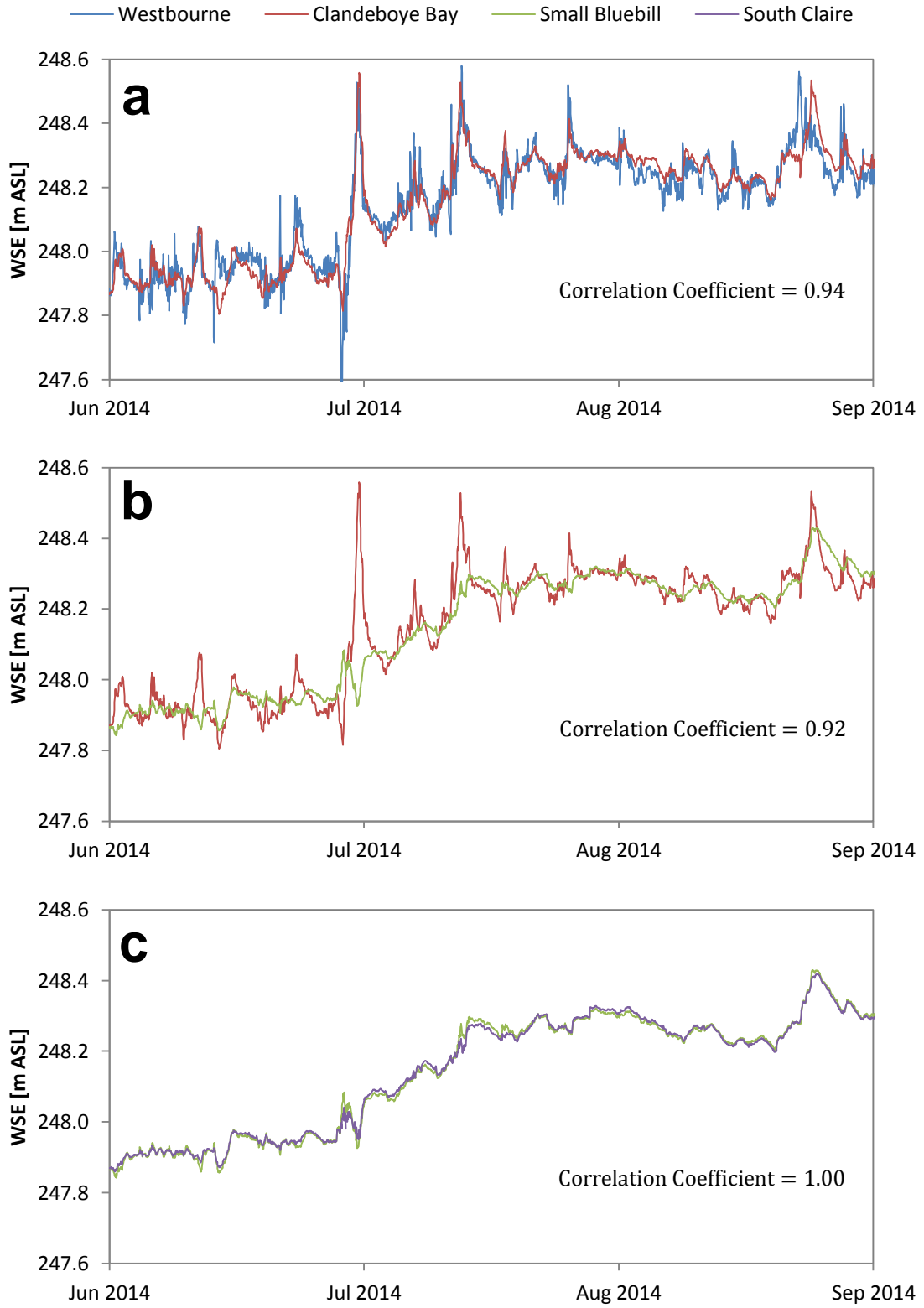


Figure 6:1 – WSE Comparisons across the East Side of Delta Marsh, 2014

a) Westbourne vs. Clandeboye; b) Clandeboye vs. Small Bluebill; c) Small Bluebill vs South Claire

As described in Section 2.1, the flux through the Clandeboye Channel was considered proportional to the sum of discharges through Waterhen, Crooked, and Fish Creeks. As mentioned in Section 4.1.1, Crooked and Fish Creeks carried considerably less water than Waterhen Creek. Recall that ADCP surveys were conducted at all three of these channels during 2013. Figure 6:2 compares the discharges through Waterhen against the discharges through the other two channels. The x and y coordinates of each point are the average measured discharges on a given day through Waterhen and the comparison channel, respectively. Note that the discharges through Crooked and Fish Creeks appeared to be 15% and 4% of those through Waterhen Creek, respectively. If these few points accurately represent the natural flow conditions on the east side, it can be postulated that around 85% of the flux through Clandeboye Channel travels through Waterhen Creek.

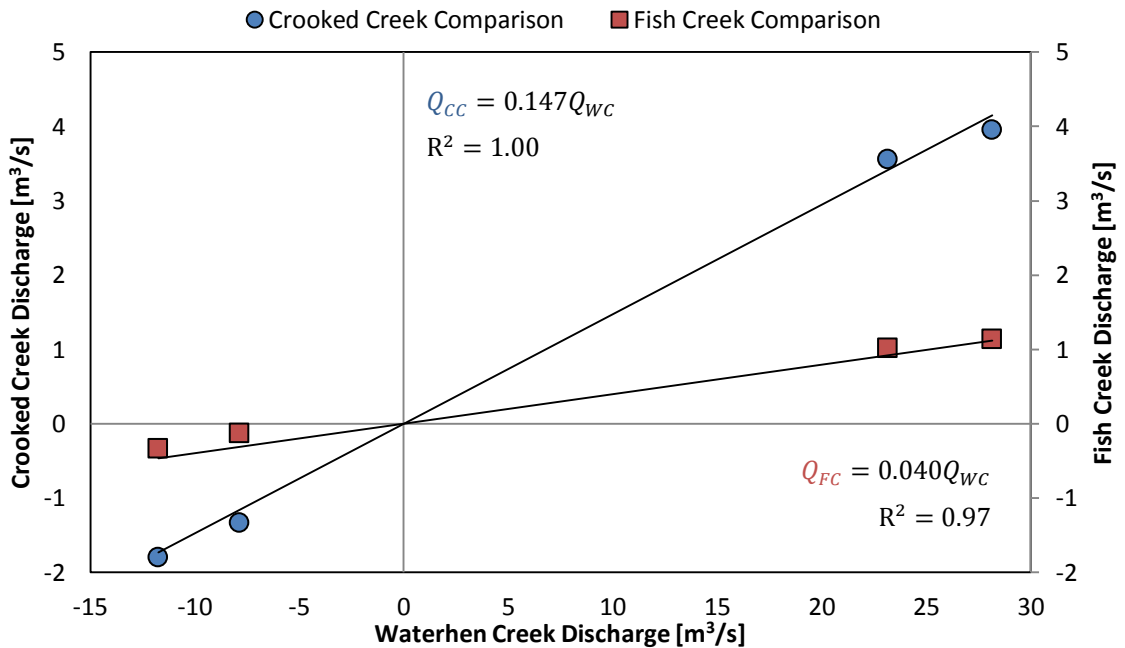


Figure 6:2 – Comparison of East-Side Channel Capacities, 2013

In fact, Waterhen Creek was observed to have the highest discharge capacity of all four metered channels. Recall that complete VIM discharge records were obtained for Delta

Channel and Waterhen Creek for 2014. Figure 6:3 shows the cumulative volumes through Delta Channel, Waterhen Creek, and both combined. On average, the discharge carried by Delta Channel is approximately 19% of the discharge carried by Waterhen Creek (fairly consistently, as the correlation coefficient between the two records is 0.99).

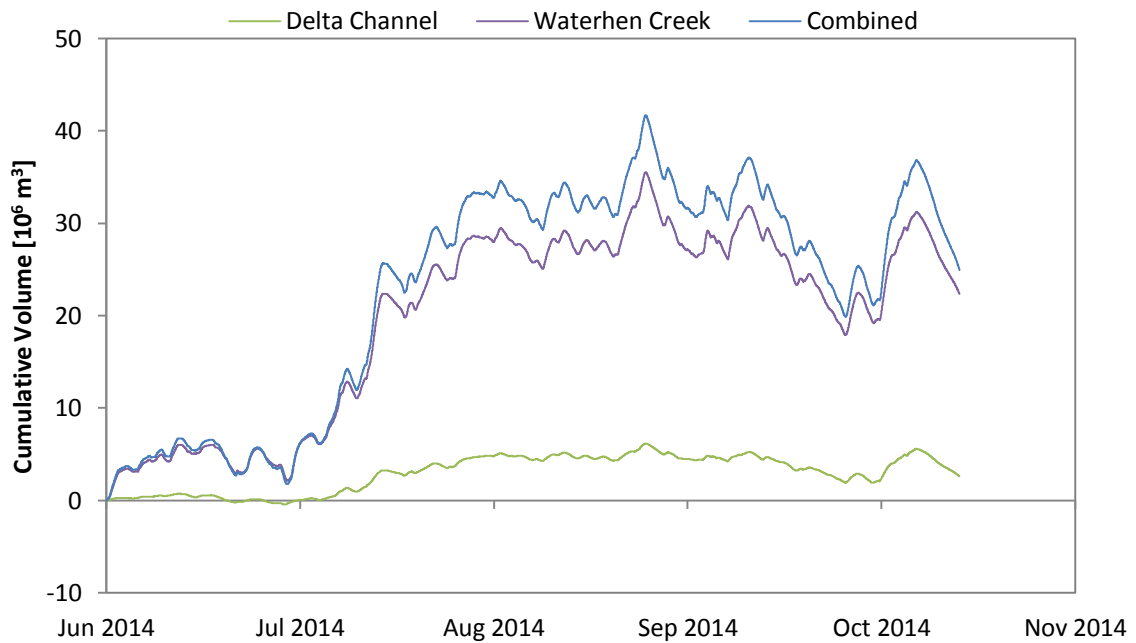


Figure 6:3 – Comparison of Delta Channel and Waterhen Creek Capacities, 2014

Assuming these approximations are consistent from year to year, the proportional capacities of each channel can be quantified as follows:

- Waterhen Creek: 73% of total flux into carp exclusion zone
- Delta Channel: 13% of total flux into carp exclusion zone
- Crooked Creek: 11% of total flux into carp exclusion zone
- Fish Creek: 3% of total flux into carp exclusion zone

Thus, modelling should show much higher rates of exchange at the east side of the marsh, specifically through Waterhen Creek.

6.1.2. Nutrient Analysis

Diurnal water samples were collected in Delta Channel and Waterhen Creek in 2014 for analysis of total phosphorus (TP) concentration. The primary purpose of this was to establish how efficiently the marsh stores nutrients, if at all. Ideally, discharges from the marsh to the lake would have lower nutrient concentrations than discharges in the opposite direction. This was not observed. Figure 6:4 shows two measurement records at Delta Channel: the diurnally-averaged discharge and the composite TP concentrations. Note that the concentration record is far less variable than the discharge record; there was no apparent correlation between concentration and the direction or magnitude of flow. Since the concentration was relatively static, it would be expected that the main factor controlling the mass flux of TP into or out of the marsh is discharge. This is supported in Figure 6:5; concentrations have been multiplied against corresponding discharges to yield a mass flux record, which fits extremely well over the discharge record. This is illustrated quantitatively in Figure 6:6 (Delta Channel) and Figure 6:7 (Waterhen Creek).

Since there are rapid and repeated changes in flow direction at these two channels, the same parcel of water may pass across the auto-sampling intake for an extended period. This may contribute to the non-variability in measured TP concentrations. However, this hypothesis relies on the assumption that the parcel of water does not disperse into the lake or marsh. Regardless, these measurements cannot be used to classify the marsh as either a source or a sink, as discharge governs mass flux. During years when the marsh experiences a net gain in water volume, it will gain nutrients; in a year where it experiences a net loss in volume, it will contribute nutrients.

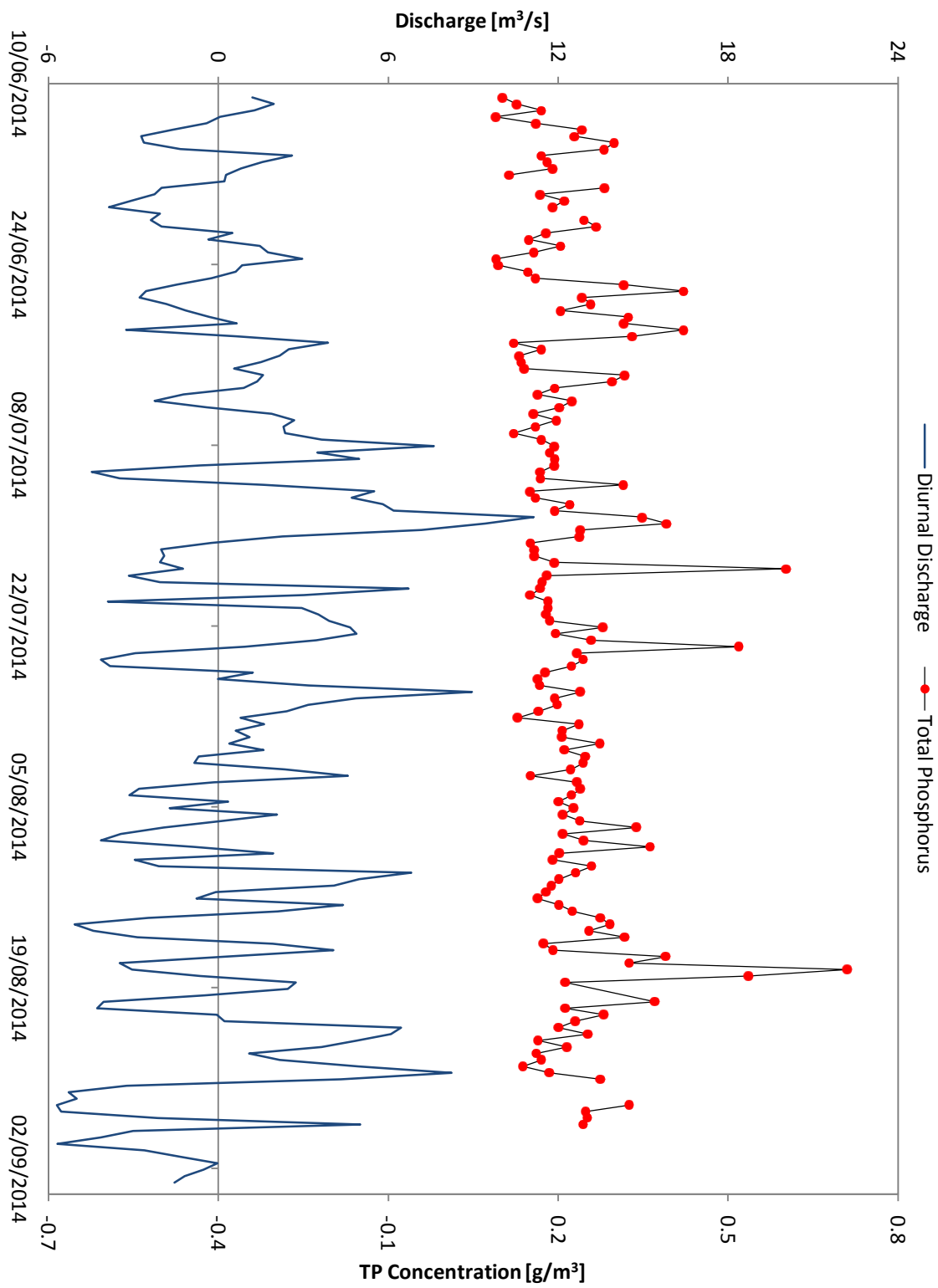


Figure 6:4 – Discharge vs. TP Concentration at Delta Channel, 2014

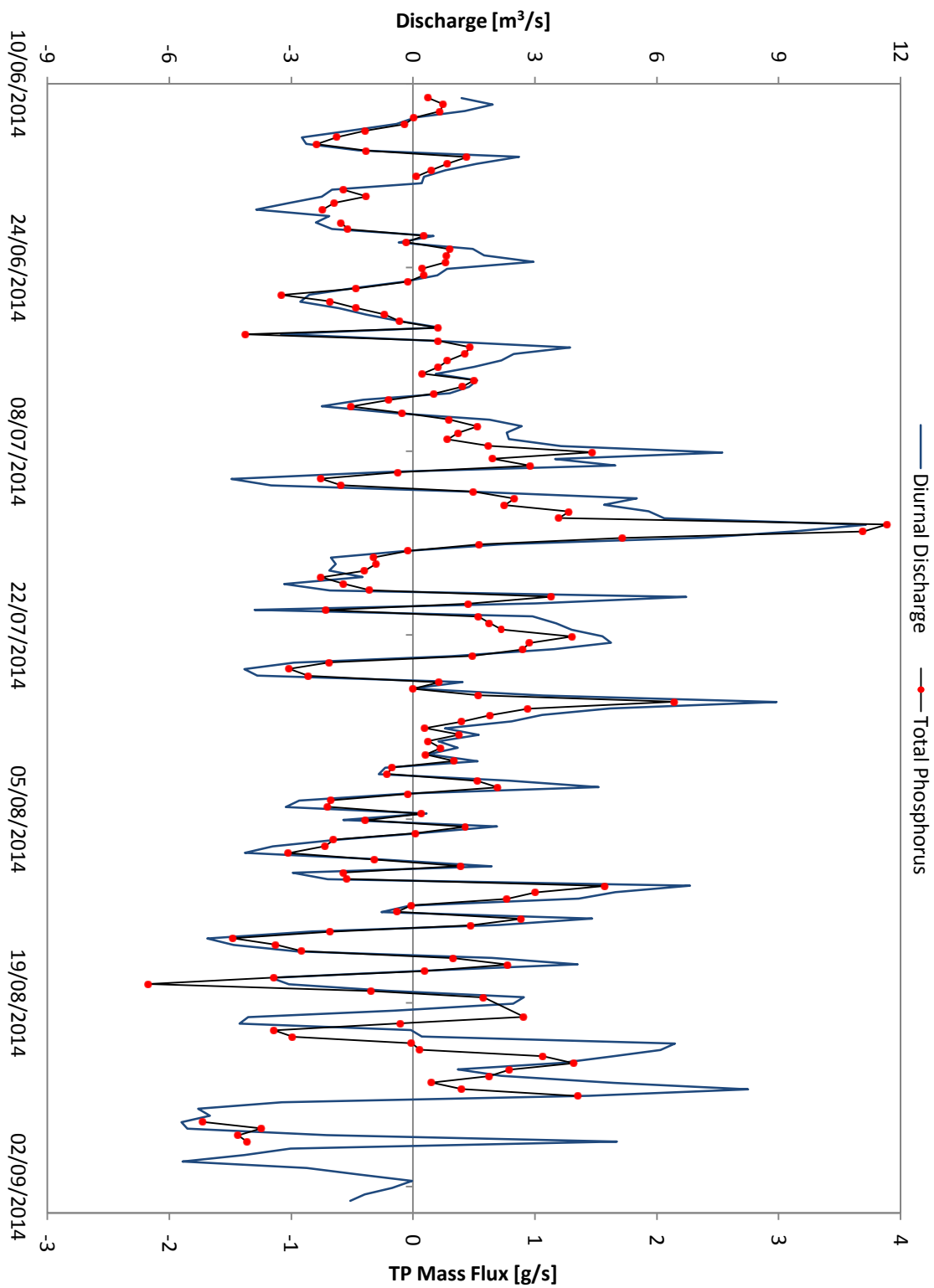


Figure 6:5 – Discharge vs. TP Mass Flux at Delta Channel, 2014

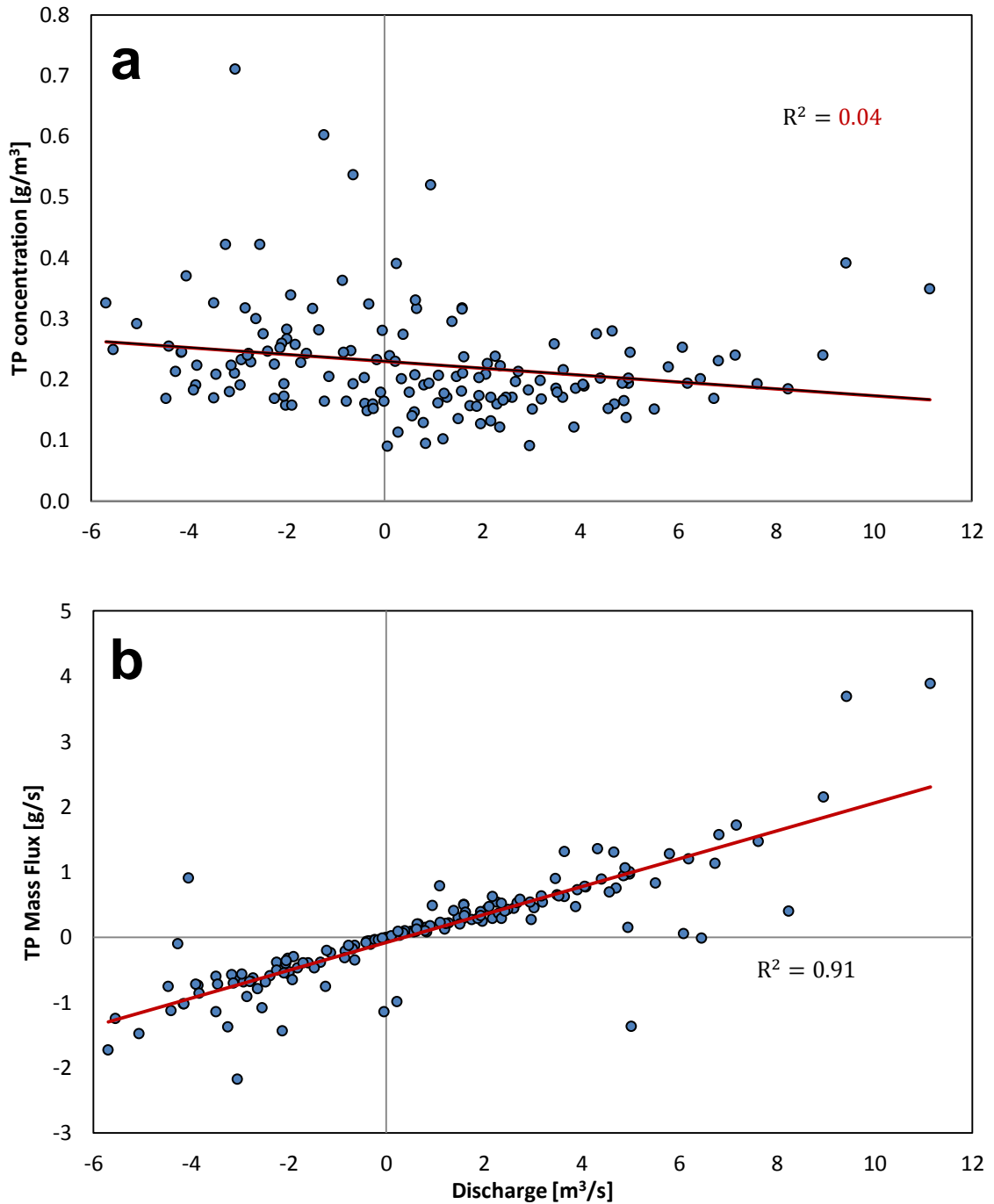


Figure 6:6 – Discharge vs. TP Correlations at Delta Channel, 2014

a) Discharge vs TP Concentration; b) Discharge vs TP Mass Flux

There is no apparent correlation between discharge and concentration (Figure 6:6a), and virtually all of the variability in mass flux is a function of discharge (Figure 6:6b).

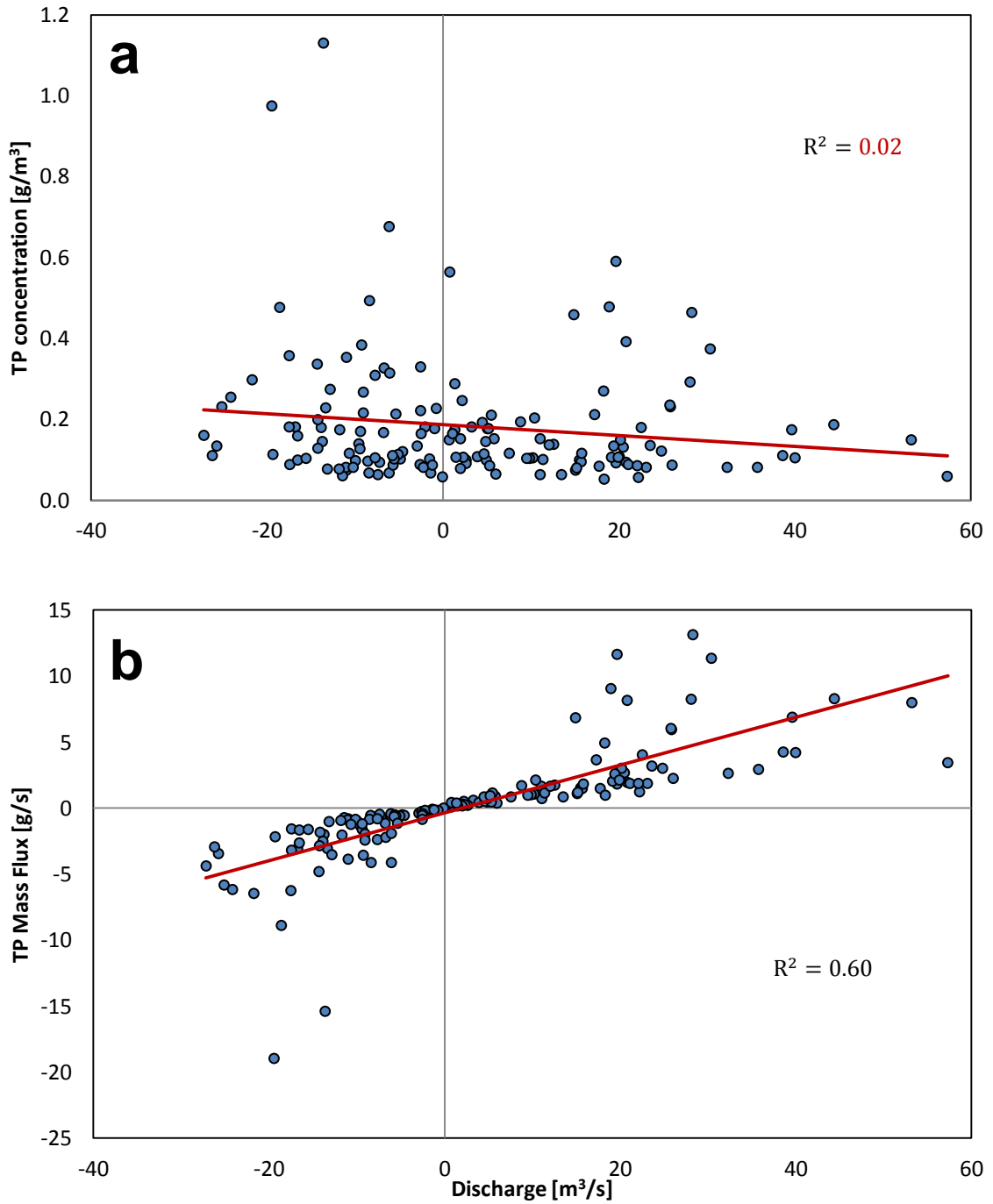


Figure 6:7 – Discharge vs. TP Correlations at Waterhen Creek, 2014

a) Discharge vs TP Concentration; b) Discharge vs TP Mass Flux

6.2. Hydrodynamic Modelling

2D Hydrodynamic and transport modelling was performed for the scenarios proposed in Section 4.2.1, and results are shown in this section. These results have been used to interpret the hydrodynamic behaviour of the marsh, the relative impacts of different physical controls, and to forecast the impact of proposed flood diversion infrastructure.

6.2.1. Baseline Conditions

The baseline hydrodynamic conditions for the 2013 and 2014 open water seasons were interpreted directly from the calibration and validation simulations, respectively. These simulations accounted for inputs to and outputs from Lake Manitoba and measured/estimated meteorology, but excluded watershed contributions (as discussed in Section 4.2.1). The model results are shown below, with inferences into the hydrodynamic behaviour of the marsh.

Water level fluctuation was compared across the same locations compared in Figure 6:1. Figure 6:8a shows the difference in WSE record between the WSC gauge at Westbourne and at Clandeboye Bay. The model supports the observation that fluctuation is damped on the marsh side. Figure 6:8b shows the difference between Clandeboye Bay and Small Bluebill Bay. Again, peak events are damped on the inside. Finally, Figure 6:8c shows the difference between Small Bluebill Bay and South Claire Lake. Water level fluctuation is marginally damped, once again matching the observations. Note that the adjacent water levels have fairly high correlation coefficients. In fact, for 2014, the correlation coefficient between any two water level outputs from inside the marsh was always above 0.9, indicating that the marsh tends to rise and fall relatively uniformly.

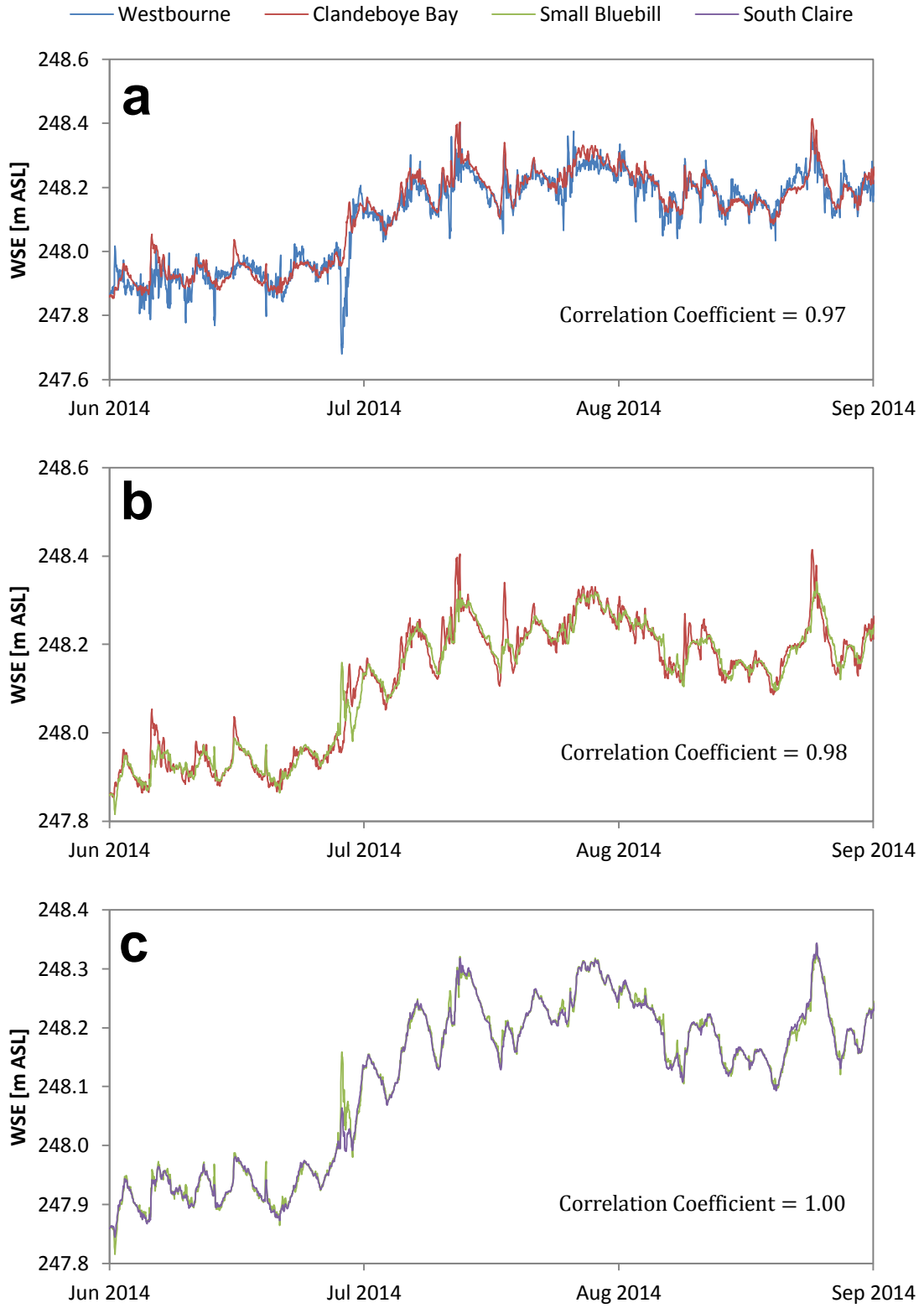


Figure 6:8 – Simulated WSE Comparisons across the East Side, 2014

a) Westbourne vs. Clandeboye; b) Clandeboye vs. Small Bluebill; c) Small Bluebill vs South Claire

Table 6:1 lists the average annual flow capacities of Crooked and Fish Creeks, relative to Waterhen Creek. Note that modelled capacities are consistent, and closely match the observed capacities. The furthest right column lists the correlation coefficients between the instantaneous modelled discharges and those at Waterhen Creek. Note that the discharges through Crooked and Fish Creeks correlate incredibly well with those through Waterhen Creek. Thus, it appears that all three channels are influenced by the same hydraulic controls, and Waterhen Creek consistently carries 80-85% of the flow entering or exiting the marsh through the east side.

Table 6:1 – Modelled East-Side Flow Capacities

Location	Year	% of Waterhen Creek		Correlation with Waterhen
		Observed	Modelled	
Crooked Creek	2013	15%	14%	0.98
	2014	N/A	16%	0.99
Fish Creek	2013	4%	6%	0.98
	2014	N/A	8%	0.98

The modelled capacities of Delta Channel are 22% and 30% of the Waterhen capacities for 2013 and 2014, respectively. These are within a similar order of magnitude as the observed 2014 capacity of 19%. From modelling, the proportional capacities of each channel can be quantified as follows (note that these values agree with the measured capacities):

- Waterhen Creek: 65-70% of total flux into carp exclusion zone
- Delta Channel: 15-20% of total flux into carp exclusion zone
- Crooked Creek: 9-11% of total flux into carp exclusion zone
- Fish Creek: 4-6% of total flux into carp exclusion zone

Recall that water level fluctuation was observed to decrease into the marsh. It was hypothesized that interior channels must carry noticeably less discharge than those connected directly to the lake. Figure 6:9a compares the cumulative instantaneous discharges through Waterhen, Crooked, and Fish creeks against the Clandeboye Channel discharges for 2014. When the internal (y-axis) discharges are lagged by one hour (Figure 6:9b), there is a negligible drop in correlation, but a noticeable drop when lagged by two hours (Figure 6:9c). Around 85% of the Clandeboye Channel inflow makes it to one of the three internal channels. Similar results were obtained for 2014 (Figure 6:10). When the internal discharges are lagged by one hour (Figure 6:10b), there is a noticeable rise in correlation, and a small drop when lagged by two hours (Figure 6:10c). Around 90% of the Clandeboye Channel inflow makes it to the internal channels.

The observations from both years can be resolved as follows: the discharge signal through Clandeboye channel takes around an hour to reach the other channels; 85-90% of the flow into the marsh through Clandeboye Channel makes it through the internal channels, while 10-15% is stored in Clandeboye Bay; conversely, 85-90% of the outflow from the marsh through Clandeboye Channel first comes through the internal channels, while 10-15% is water that was stored in Clandeboye Bay. Thus, the discharges through Waterhen Creek, Crooked Creek, Fish Creek, and Clandeboye Channel can be estimated confidently as long as discharge measurements are obtained for at least one of the channels.

Similar comparisons were attempted between Delta Channel and The Gap in Figure 6:11. There was no correlation between flows for either year, implying that The Gap is not hydraulically controlled by Delta Channel. Lagging did not improve correlation.

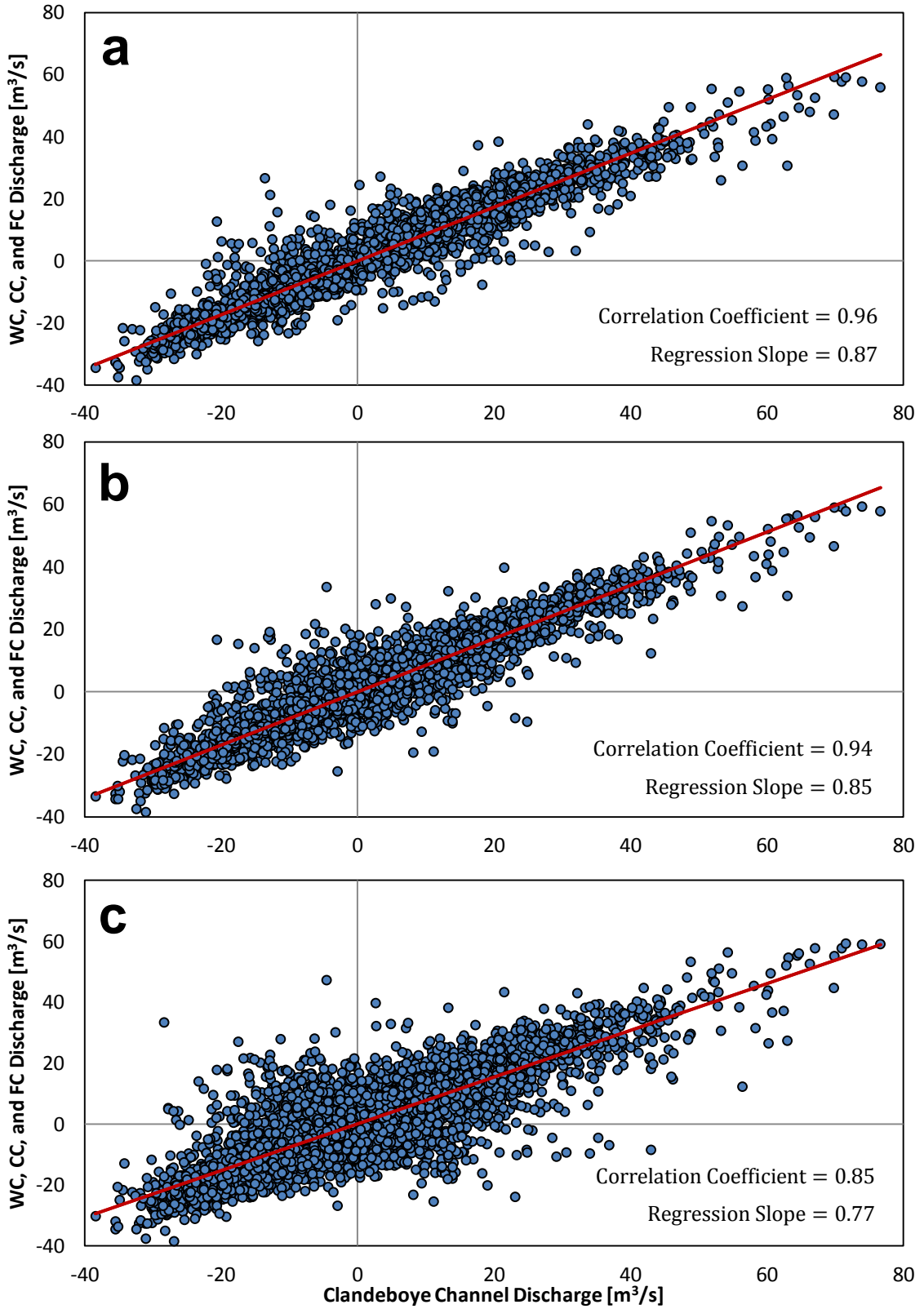


Figure 6:9 – Clandeboye Channel Discharge Comparison, 2013

a) Default comparison; b) internal discharges lagged by one hour; c) lagged by two hours

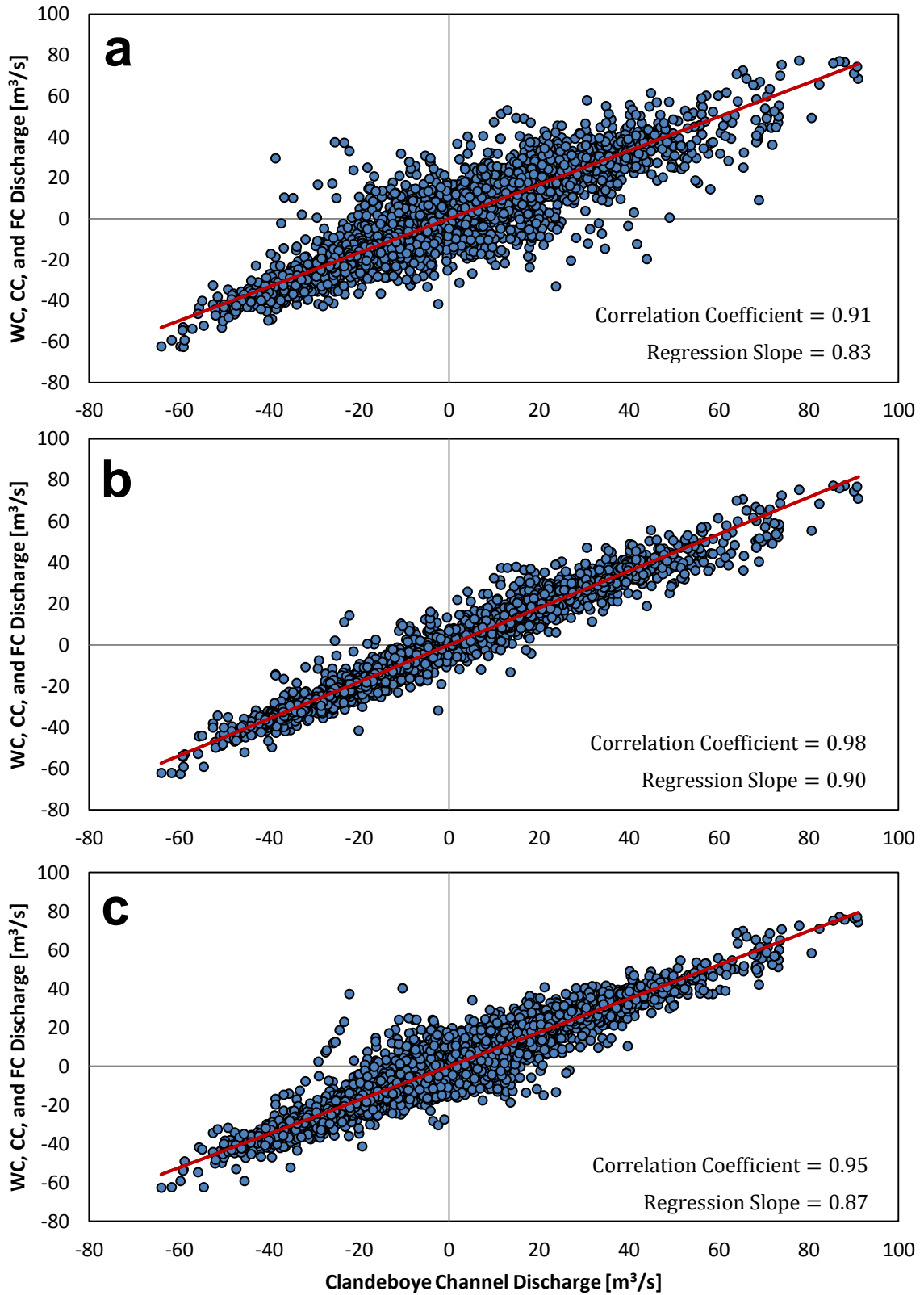


Figure 6:10 – Clandeboye Channel Discharge Comparison, 2014

a) Default comparison; b) internal discharges lagged by one hour; c) lagged by two hours

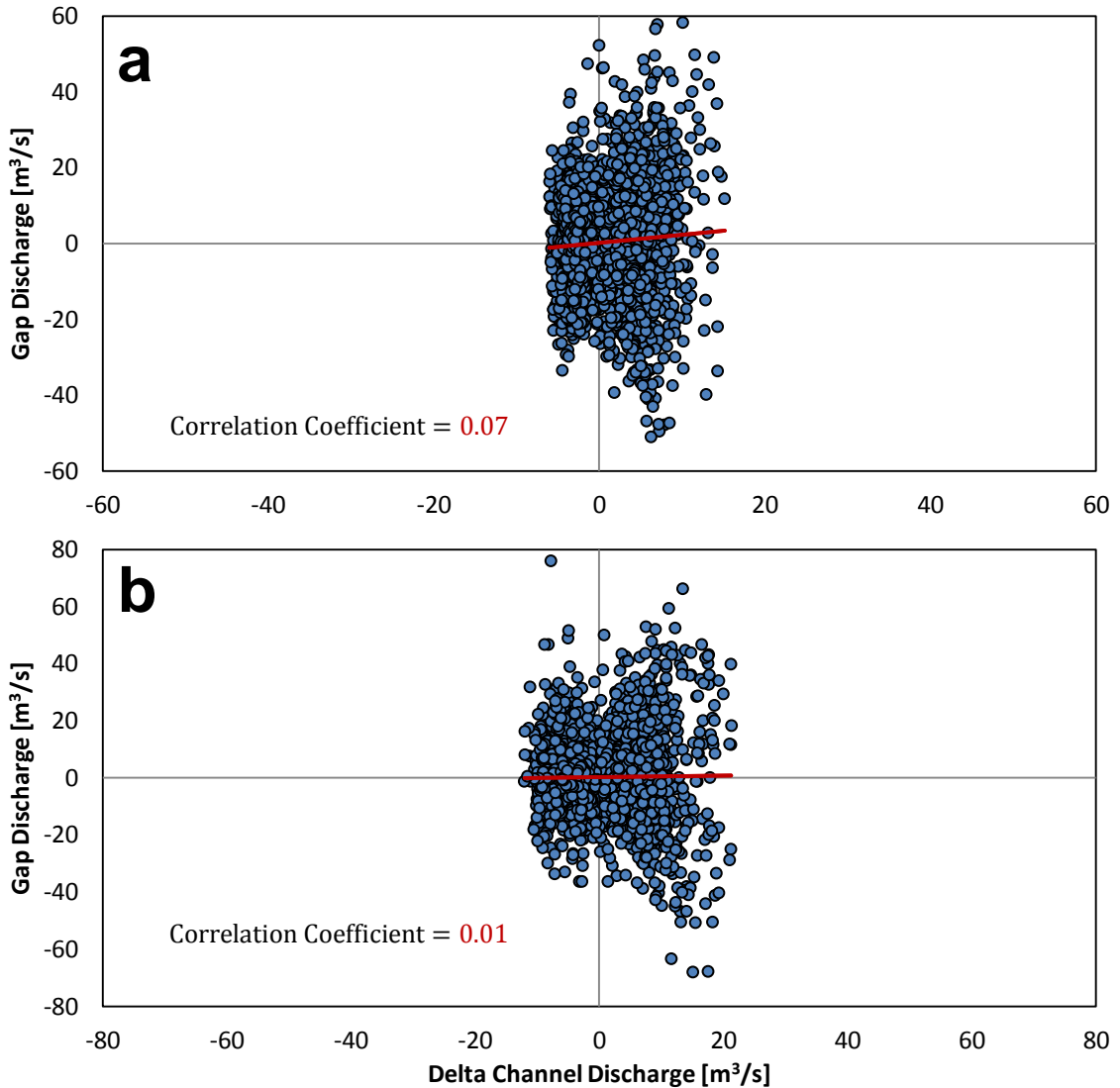


Figure 6:11 – Delta Channel/ The Gap Discharge Comparison

a) 2013; b) 2014

In fact, the magnitudes of discharge through The Gap greatly exceed those through Delta Channel. Thus, it is more likely that discharge through The Gap is controlled from the east side. Discharge may be controlled by a combination of east-side inflows (through Clandeboye Channel) and wind set-up across Simpson Bay. This can be investigated by interpreting model results, but can only be confirmed by collecting discharge measurements directly at The Gap.

To identify the extent of the influence of east-side fluxes, similar discharge comparison was performed working inwards from the Waterhen Creek area (recall that Figure 4:4 shows the location of the discharge output planes). The summed discharges through Waterhen and Fish Creeks were compared against those from Waterhen Bay to Bluebill Bay (Figure 6:12a). The summed discharge through Bluebill-Waterhen and Crooked Creek was compared against the discharge from Bluebill Bay to Simpson Bay (Figure 6:12b). Finally, the discharge through Simpson-Bluebill was compared against the discharge through The Gap (Figure 6:12c). Note the negative correlation in the latter comparison. This was due to the convention of positive discharge at each plane; eastward at The Gap, westward through Simpson-Bluebill.

For both years, the modelled discharge signal is transmitted very well from the east end of the marsh through to The Gap, supporting the hypothesis that changes in storage throughout the majority of the marsh are governed by discharges through Clandeboye Channel. During 2013, 92% of the discharge through Waterhen and Fish Creeks passed from Waterhen Bay into Bluebill Bay. Less than 10% of the discharge was stored between these two planes. All of the discharge through Crooked Creek and Waterhen-Bluebill passed into Simpson Bay, implying that, on average, Bluebill Bay did not store water. This raises suspicion in the confidence of the comparison; perhaps the sum of Crooked Creek and Bluebill-Waterhen flows did not fully capture the discharge from the east. Regardless of the regression slope, there was a strong correlation between the discharge records, implying that the signal was transmitted well. Finally, 51% of the discharge through Bluebill-Simpson passed through The Gap. Half the water passed into Cadham Bay, and half was stored in Simpson Bay. Results for both years are summarized in Table 6:2.

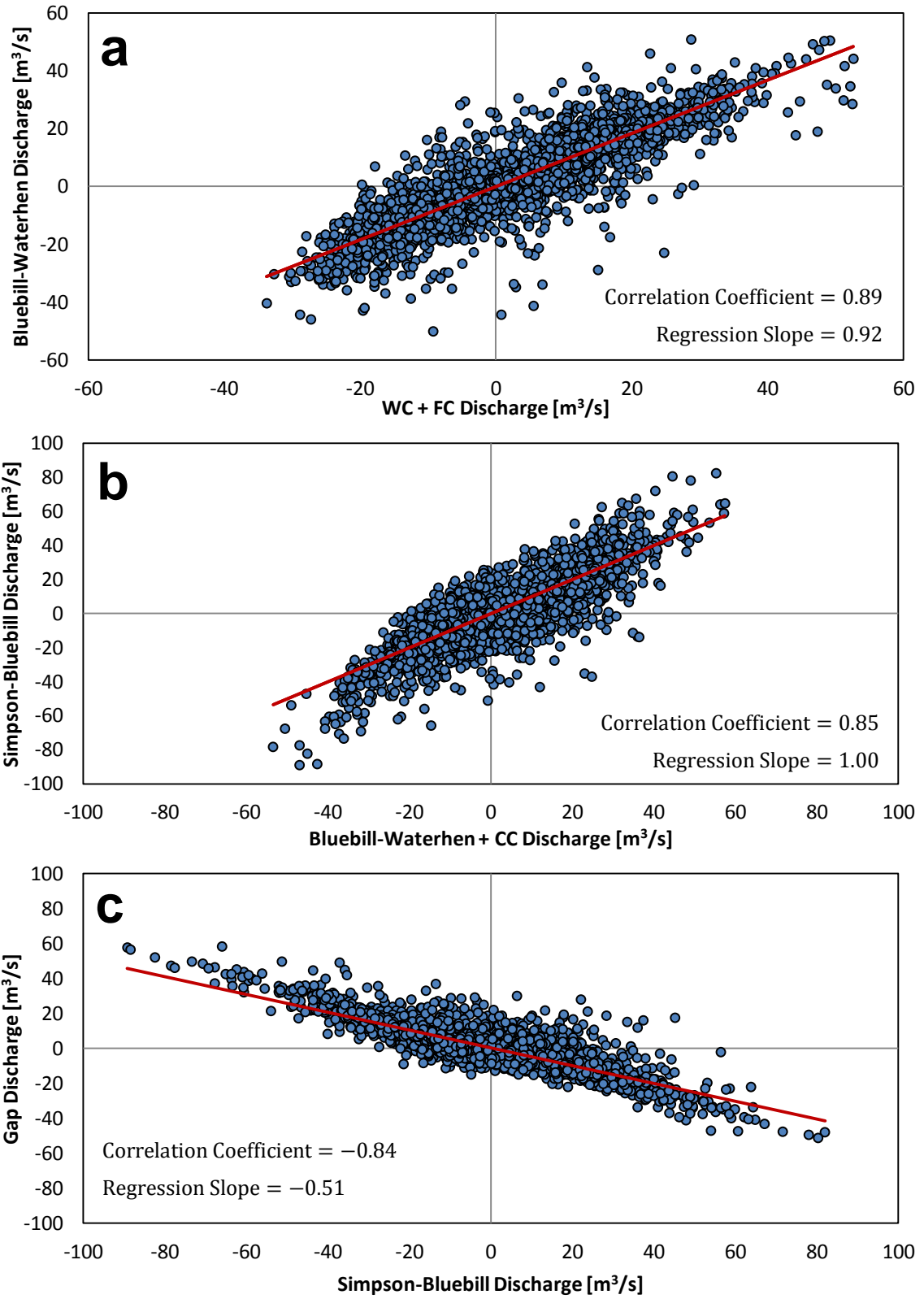


Figure 6:12 – Internal Discharge Comparison, 2013

a) Bluebill-Waterhen / WC+FC; b) Simpson-Bluebill / Bluebill-Waterhen; c) Bluebill-Waterhen / Gap

Table 6:2 – Summary of Discharge Comparison Results

Planes Being Compared		Year	Correlation	Regression	Lag
Exterior	Interior		Coefficient	Slope	[hr]
Clandeboye Channel	WC + CC + FC	2013	0.96	0.87	0
		2014	0.98	0.90	1
WC + FC	Bluebill-Waterhen	2013	0.89	0.92	1
		2014	0.93	0.89	0
Bluebill-Waterhen + CC	Simpson-Bluebill	2013	0.85	1.00	0
		2014	0.85	0.84	0
Simpson-Bluebill	Gap	2013	-0.84	-0.51	0
		2014	-0.72	-0.41	0

Since the discharge signal was transmitted well from plane-to-plane, direct correlation may be expected between discharges through Clandeboye Channel and The Gap. This is not the case, as illustrated in Figure 6:13. Lagging did not improve the correlation.

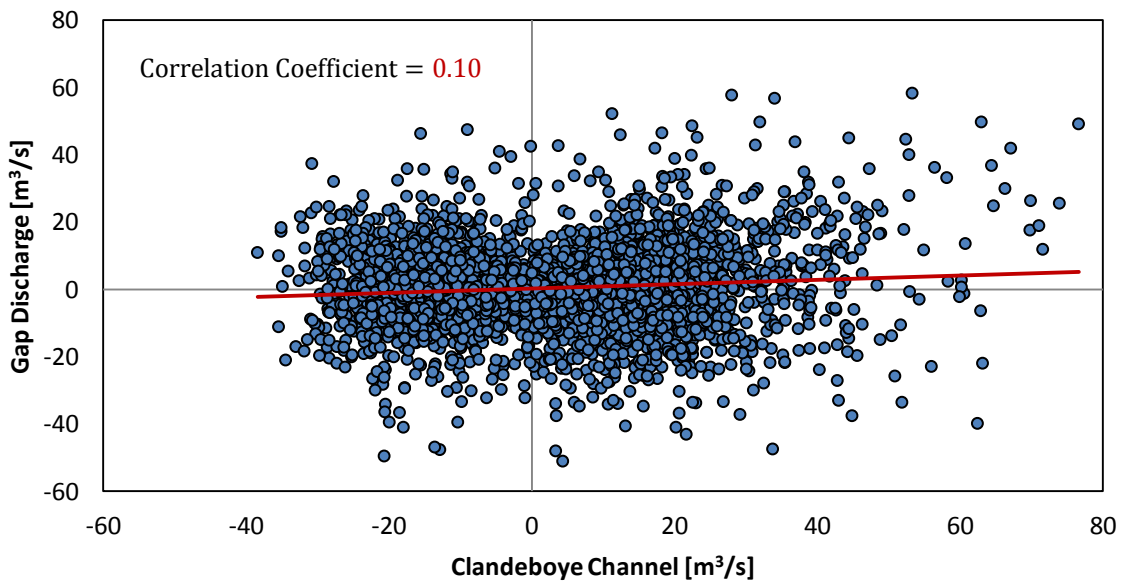


Figure 6:13 – Clandeboye Bay / The Gap Discharge Comparison, 2013

Unfortunately, discharge through The Gap cannot be estimated directly from discharge through either Delta or Clandeboye Channels. However, it was observed that the discharge across any of these output planes could be estimated reasonably by applying linear regression to the discharges across an adjacent plane. Thus, it was hypothesized that discharge through The Gap could be estimated as follows, accounting for lagging where identified:

1. Crooked Creek as a linear function of Waterhen Creek
2. Fish Creek as a linear function of Waterhen Creek
3. Bluebill-Waterhen as a linear function Waterhen and Fish Creeks combined
4. Simpson-Bluebill as a linear function of Bluebill-Waterhen and Crooked combined
5. The Gap as a polynomial linear function of Simpson-Bluebill and Delta Channel

This method was tested using the modelled Delta Channel and Waterhen Creek discharges for 2013, as detailed in Table 6:3. Note that R^2 values relate to the performance of the simulated discharge record across a plane against the modelled discharges at the same plane. Unfortunately, compounding error impeded successful simulation.

Table 6:3 – Results of Successive Linear Regression of Cross-Marsh Discharges

Step	Plane to be simulated	Plane(s) used as input	R^2
1	Crooked Creek	Waterhen Creek	0.97
2	Fish Creek	Waterhen Creek	0.96
3	Bluebill-Waterhen	Waterhen and Fish Creeks	0.80
4	Simpson-Bluebill	Bluebill-Waterhen and Crooked Creek	0.34
5	The Gap	Simpson-Bluebill and Delta Channel	0.11

Estimation of discharge through The Gap may have been confounded by wind-driven changes in momentum across Simpson and Bluebill Bays. These winds likely influence the discharge signal as it is transmitted from east to west. Despite this, the previous interpretation of flow behaviour holds true; inflow from the east end propagates toward The Gap. Note that all interpretations of water movement throughout the marsh were based on modelled discharges. In order to gain confidence in these interpretations, discharge should be monitored at The Gap.

Modelling also supported the hypothesis that Portage Creek acts as a storage zone for the marsh. The channel conveys snowmelt runoff from the watershed to the marsh during the first several weeks of spring. Afterwards, increases in the marsh level cause water to backup into the creek. Figure 6:14 shows net inflow into the mouth of Portage Creek from Simpson Bay in 2013 (note that negative values represent marsh-to-creek flow). Also note that although overland runoff through the channel has been neglected, the storage trend continues throughout the season.

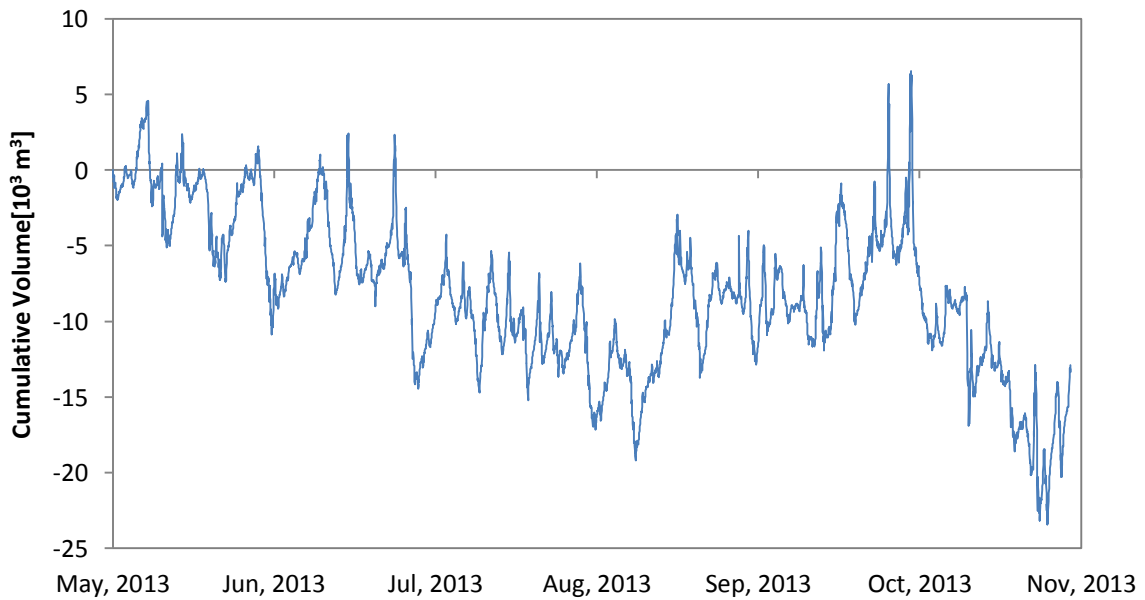


Figure 6:14 – Cumulative Volume through Portage Creek, 2013

It appears that the hydrodynamic behaviour of Portage Creek, like the rest of the marsh, is governed by water level fluctuation on the southern shore of Lake Manitoba. Figure 6:15 shows the comparison of discharges through Simpson-Bluebill and Portage Creek. There is a moderate correlation between both discharge records, implying that the discharge signal from the east end influences discharge at Portage Creek to some extent.

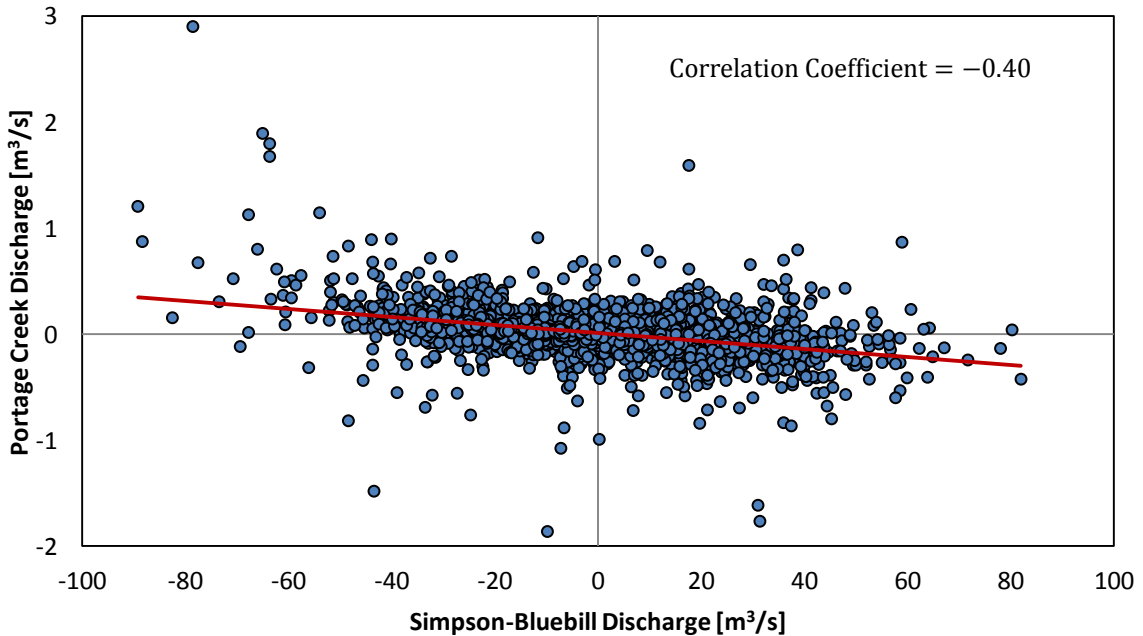


Figure 6:15 – Simpson-Bluebill / Portage Creek Discharge Comparison

The flux rates across all of these planes can be expressed as a percentage of the total flux into and out of the marsh. Consider Waterhen Creek as an example; 86% of the discharge into and out of the marsh passes through Clandeboye Channel, 89% of that flow passes through Waterhen, Crooked, and Fish Creeks combined, and Waterhen Creek accounts for 82% of the flow through those three channels. Therefore, roughly 65% of the total marsh flux passes through Waterhen Creek. These percentages are shown in Figure 6:16 for several locations across the marsh.

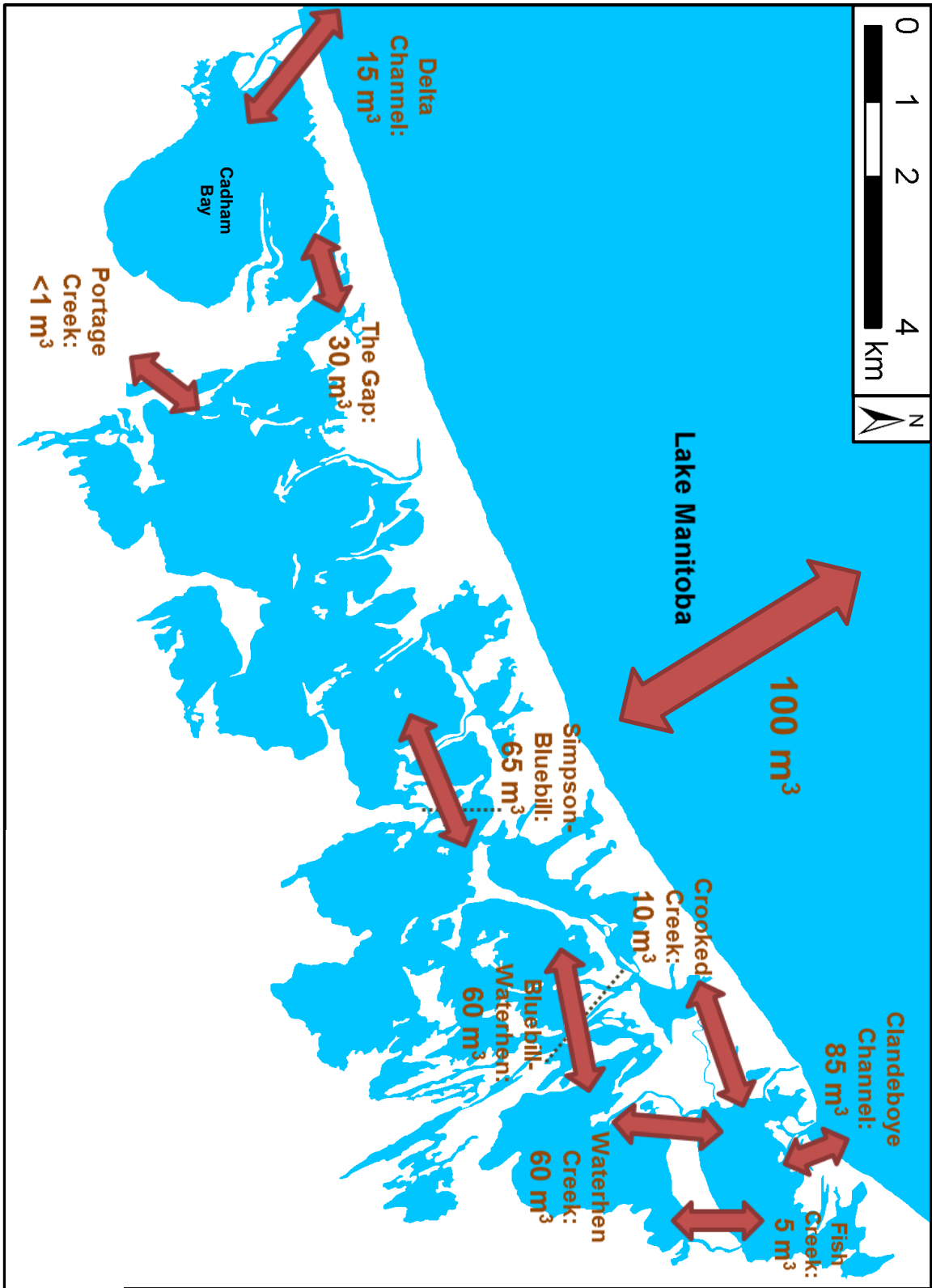


Figure 6:16 – Long-Term Average Flux Rates as Proportions of Total Marsh Flux

The hydrologic residence time of the marsh is another important hydrodynamic characteristic that must be assessed, as changes in residence time can impact the nutrient storage efficiency of a marsh. Residence time is estimated as the average volume of a water body divided by its average outflow. This is simple in a river or lake, where there is a clear and consistent average path that the water follows from the inlet to the outlet. Unfortunately, this is much more complicated at Delta Marsh, for several reasons:

- Two-directional flow occurs at Delta and Clandeboye Channels, and overland inflow occurs variably along the southern border. In a river, flow is one-directional, so all water moves in the same direction. At Delta Marsh, there is no idea of the long-term average path of water movement, and thus “average residence” is effectively meaningless. Residence time can range from minutes to years (or even tens of years) based on a particle’s point of entry and the immediate wind pattern.
- The simplifying assumption of constant storage cannot be applied as it is in a river. Notably, there are drastic yet inconsistent changes to the storage of the entire system due to the irregular operation of the Portage Diversion.

Simply put, the marsh was not observed to be in a hydrologically steady state over either open water season. Thus, the standard approach for the estimation of residence time is not applicable. Instead, isotope hydrology will be used to quantify marsh residence times by Glavonić (in progress). In this thesis, results from the MIKE 21 transport module helped explain the water movement and mixing phenomena in the marsh and lake. By simulating the concentrations, cumulative volumes, and flow paths of waters from the Portage Diversion, Whitemud River and Waterhen River, the model provided an understanding of how, when, and in what quantity water enters and exits different sections of the marsh.

Cumulative discharges through Delta Channel and Clandeboye Bay are shown in Figure 6:17 for 2013 and Figure 6:18 for 2014. Note that cumulative discharge from Waterhen River has not been included in the figures, as water from this source did not reach the marsh. Additional tracer distribution maps are included in Appendix B.

Consider Delta Channel, 2013 (Figure 6:17a); in early May, there was rapid inflow into the marsh that was mostly comprised of water from the Portage Diversion. This was immediately followed by outflow that continued to mid-June. During this outflow period, the cumulative volume of Portage Diversion water only decreased marginally. It appeared that once diversion water had entered Cadham bay, it dispersed quickly, and outflow was mostly comprised of original marsh water. Inflow picked up again in mid-June, when the diversion reopened. Most of the inflow between mid-June and August was water directly from the Portage Diversion. Water continued to flow into marsh after the diversion closed at the start of August, but this inflow was comprised almost entirely of Lake Manitoba water.

Water entered the marsh similarly through Clandeboye Channel in 2013 (Figure 6:17b), and both locations in 2014 (Figure 6:18). Diversion water dominated the composition of inflow waters during operation of the diversion, but did not get flushed out as rapidly when discharge changed direction. In fact, during 2014, the marsh experienced a net loss of total water, but a net gain of diversion water.

Whitemud River water appeared to enter the marsh slightly faster when the diversion was not in operation. Note the interesting trend in the cumulative volume of Whitemud River

water for Figure 6:18. Beginning in July, 2014, the net Whitemud River volume in the marsh steadily increased, while the total net volume decreased. Again, this occurred due to mixing; parcels that had higher concentrations of Whitemud water would enter the marsh during shorter inflow periods, this water would dilute immediately, and much lower concentrations of Whitemud water would exit the marsh during longer outflow periods.

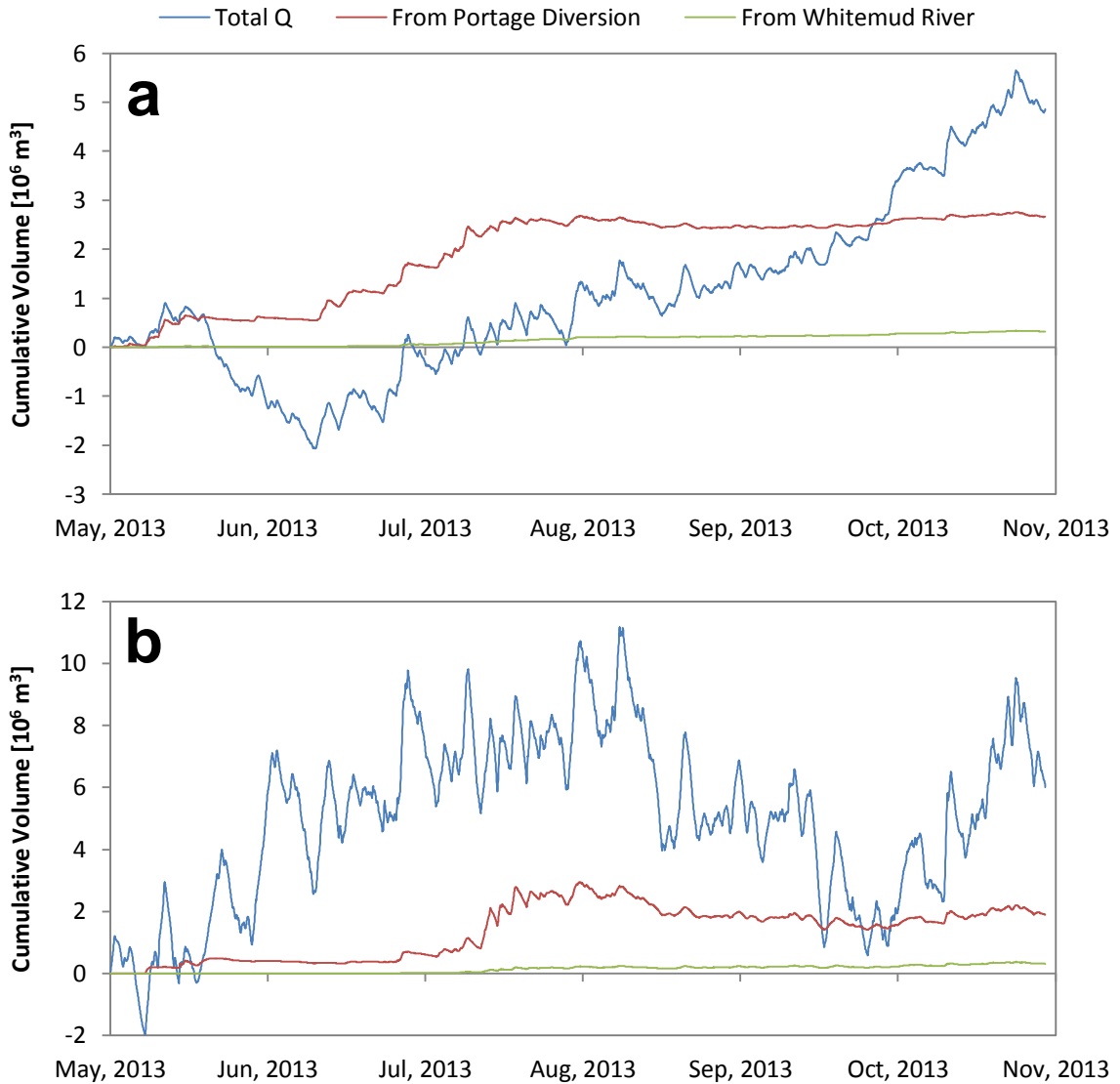


Figure 6:17 – Source-Separated Cumulative Volume into Marsh, 2013

a) Via Delta Channel; b) via Clandeboye Channel

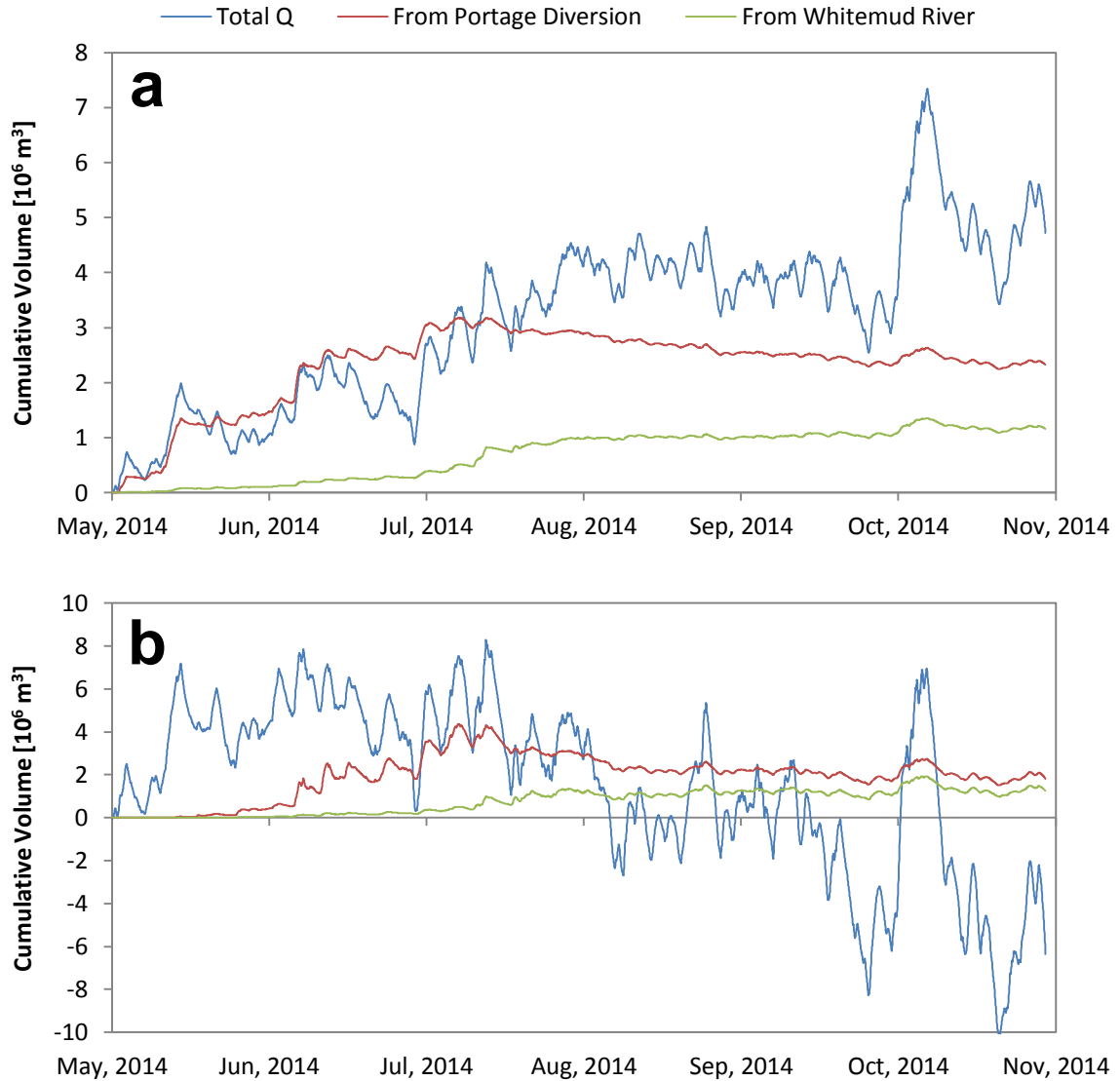


Figure 6:18 – Source-Separated Cumulative Volume into Marsh, 2014

a) Via Delta Channel; b) via Clandeboye Channel

This dilution and mixing phenomenon is illustrated in Figure 6:19 for Portage Diversion inflow to Cadham Bay during May, 2013. Note that the color scale represents the fraction of a unit volume of water that is originally from the Portage Diversion (for example, an element with a value of 0.25 means that 25% of the water in that element at that time step originated from the diversion).

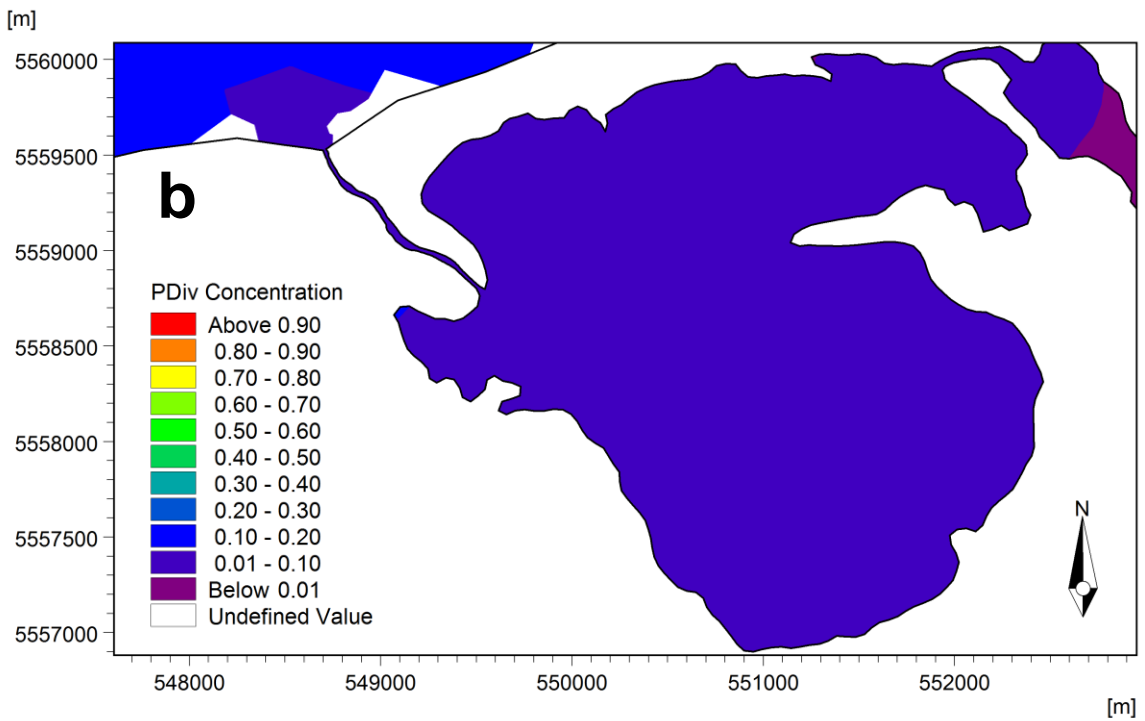
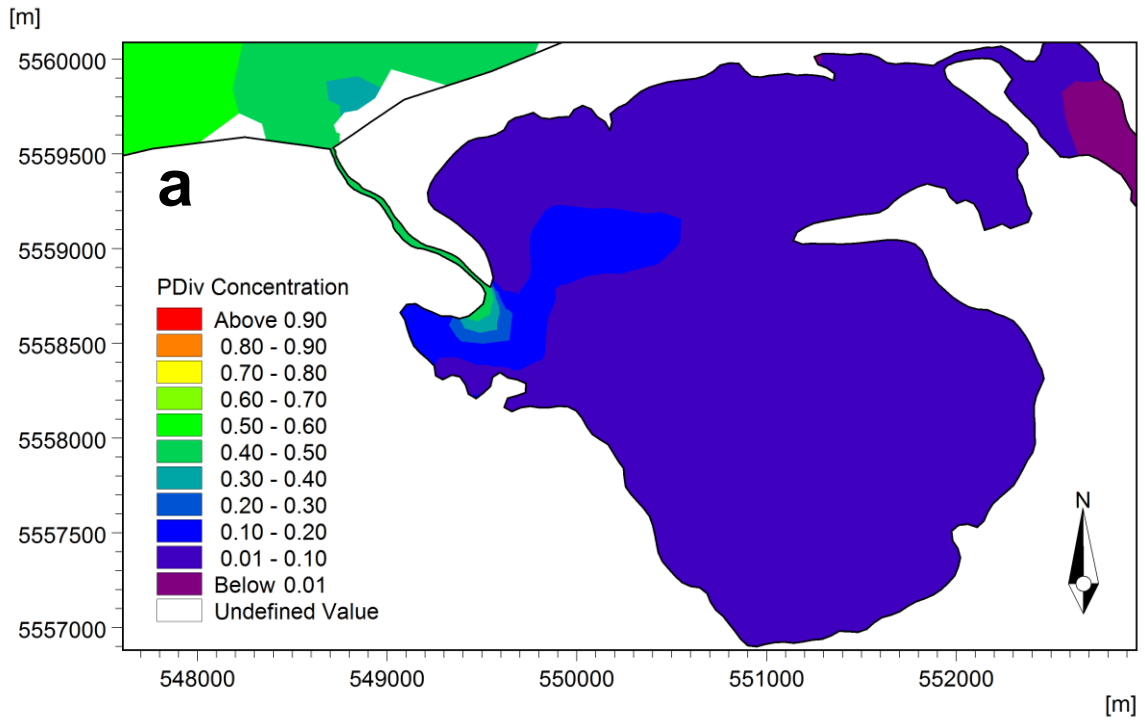


Figure 6:19 – Simulated Diversion Water Concentration across Cadham Bay, 2013

a) High concentration at inflow: 19/05/2013; b) Low concentration at outflow: 21/05/2013

Figure 6:19a shows the distribution of diversion water during an inflow condition. The water flowing in through Delta Channel had a diversion concentration of 40-50%. The concentrated inflow plume diluted fairly quickly once it entered the bay (by this point in May, the majority of Cadham Bay had a diversion concentration of 1-10%); by the time flow had reversed 48 hours later (Figure 6:19b), the outflowing water had a much lower diversion concentration.

Water from the Portage Diversion reached Delta Channel almost immediately (02/05/2013, Figure 6:20a), yet it took an additional six days to reach Clandeboye Channel (08/05/2013, Figure 6:20b) across the lake. Recall that most of the volume into the marsh passed through Clandeboye Channel. It may have been expected that most of the Portage Diversion water enters through the east side, but this was not the case. By the end of October, 2013, 41% of the net volume into the marsh was from the diversion; 24% through Delta Channel, and 17% through Clandeboye Channel. Despite the capacity of Clandeboye Channel, Delta Channel is under 5.5 times the distance from the diversion, and is thus a more direct route for diversion water to enter the marsh.

In 2013, water from the Portage Diversion had spread throughout the marsh by the second half of August (Figure 6:21a). At this point in the season, virtually all of the marsh had a diversion water concentration of at least 1% (excluding some of the more remote bays). Water from the Whitemud River, on the other hand, did not spread as far. By the end of the 2013 simulation, it had not spread into Simpson Bay in any significant concentration (Figure 6:21b).

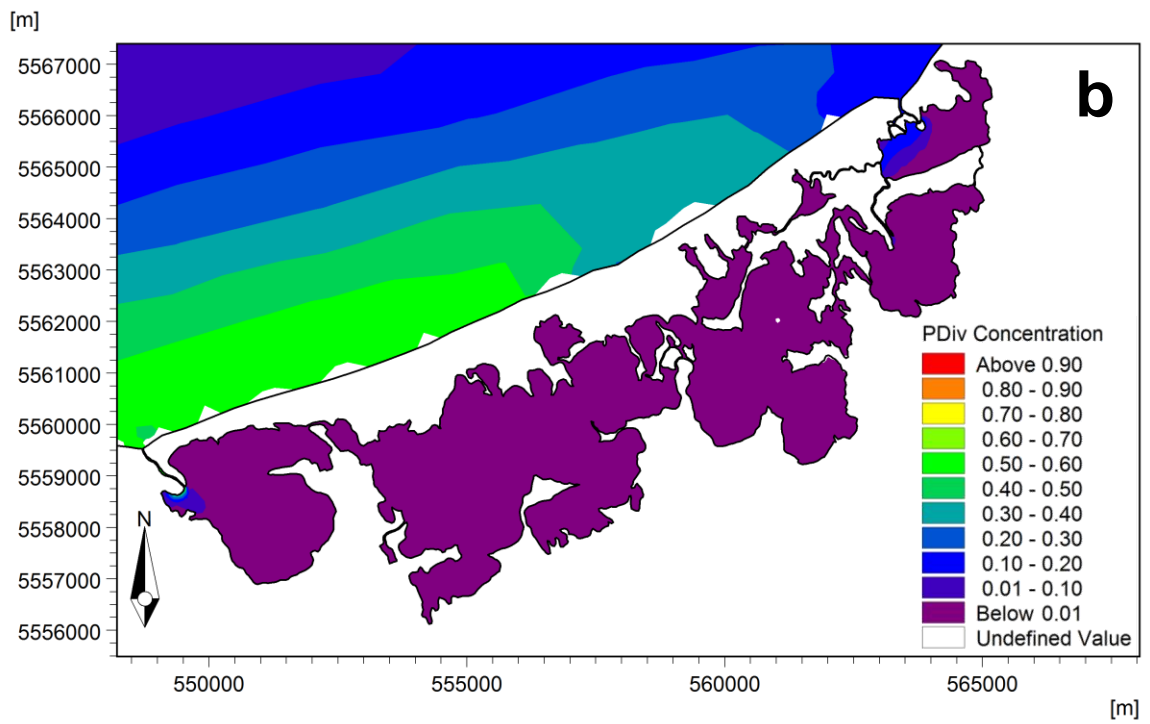
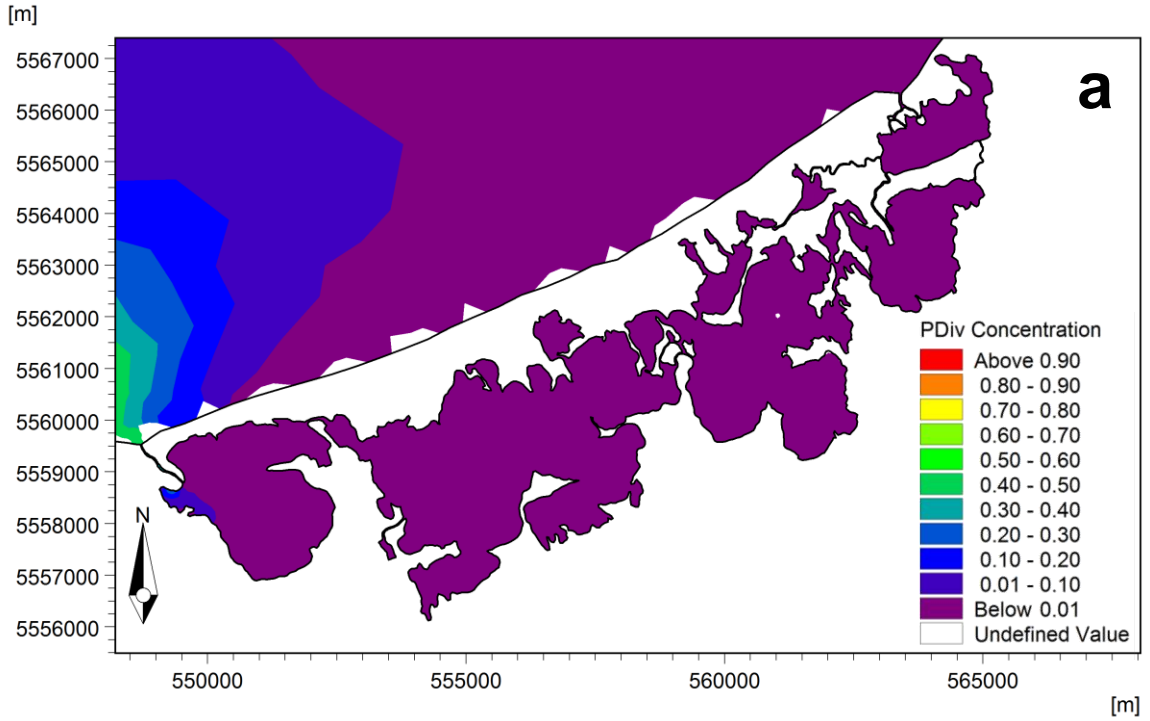


Figure 6:20 – Time of Entry of Portage Diversion Water

a) Delta Channel: 00:00 02/05/2013; b) Clandeboye Channel: 00:00 08/05/2013

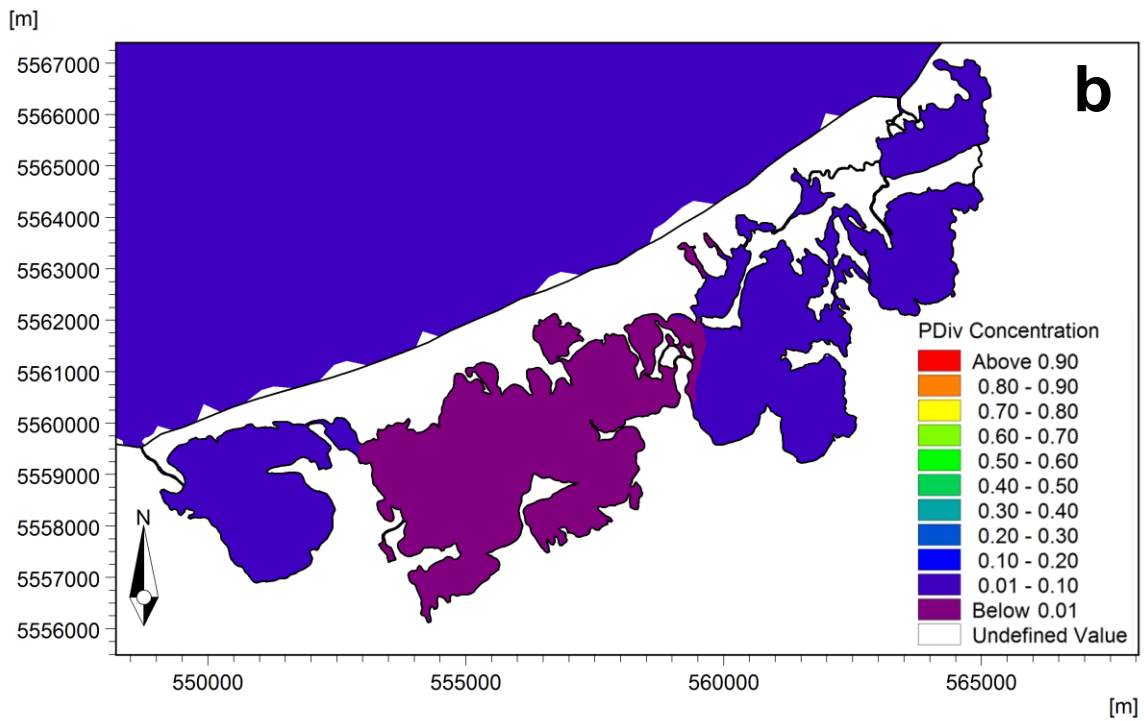
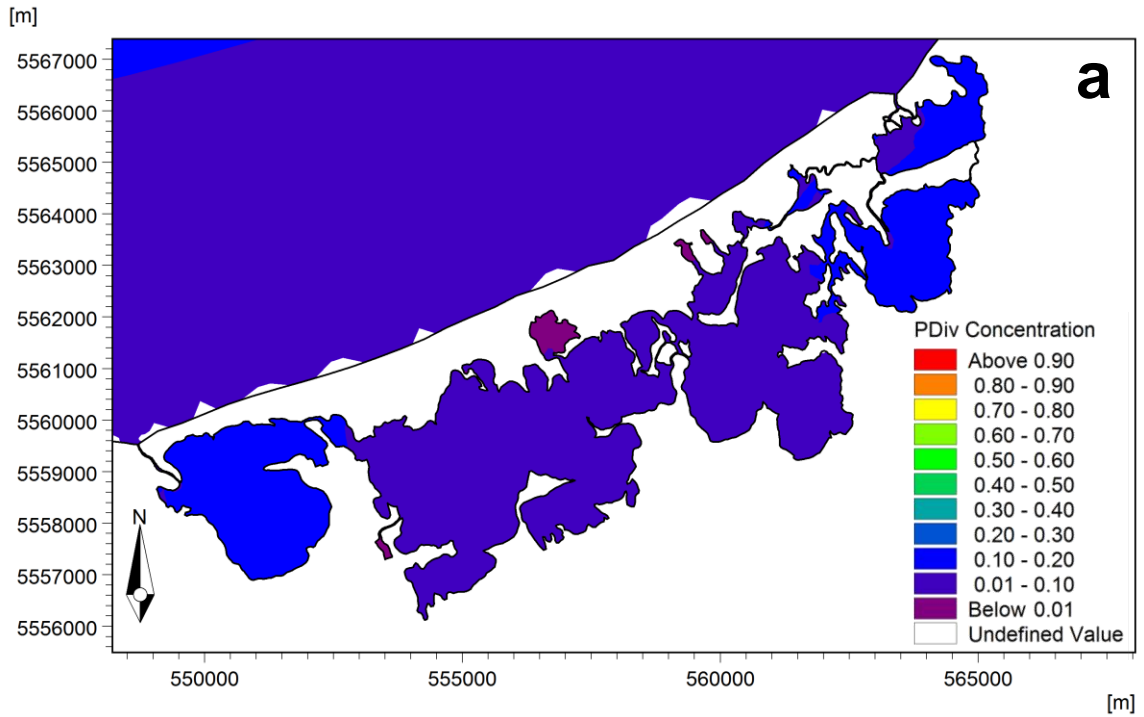


Figure 6:21 – Diversion Tracer Concentrations across Delta Marsh

a) Portage Diversion Water: 00:00 22/08/2013; b) Whitemud River Water: 00:00 31/10/2013

6.2.2. Relative Contribution Assessment

For both simulation years, three scenarios were modelled in an attempt to assess the relative impacts of various controls on marsh hydrodynamics. In each case, the control in question was disabled, and results were compared against the baseline. This section shows the results for all three scenarios. Changes in water level, discharge, and transport behaviours have been identified and discussed. The following controls were assessed:

1. Seiching at the lake-marsh interface
2. Inflow from the Portage Diversion
3. Inflow from Whitemud and Waterhen Rivers

The impact of seiching was assessed by disabling the entire wind component, while leaving all other components unchanged from the baseline. Physically, this represented the absence of shear friction at the water-air interface. Numerically, this eliminated the surficial shear stress terms (τ_{sx}, τ_{sy}) from Equations 3:2 and 3:3, respectively. Figure 6:22 compares the simulated baseline and no-wind water levels at Delta Channel, for both simulation years. Without the application of wind, the model simulated a rise and fall in water level that matched the general trend of the baseline water level (note the high correlation coefficients), but did not fluctuate to the peaks. This was expected, since setup-driven inflows and drawdown-driven outflows have been observed to cause noticeable changes in marsh storage over a short-term period. On its own, this figure may lead to the notion that wind does not ultimately have a great impact on net flux into the marsh.

This is of course not the case. Figure 6:23 shows the cumulative volume into the marsh through Clandeboye Channel, as well as the net inflow directly from the Portage

Diversion, for both simulation years. The total volumes from the no-wind simulations somewhat match the baseline trends, with correlation coefficients of 0.65 and 0.70 for 2013 and 2014, respectively. That being said, the instantaneous discrepancy between the baseline and no-wind volume records can exceed 10 million cubic meters. Moreover, there was a drastic change in the inflow of Portage Diversion water.

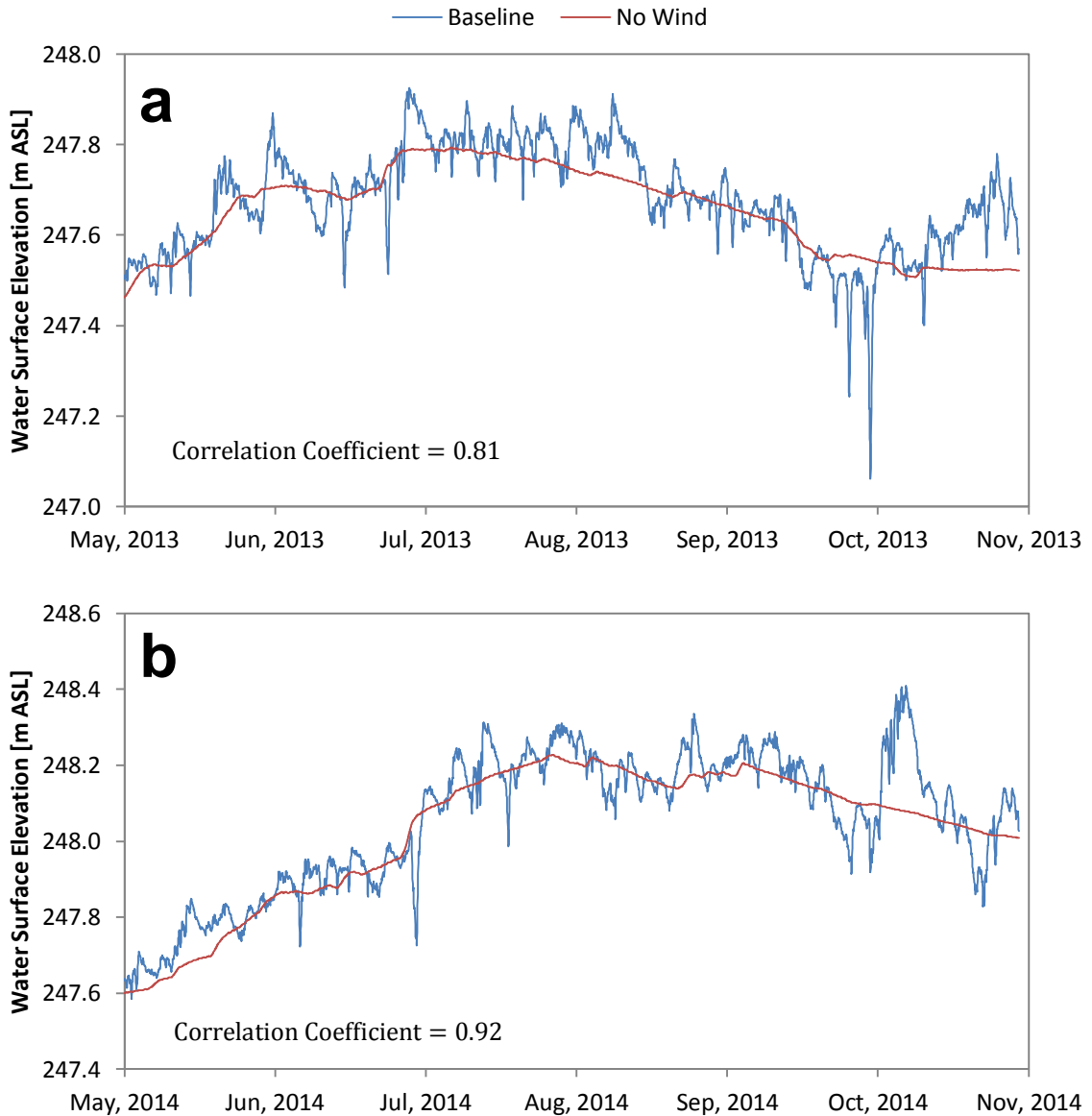


Figure 6:22 – Delta Channel WSE: Impact of Wind

a) 2013; b) 2014

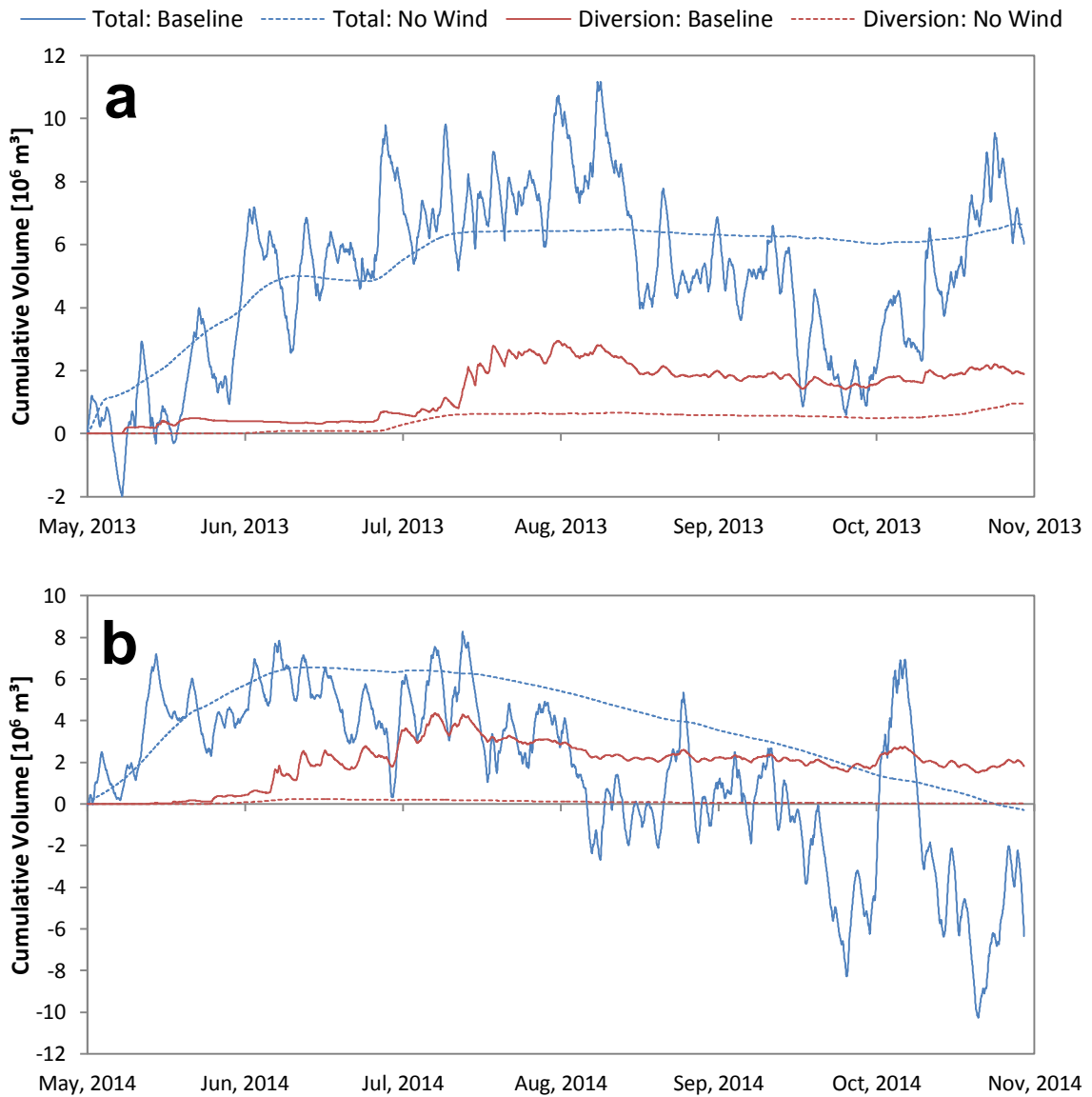


Figure 6:23 – Clandeboye Channel Discharge: Impact of Wind

a) 2013; b) 2014

Although the operation of the diversion still caused inflow to the lake due to increased storage, this water reached Clandeboye Channel weeks later, and in a smaller quantity. The same wind-induced shear stresses that force setup-inflow also distribute parcels of water throughout the lake. In reality, northwest winds likely push the diversion outflow

toward Delta Marsh. When wind is removed from the simulation, this rapid transport phenomenon does not occur; increases in water level at the diversion outlet force the slow advection of water toward the marsh.

Figure 6:24a shows the comparison of cumulative volume northward through The Narrows and Figure 6:24b shows the same eastward across the north basin of Lake Manitoba (both of these planes were outlined on Figure 4:5).

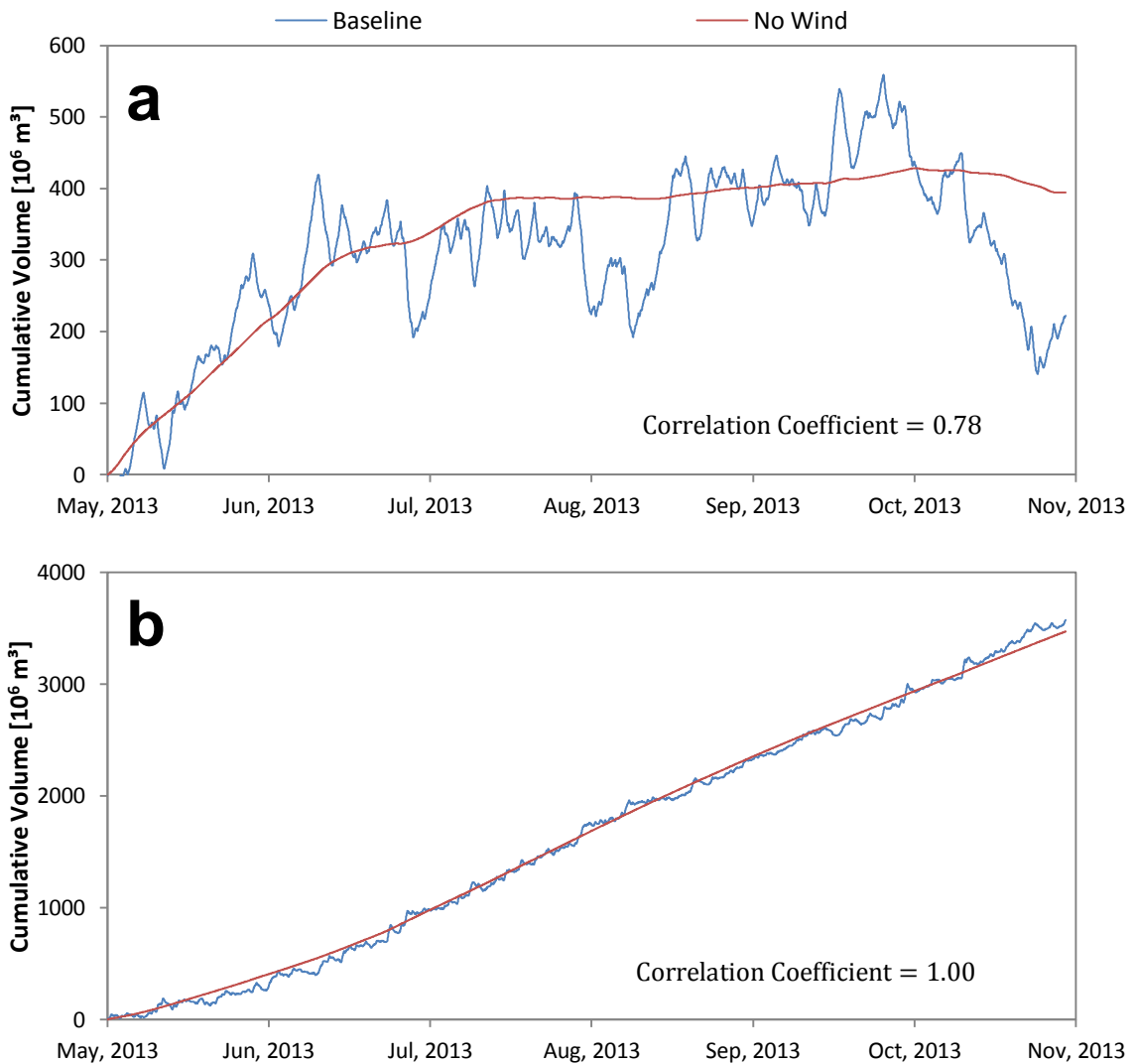


Figure 6:24 – Lake Manitoba Discharge: Impact of Wind, 2013

a) The Narrows; b) North Basin

Without wind, the cumulative volume through The Narrows somewhat matched the trend of the baseline record. Like the discharge records into the marsh, there were major discrepancies between these records at times. No such discrepancies were observed in the north basin, however. The absence of wind friction and changes in the discharge through The Narrows did not appear to have any significant impact on the movement of water from west to east. Instead, water movement was likely controlled by the balancing inflows through Waterhen River and outflows through the FRWCS.

The impact of the Portage Diversion was assessed by disabling the associated point source in the model, while leaving all other components unchanged from the baseline. Physically, this represented a decrease in the contribution to lake storage. Numerically, this diminished the incoming discharge term (S) in Equation 3:1 variably throughout the simulation period. It is crucial to note that outflow at Fairford was not adjusted to account for the decreased input. Thus, the lake and marsh level drew down below what would be expected for a typical non-diversion year. In future modelling, the use of a rating curve at Fairford would allow for reflexive changes in discharge based on changes in storage or momentum. Regardless, the comparisons shown below are still valuable; they illustrate the impact that lake storage has on the hydrodynamic behaviour of the domain.

Figure 6:25 compares the simulated baseline and no-diversion water levels at Delta Channel. The no-diversion levels closely matched the shapes of the baseline records, but were offset by and 15 cm by the end of both years. Without the diversion inflows, the lake and marsh level dropped noticeably, but wind-driven fluctuations in marsh level appeared to occur naturally.

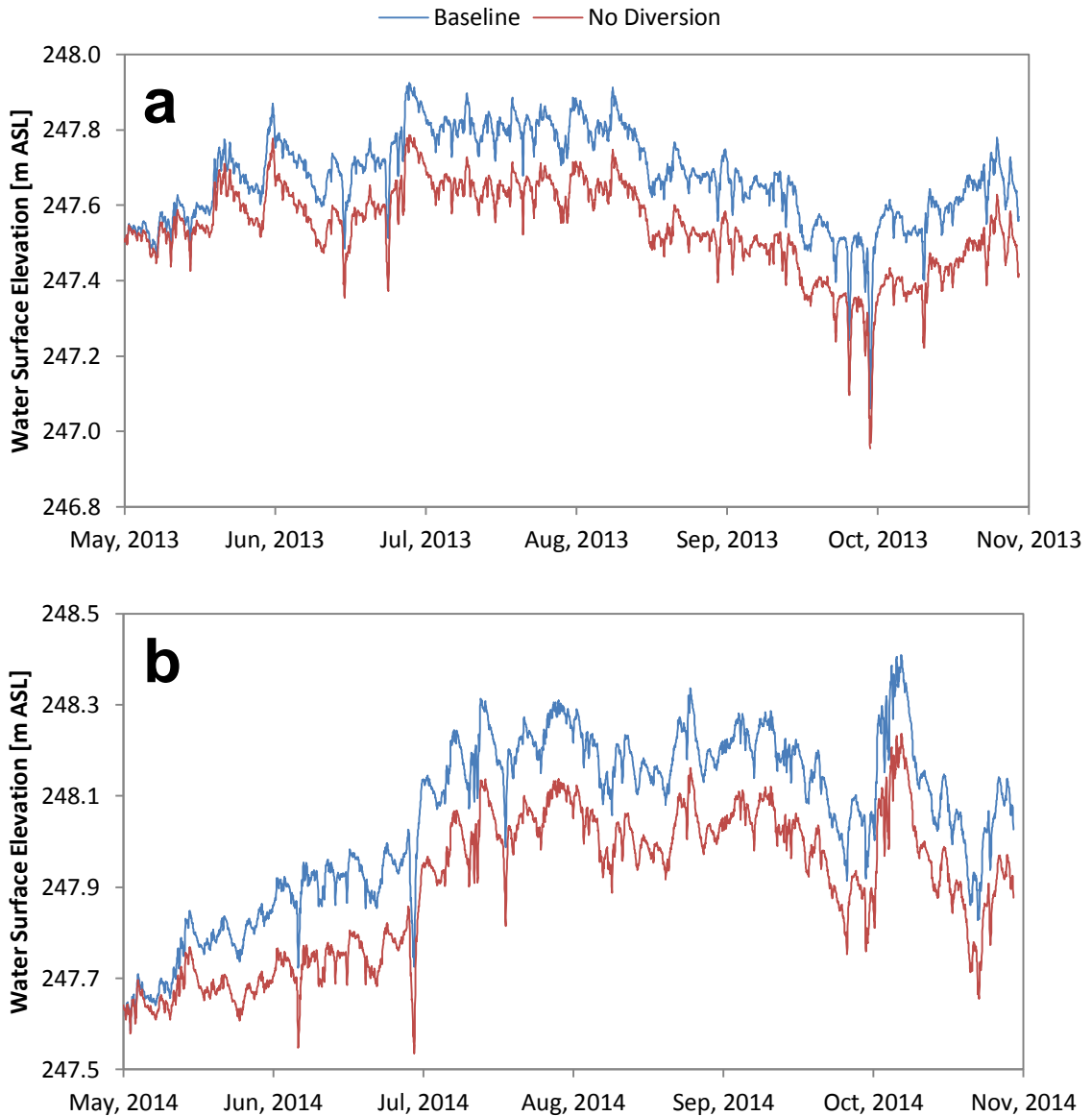


Figure 6:25 – Delta Channel WSE: Impact of Diversion

a) 2013; b) 2014

Figure 6:26 shows the cumulative volume into the marsh through Clandeboye Channel, for both simulation years. The cumulative volumes from the no-diversion simulations matched the shape of those of the baseline records, but were between five and eight million cubic meters less for both years.

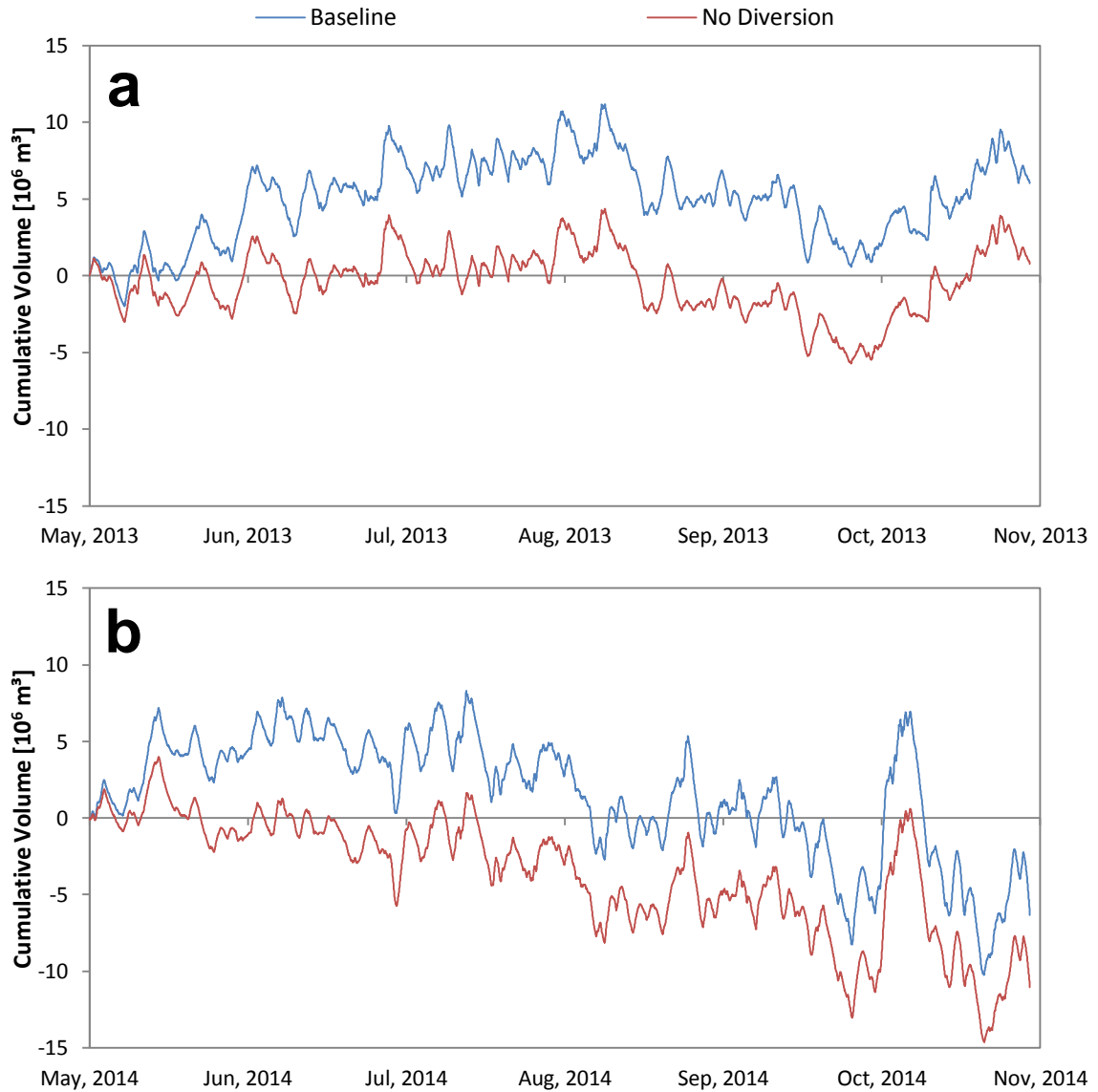


Figure 6:26 – Clandeboye Channel Discharge: Impact of Diversion

a) 2013; b) 2014

These previous figures illustrate the massive impact that the diversion can have on marsh storage. A significant amount of the inflow to the marsh occurs as a direct result of the enormous and rapid diversion of Assiniboine River Waters into the south basin. While not all of this inflow is directly from the diversion, increased volume at the diversion outlet causes the rapid advection of lake water into the marsh.

Cutting off the diversion had interesting results for the north half of Lake Manitoba. Figure 6:27 shows the comparison of simulated cumulative volumes through The Narrows and the north basin of Lake Manitoba. The decreased south basin volume in the no-diversion simulation caused the average pressure gradient through The Narrows to slant towards the south basin. The north basin was only marginally influenced. Since less water passed through The Narrows, the west-to-east flow gradient was slightly steeper.

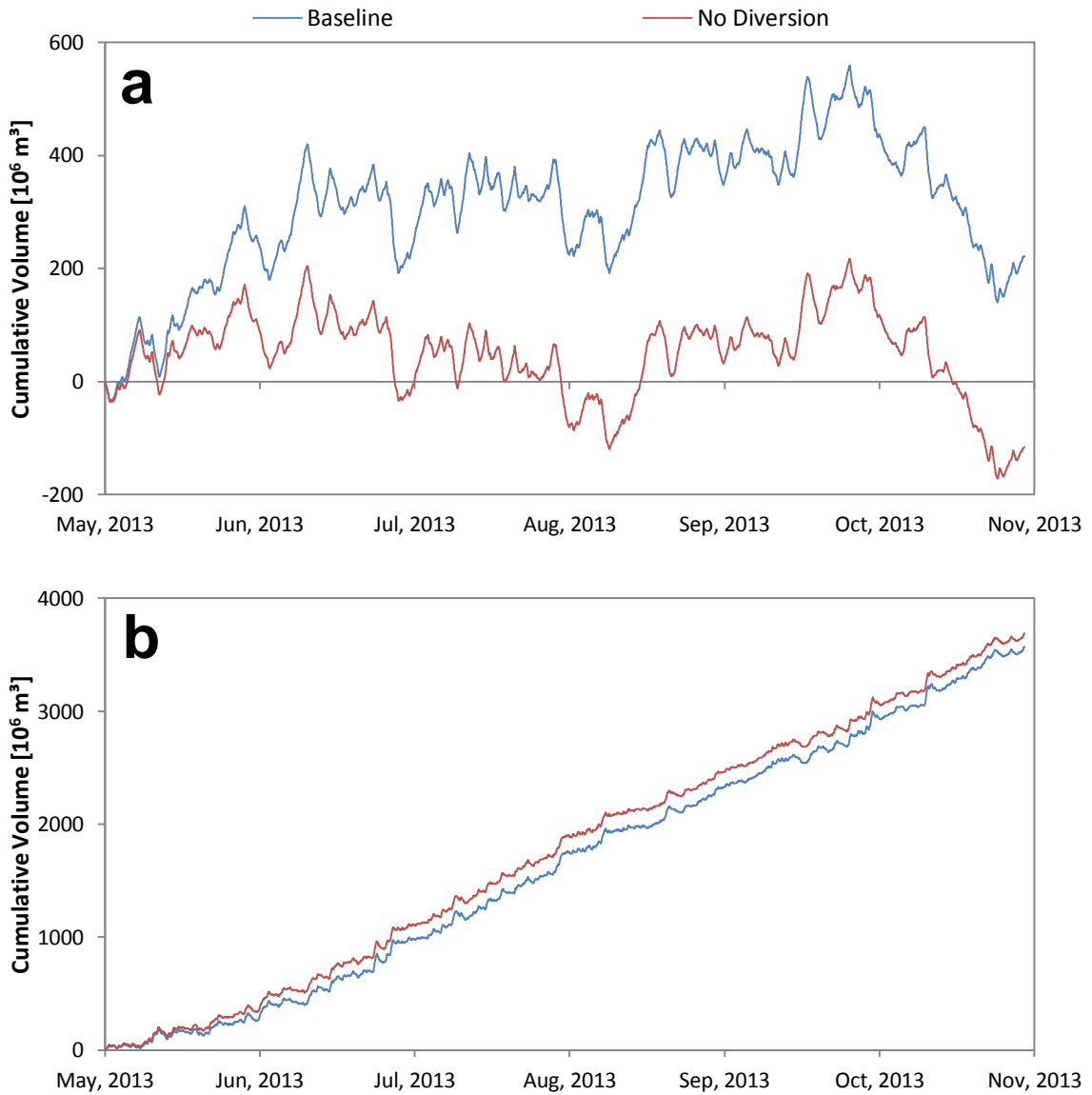


Figure 6:27 – Lake Manitoba Discharge: Impact of Diversion, 2013

a) The Narrows; b) North Basin

The impact of Whitemud and Waterhen Rivers (hereafter referred to as the “natural inflows”) was assessed by disabling the associated point and boundary sources within the model, respectively, while leaving all other components unchanged from the baseline. Physically, this represented a decrease in the contribution to lake storage. Numerically, this diminished the S term in Equation 3:1, variably throughout the simulation period. Again, the outflow at Fairford was not adjusted to account for the decreased input, and therefore an unnatural drawdown was simulated.

Note that this condition was physically unrealistic, as the diversion would not flow during a dry year. If the objective had been to compare the behaviour of the marsh under wet and dry conditions, it would be more reasonable to simulate a no-diversion-no-natural-inflow dry condition to compare against the wet baseline. However, recall that the purpose of this approach was to assess the relative impacts of the physical controls; the diversion and the natural inflows were toggled independently so that their effects would be isolated and comparable against each other. This would not have been possible with wet/dry modelling. Since the objective was to perform sensitivity analysis and not to simulate natural conditions, the physical improbability of this condition is clearly a non-issue.

Figure 6:28 compares the simulated baseline and no-natural-inflow water levels at Delta Channel for 2013. Like the no-diversion simulations, these simulations drift from the baseline; however, these biases continue to increase throughout the season. Although Whitemud River has a relatively low capacity, and although Waterhen River enters Lake Manitoba almost 200 km away from Delta Marsh, the exclusion of these inflows causes a drop in marsh level that exceeds the drop caused by excluding the diversion.

This is further illustrated in Figure 6:29. By the end of the baseline simulation, the marsh experienced a net gain of total water through Clandeboye Channel, roughly a third of which was from the Portage Diversion. By the end of the no-natural-inflow simulation, the marsh experienced a massive net loss of total water through the Clandeboye Channel. Note that some diversion inflow was retained; this further supports the idea that mixing and dilution causes inflow retention in the marsh regardless of the net change in volume.

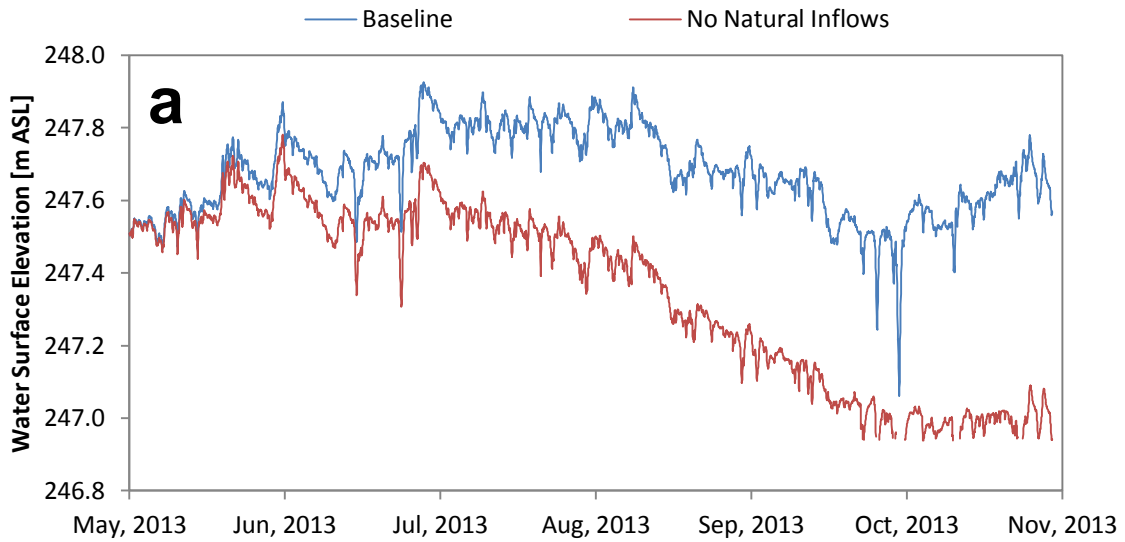


Figure 6:28 – Delta Channel WSE: Impact of Natural Inflows, 2013

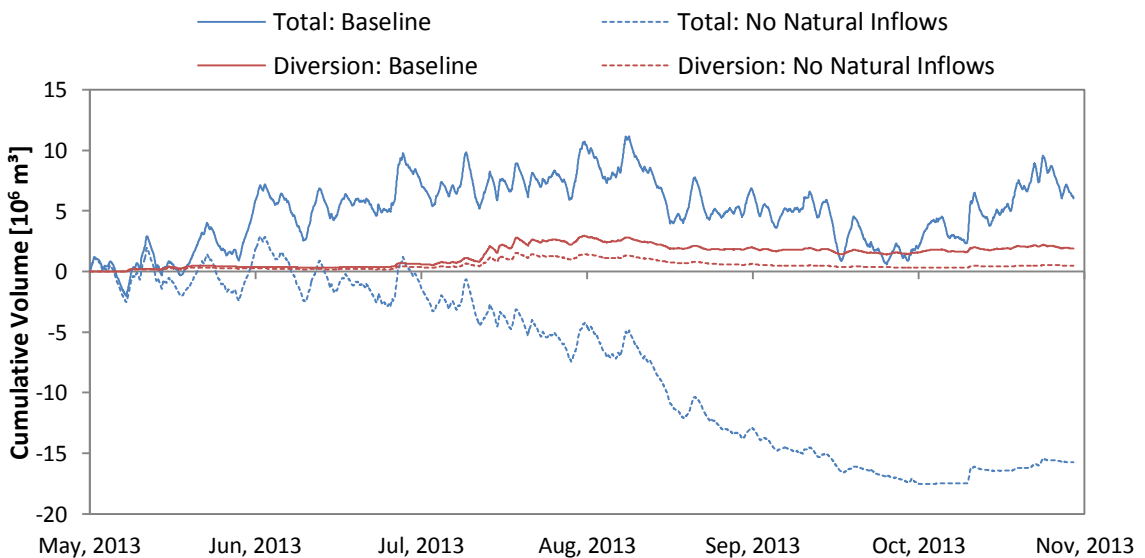


Figure 6:29 – Clandeboye Channel Discharge: Impact of Natural Inflows, 2013

The massive impact of natural inflows on marsh volume can be explained by inspecting the change in flow dynamics at The Narrows and across the north basin. Figure 6:30 shows the significant increase in discharge through The Narrows, and the significant decrease in discharge across the north basin when natural inflows were excluded. This was the only simulation with an imbalance of flows in the north basin. The outflow through Waterhen River caused a drawdown in the north basin, which lowered the pressure head at the northern mouth of The Narrows, drastically increasing northward flow.

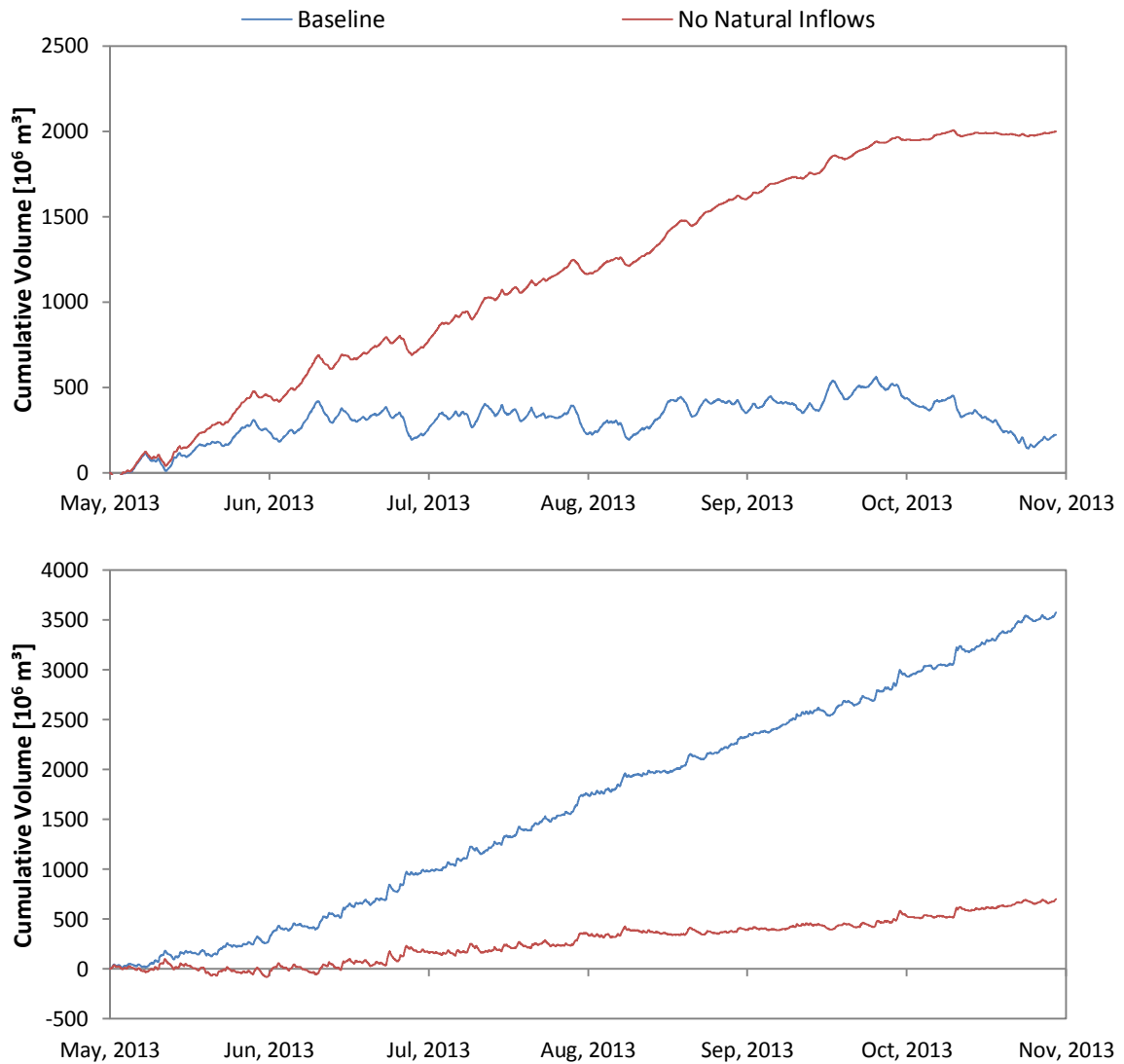


Figure 6:30 – Lake Manitoba Discharge: Impact of Natural Inflows, 2013

a) The Narrows; b) North Basin

Recall that marsh function can be influenced by water quantity and water composition. The three tested controls were observed to influence marsh hydrodynamics in different ways, and over different timescales. Therefore, ranking their relative impacts was fairly subjective. Controls were ranked by the “reach” of their influence; wind setup influenced short-term discharge fluctuation and water composition, while the diversion and natural inflows mainly influenced volume.

Wind setup has the largest impact on the timing and composition of marsh flux, despite the having no significant impact on the seasonal trend of total marsh volume. Without wind, rapid discharges to and from the marsh are non-existent, as are the frequent changes in flow direction. This was expected. The more interesting observation is that without wind, much less diversion water made it into the marsh, likely for two reasons. First, wind friction across Lake Manitoba promotes the mixing of diversion water throughout the south basin, and accelerates the advection of this water toward the marsh inlets. Second, as observed in the baseline simulations, a parcel of water with a certain tracer concentration disperses fairly quickly after entering the marsh, and the parcel of water that eventually flows out has a much lower tracer concentration. Without wind, the same net volume will enter the marsh over the season, but the sum of just the inflows is much lower, and thus less diversion-rich water enters the marsh.

The Portage Diversion ranks second to wind setup. The natural inflows to the lake account for a larger fraction of the total storage, and they are continuously active, but the Portage Diversion was ranked higher, due in part to its discontinuous nature. The range of discharges through the diversion is much higher than through the natural inflows, and

thus the physical influence of the diversion on the marsh falls within a very wide range. This variability in influence is more significant than the magnitude of influence. In other words, since the natural inflows are far more consistent from year to year than those from the diversion, the changes in net volume from year to year are likely much smaller. Second, consider that the diversion deposits water from an entirely different hydrologic system. The water from the Assiniboine River system likely has a different composition than water within the Lake Manitoba system. Now, consider the distinction in how the two simulations affected marsh storage. When diversion inflows were excluded, less lake water entered the marsh, but, of course, no Assiniboine River water entered the marsh. When natural inflows were excluded, the net volume into the marsh was even lower, but this was due to increased discharge toward the north basin. A considerable quantity of diversion inflows still entered and remained within the marsh despite the net outflow. Due to its proximity to the marsh, its discontinuity, and the distinction of its water composition, the Portage Diversion was ranked second most influential after wind.

That is not to say that the natural inflows do not influence marsh hydrodynamics. They contribute a tremendous amount of volume to the storage of the lake/marsh system. However, since a small amount of marsh inflow is directly from Whitemud River, and none is from Waterhen River, the natural inflows do not influence the composition of marsh inflows to the same degree as the Portage Diversion. Finally, recall the caveat that both storage-altering simulations did not account for decreased outflow at the FRWCS. The influences discussed above are likely exaggerated, and would be diminished if more reasonable estimates of outflow were applied.

6.2.3. Proposed Improvements to Flood Diversion Infrastructure

The Province of Manitoba recently announced plans to permanently increase the capacity of the Portage Diversion from 700 to 960 m³/s, and to construct an emergency outlet channel to Lake St. Martin with a capacity of 210 m³/s (Manitoba Infrastructure and Transportation 2014). As observed in the baseline and relative impact simulations, there can be considerable changes in marsh storage and water composition due to inflows from the Diversion and the imbalance of flows in the north basin of Lake Manitoba. Thus, expansions to diversion infrastructure will likely have an impact on marsh dynamics. These changes were tested in the MIKE 21 model creating artificial rectangular hydrographs for each inlet and outlet condition, as summarized in Table 6:4. Note that these manufactured diversion flows replaced the measured inputs, but all other controls (meteorology, natural inflows, etc.) remained unchanged. Also note that measured diversion inflows for both years were consistently below the maximum capacity. The artificial inflows and outflows all began on May 1, 2013.

Table 6:4 – Flood Diversion Expansion: Modelling Scenarios

Case	Diversion Q [m ³ /s]	Outlet Q [m ³ /s]	Notes
1	700	0	Artificial baseline
2	960	0	Expanded diversion
3	700	210	Lake outlet
4	960	210	Both expansions

The first case was the artificial baseline condition. 1.7 billion cubic meters of water passed through the Portage Diversion over 28 consecutive days, at the lower capacity of 700 m³/s. For the second case, this same arbitrary volume was passed through the diversion over 21

consecutive days, but at the expanded capacity of 960 m³/s (the two sets of flowrates and durations result in equal volumes of water delivered to the marsh). These two inflow conditions were reused for the third and fourth simulations, with the addition of a new 210 m³/s outflow point near the FRWCS. The same volume was passed out of this point uniformly over 95 days (to remove all of the diversion inflow volume).

The influence of expanding the Portage Diversion was estimated by comparing case 2 against case 1. Note that the same net volume entered the domain through the diversion in both scenarios, but over a shorter duration in the latter. Figure 6:31 shows how the simulated WSE in Clandeboye Bay was influenced by increasing the runoff rate to the south basin. The level rose more steeply to a peak in May, but both WSE records converged immediately after spring inflow. From June on, the water level across the marsh was identical between both simulations. Thus, changes to the diversion capacity likely have no long-term impact on marsh volume trends.

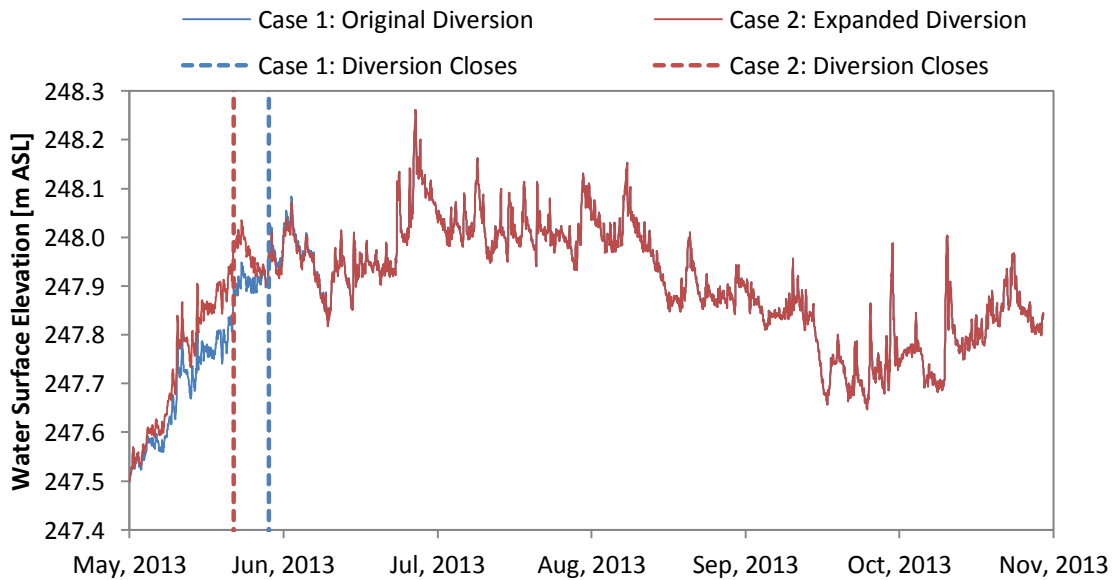


Figure 6:31 – Clandeboye Bay WSE: Impact of Diversion Expansion, 2013

This was further supported by inspecting the cumulative volume and tracer transport through Clandeboye Channel, shown in Figure 6:32. The simulated cumulative volumes into the marsh through Clandeboye Channel converged by June, and the cumulative diversion inflow records converged by mid-July.

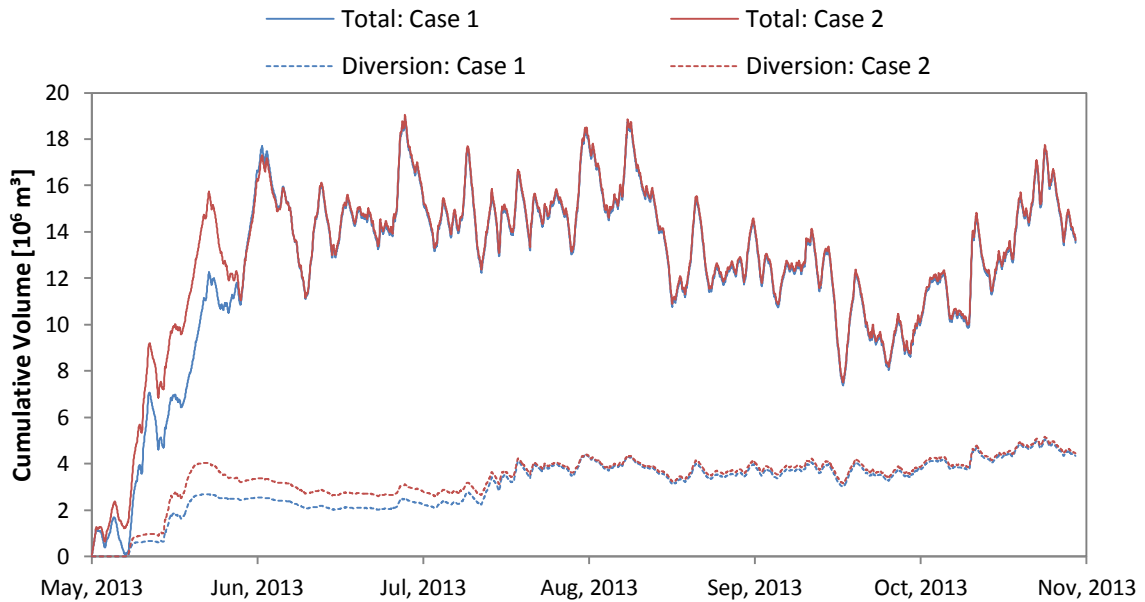


Figure 6:32 – Clandeboye Channel Discharge: Impact of Diversion Expansion, 2013

The influence of the emergency outlet channel was estimated by comparing case 3 against case 1. Note that the same net volume exits the marsh through this outlet as enters through the diversion, but over a much longer duration. Also note that this was another simulation that could have benefitted from more realistic outflows at the FRWCS. The simulated decrease in lake and marsh storage was likely exaggerated, since, in reality, increased outflows through the emergency outlet would likely be complemented by reduced outflows through the FRWCS.

Figure 6:33 shows the change in simulated WSE in Clandeboye Bay with the addition of the outlet channel. At first glance, these changes seemed similar to those observed in the

no-diversion simulation, discussed in Section 6.2.2. The discrepancy between simulations steadily increased until the outlet discharge ceased at the start of August. The distinction, of course, was that a tremendous amount of diversion water still made it into the marsh, as illustrated in Figure 6:34.

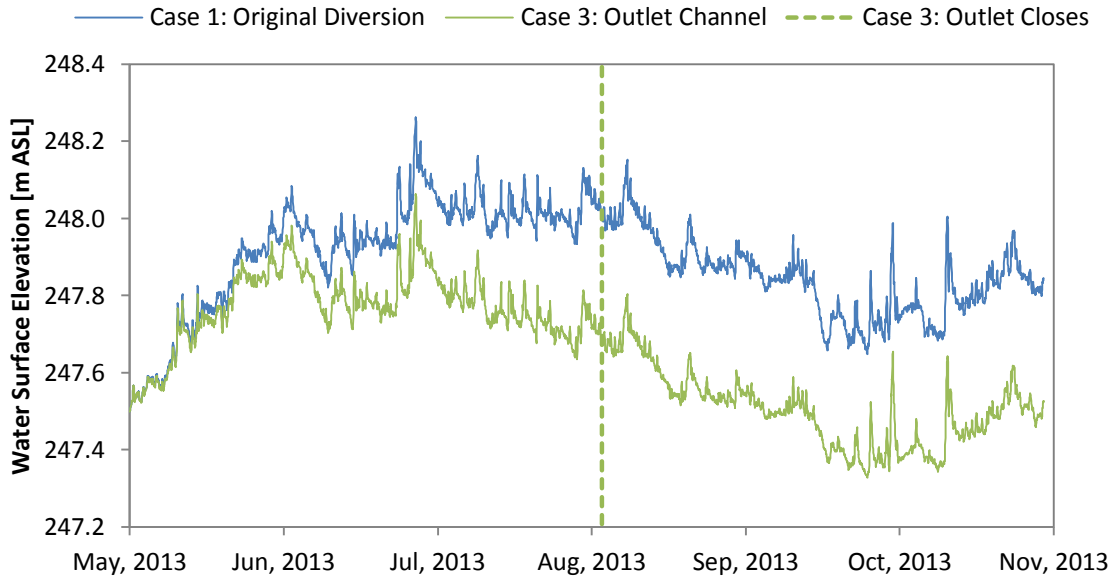


Figure 6:33 – Clandeboye Bay WSE: Impact of Outlet Channel, 2013

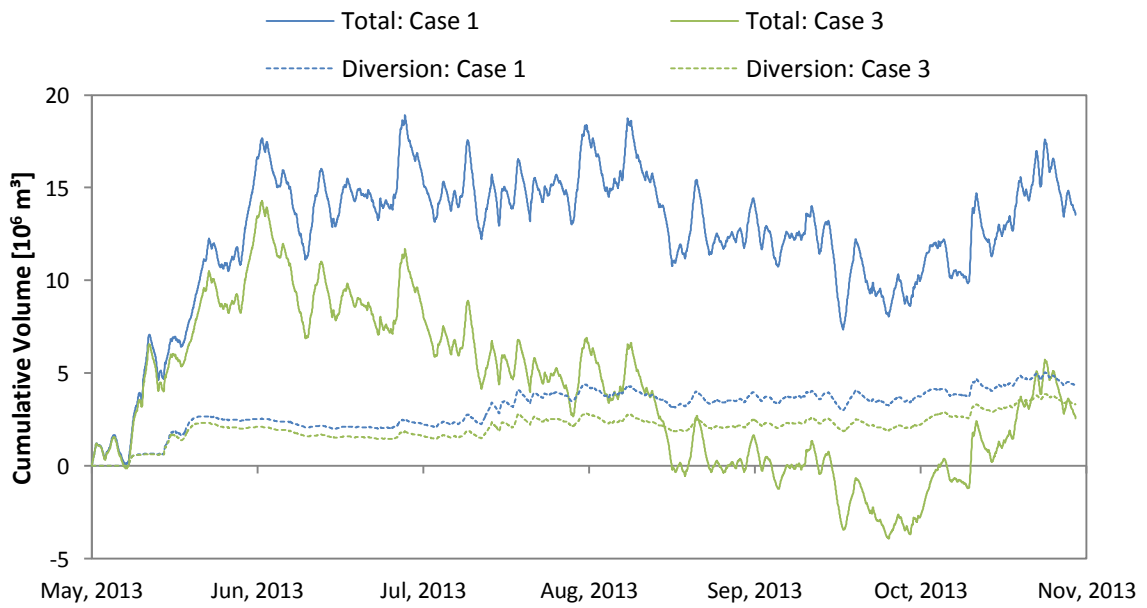


Figure 6:34 – Clandeboye Channel Discharge: Impact of Outlet Channel, 2013

In fact, since the increased outflow in case 3 caused such a drastic drawdown in the marsh level, the net volume into the marsh at the end of the year was virtually equal to the cumulative inflow of diversion water. Thus, not only is the marsh sensitive to changes in lake volume, marsh water composition is greatly influenced by the mechanism of volume change. Decreased diversion inflow and increased outlet discharge may both have similar influences on lake level and total volume flux, but the first will reduce the amount of Assiniboine River water entering the marsh.

Two other comparisons were performed: comparing both outflow conditions with inflow held constant at $960 \text{ m}^3/\text{s}$ (case 2 against case 4); and comparing inflow conditions with outflow held constant at $210 \text{ m}^3/\text{s}$ (case 3 against case 4). These results of these comparisons echoed those of the first two comparisons, and can be found in Appendix B.

6.3. Discharge Estimation Methods

Three novel methods of discharge estimation for two-directional channels were introduced in Section 4.5, and calibrated against 2013 data in Section 5.3. The following section details the validation of these methods against 2014 data. During testing, it became clear that simply comparing performance statistics from year to year may be misleading. Consider a scenario where one method had strong performance statistics for the calibration year and relatively lower statistics for the validation year. The conclusion may be drawn that the coefficients are not transferable from year to year. However, the drop in score may have been due to the validation discharge record itself; if the record contained dramatic events that were difficult to simulate, the score would be lower even if recalibrated coefficients were used. This is the case for 2014, when intense rain and wind events forced large and rapid fluxes into the marsh. Thus, analysis of the methods was as follows:

1. Calibrate the method to 2013 data (Section 5.3)
2. Apply the calibrated method to 2014 data
3. Re-calibrate the method against 2014 data to obtain the maximum scores
4. Compare the validation scores (step 2) against the calibration scores (steps 1 & 3)

6.3.1. Regressed Slope Manning Method

The results of the RSMM are summarized in Table 6:5. Note the structure of the table: the calibration scores are in the “2013” rows, while the “2014” rows show the validation scores followed by the maximum (recalibrated) scores in parentheses. A note on the RSMM coefficients: the β_1 term is used to account for the bias between the interior and exterior gauges, and was thus calibrated to each year. In order to avoid this, future testing of the RSMM must use data that has been corrected to a datum with sub-centimetre accuracy.

Table 6:5 – RSMM: Temporal Validation Results

Location	Year	R ²	NSE	R Slope	RMSE [m ³ /s]
Delta Channel	2013	0.62	0.61	0.71	1.90
	2014	0.68 (0.69)	0.18 (0.68)	1.26 (0.65)	3.14 (1.98)
Waterhen Creek	2013	0.92	0.92	0.92	3.87
	2014	0.76 (0.77)	0.51 (0.76)	1.20 (0.76)	11.7 (8.13)

Validation appears semi-successful for Delta Channel. The regression slope indicates that the model is, on average, overestimating discharge by a factor of 1.26 (Figure 6:35). This has resulted in a lower NSE and a higher RMSE. The recalibrated scores are better, implying that the method itself is generally applicable to Delta Channel, but perhaps the calibration coefficients are not temporally transferable.

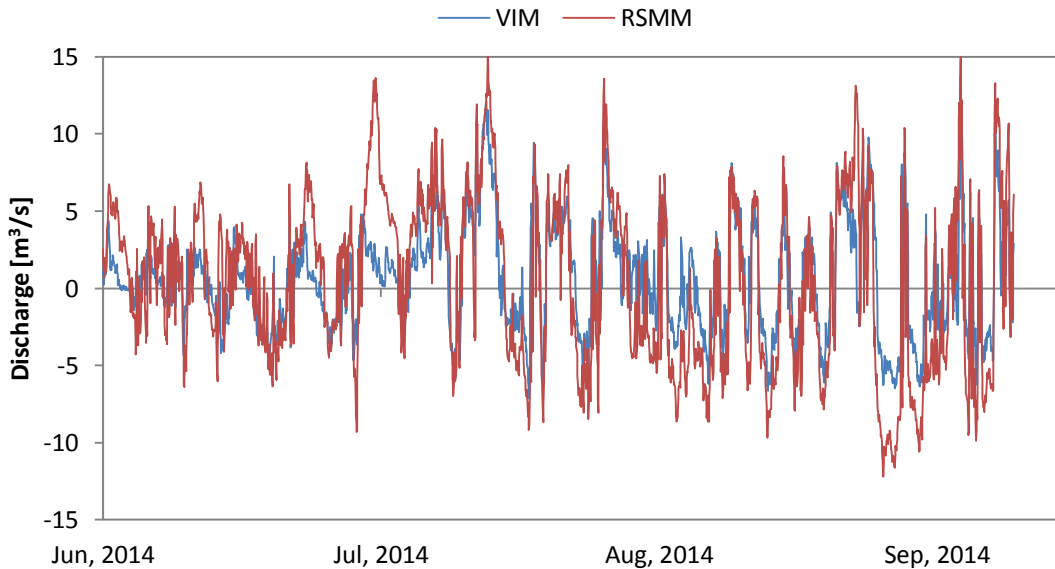


Figure 6:35 – RSMM Validation: Delta Channel, 2014

At Waterhen creek, however, model overestimation causes a smaller drop in fit during the validation year (Figure 6:36a). While the peak event at the start of July is overestimated,

the rest of the discharge record looks quite reasonable. Figure 6:36b shows the VIM, validation, and recalibration cumulative volume records for Waterhen Creek. Although the recalibrated record closely matches the VIM record, the validation record does not stray very far compared to those of the other methods, as discussed in the following sections.

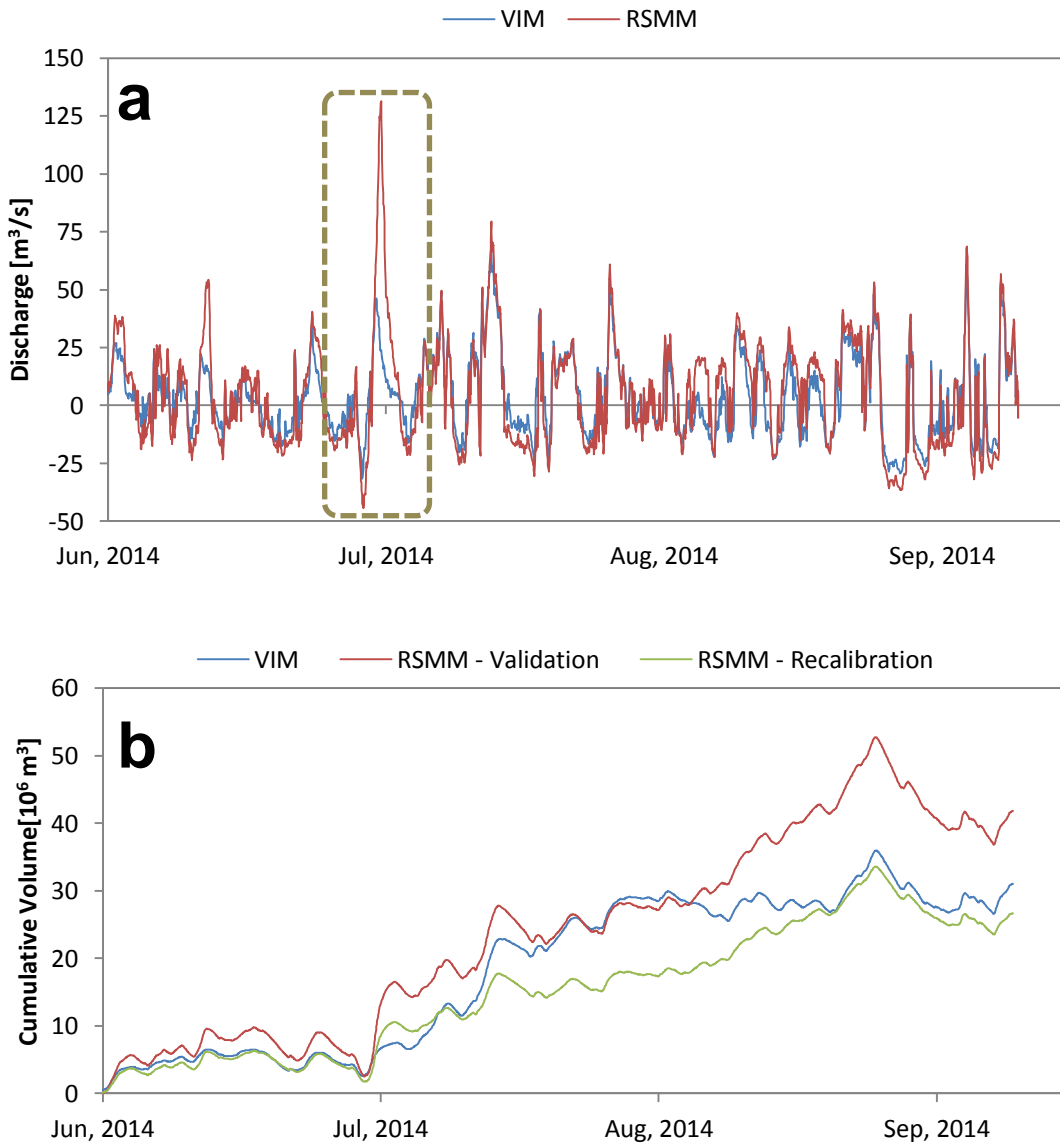


Figure 6:36 – RSMM Validation: Waterhen Creek, 2014

a) Validation of the RSMM with peak overestimation; b) validation vs. recalibration

The final test of the method was spatial validation. If calibration statistics from one location can be applied successfully at another, the method is considerably more reliable. Table 6:6 lists the results of the spatial validation. Note the structure of the table: cells contain performance statistics from simulations using the calibration statistics from the other location (for the same year), followed by the original calibration scores in parentheses. Also note that β_1 was not altered.

Table 6:6 – RSMM: Spatial Validation Results

Location	Year	R ²	NSE	R Slope	RMSE [m ³ /s]
Delta Channel	2013	0.62 (0.62)	0.44 (0.61)	0.95 (0.71)	2.28 (1.90)
	2014	0.65 (0.69)	0.39 (0.68)	1.07 (0.65)	2.72 (1.98)
Waterhen Creek	2013	0.92 (0.92)	0.86 (0.92)	0.68 (0.92)	5.11 (3.87)
	2014	0.75 (0.77)	0.63 (0.76)	0.46 (0.76)	10.2 (8.13)

Remarkably, there was not a considerable drop in performance when the calibration statistics were swapped. However, note that for both years, the regression slope decreased at Delta Channel and increased at Waterhen Creek. This suggests that there may be unique physical features of the channels that have not been considered. Recall that the friction slope is defined as the change in depth over the channel, divided by the length of the channel (L). During the derivation of the RSMM (Equations 4:19 and 4:20), L was lumped into the α_1 term. The method may be even more spatially transferable if it is re-developed to include the L term as an input.

6.3.2. Regressed Level Manning Method

The results of the RLMM are summarized in Table 6:7. Recall that this method is not applicable at Delta Channel; the friction slope through the channel cannot be estimated using marsh-side depth measurements. If this method is to be retested at Delta Channel, depth measurements must be recorded directly at the lakeside mouth.

Table 6:7 – RLMM: Temporal Validation Results

Location	Year	R ²	NSE	R Slope	RMSE [m ³ /s]
Delta Channel	2013	0.08	0.08	0.09	2.92
	2014	0.03 (0.06)	-0.43 (0.06)	0.12 (0.05)	4.19 (3.39)
Waterhen Creek	2013	0.66	0.66	0.68	7.81
	2014	0.47 (0.50)	0.23 (0.50)	0.80 (0.51)	14.9 (12.1)

Consider the results for Waterhen Creek. The R² value is only slightly less than the maximum, the NSE score is acceptable. An initial conclusion may be that the calibration coefficients may be transferable. However, note the peculiarity in the regression slopes. The validation regression slope is closer to 1.0 than the recalibrated slope, but the RMSE is higher. This testifies to the influence of the peak overestimation highlighted in Figure 6:37a; in order to minimize the negative impact of the peak overestimation, the method must consistently underestimate the rest of the discharge record. Regardless of the temporal transferability of the coefficients, this method is vulnerable to peak events. Figure 6:37b compares the simulated cumulative volumes through Waterhen Creek in 2014. Despite the similarity in performance statistics between the validation and recalibration attempts, there is a large difference in total volume that passes through the

channel. The calibration coefficients are certainly not temporally transferable. Also, note that all scores are consistently lower than for the RSMM. Finally, note that spatial validation cannot be performed, since simulations were not successful at Delta Channel.

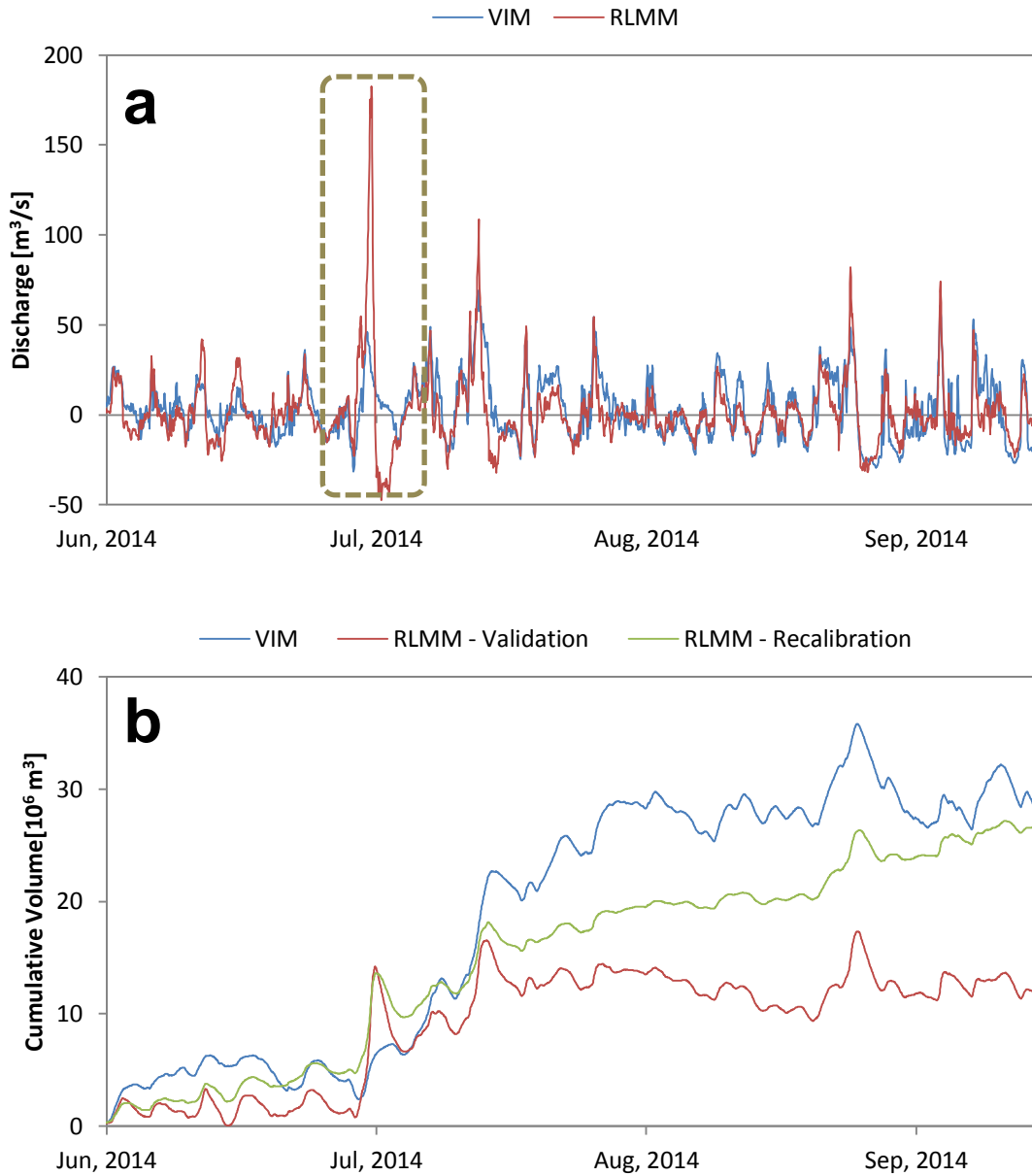


Figure 6:37 – RLMM Validation: Waterhen Creek, 2014

a) Validation of the RLMM with peak overestimation; b) validation vs. recalibration

6.3.3. Polynomial Regression Method

The results of the PRM are summarized in Table 6:8. The performance statistics are generally acceptable. The regression slopes are low in general, and again, note that the recalibration slopes are lower than the validation slopes. The PRM is vulnerable to higher events, and underestimates lower flows to compensate (Figure 6:38, Figure 6:39a).

Table 6:8 – PRM: Temporal Validation Results

Location	Year	R ²	NSE	R Slope	RMSE [m ³ /s]
Delta Channel	2013	0.58	0.58	0.58	1.96
	2014	0.32 (0.34)	0.27 (0.34)	0.43 (0.34)	2.98 (2.84)
Waterhen Creek	2013	0.71	0.71	0.71	7.29
	2014	0.48 (0.50)	0.46 (0.50)	0.52 (0.50)	12.4 (12.0)

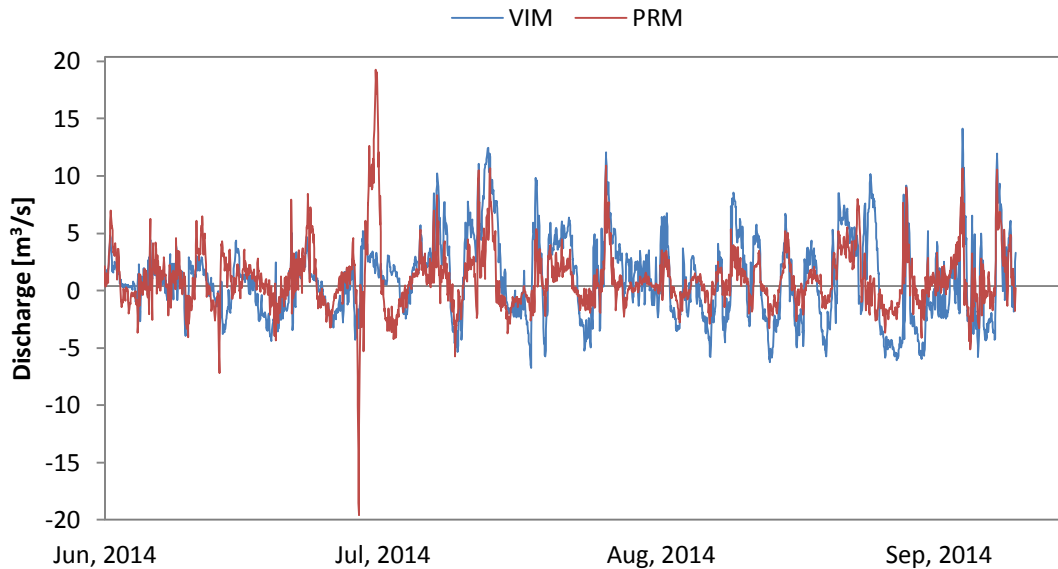


Figure 6:38 – PRM Validation: Delta Channel, 2014

The PRM validation statistics are very close to the recalibration statistics. However, the validated cumulative volume record does not match does not match the VIM record, whereas the recalibrated record matches much more closely (Figure 6:39b). It appears that the calibration parameters are not temporally transferable.

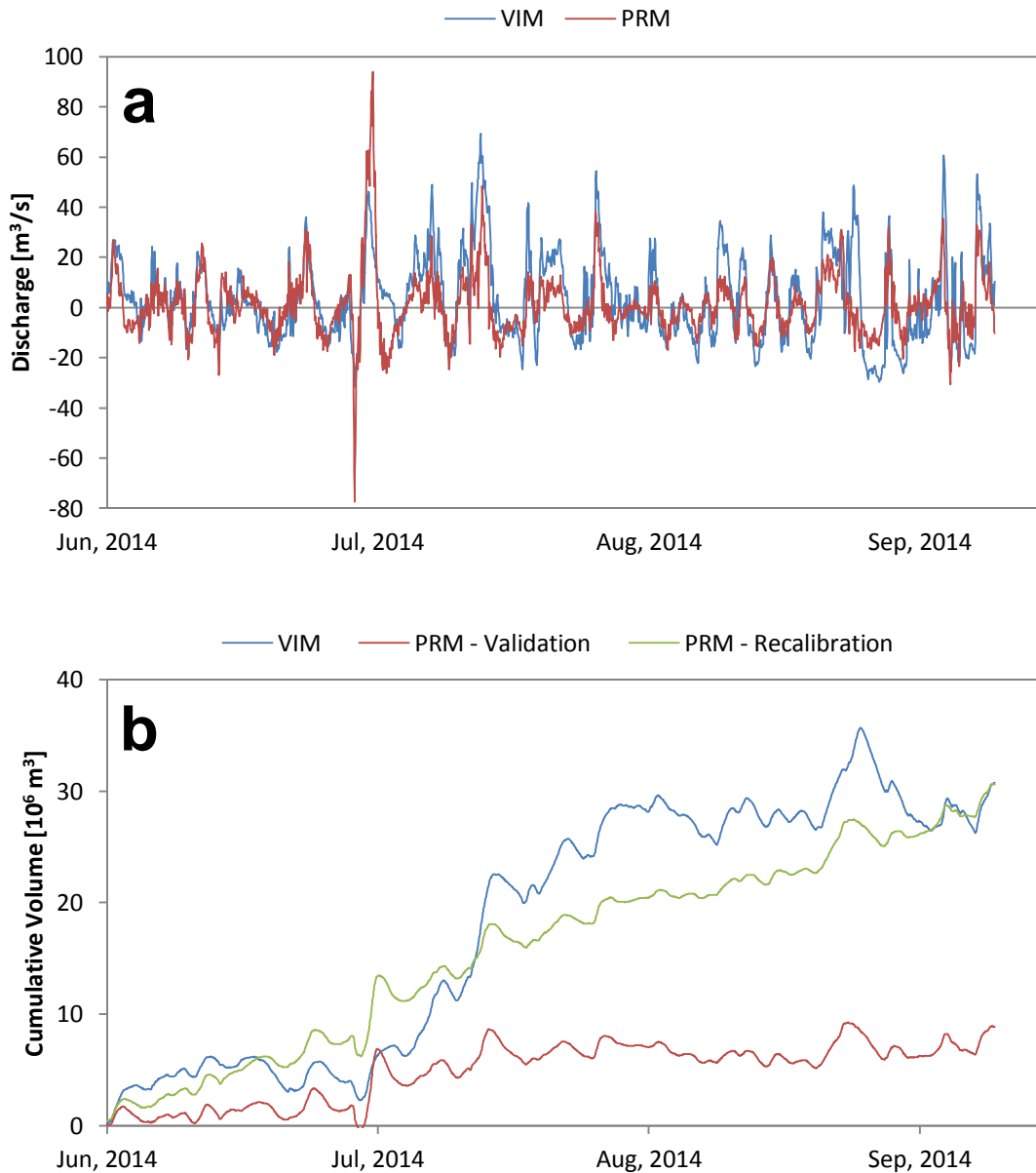


Figure 6:39 – PRM Validation: Waterhen Creek, 2014

a) Validation of the PRM with over/underestimation; b) validation vs. recalibration

Table 6:9 lists the results of the spatial validation. The results were interesting. A tremendous drop in NSE scores was observed, and the regression slopes are far from 1. This makes sense; the PRM calculates discharge directly, without estimating any geometric properties, and thus the same coefficients cannot be used to produce different discharges through different channel sizes. However, the R^2 values have only reduced marginally; the selected parameters apply, but the coefficients are of the wrong order of magnitude. Perhaps this can be accounted for by applying unique multipliers to each channel. For the RSMM, it has been suggested to include channel length as a constant input. This can be done for the PRM as well, but the most important geometric characteristics that have been neglected are area and wetted perimeter. To add both into the method would be to recreate the RLMM, which was observed to perform worse than the PRM. At the very least, it can be concluded that there is a lot of correlation across the large parameter set.

Table 6:9 – PRM: Spatial Validation Results

Location	Year	R^2	NSE	R Slope	RMSE [m ³ /s]
Delta Channel	2013	0.53 (0.58)	-7.18 (0.58)	2.56 (0.58)	8.70 (1.96)
	2014	0.30 (0.34)	-8.46 (0.34)	1.86 (0.34)	10.8 (2.84)
Waterhen Creek	2013	0.63 (0.71)	0.26 (0.71)	0.15 (0.71)	11.6 (7.29)
	2014	0.46 (0.50)	0.12 (0.50)	0.08 (0.50)	15.8 (12.0)

6.3.4. Comparison of Methods

The performance statistics and observations outlined in the previous sections are compared below. Table 6:10 lists the practical advantages and disadvantages of the

methods. These are general observations regarding the numerical bases and utilization of each. Table 6:11 lists the qualitative and quantitative findings obtained during testing.

Table 6:10 – Practical Advantages and Disadvantages of the Proposed Methods

Method	Advantages	Disadvantages
RSMM	<ul style="list-style-type: none"> • Most physically-based; most direct approximation of unknown terms • Numerical methodology is relatively simple 	<ul style="list-style-type: none"> • Requires the most equipment (ADCP, submersible ADV, 2 depth gauges) • Requires vertical datum in order to be performed repeatedly, otherwise β_1 must be recalibrated annually
RLMM	<ul style="list-style-type: none"> • Simple methodology; parameter space is open to adjustment in future testing 	<ul style="list-style-type: none"> • Prone to over-fitting
PRM	<ul style="list-style-type: none"> • Makes use of free second-hand data • Simple methodology; parameter space is open to adjustment in future testing • Requires the least equipment (ADCP, submersible ADV) 	<ul style="list-style-type: none"> • Least physically-based; does not incorporate knowledge regarding cross-sectional geometry dynamics, • Prone to over-fitting

Table 6:11 – Overall Performance of the Proposed Methods

Criteria	RSMM	RLMM	PRM
Can the method be calibrated?	Yes	WC Only	Yes
Are the coefficients temporally transferable?	Somewhat	No	No
Are the coefficients spatially transferable?	Somewhat	Not Tested	No
Are peaks estimated reasonably?	Somewhat	No	No
2013 Waterhen Calibration: NSE	0.92	0.66	0.71
2013 Waterhen Calibration: RMSE (m ³ /s)	3.87	7.81	7.29
2014 Waterhen Calibration: NSE	0.76	0.50	0.50
2014 Waterhen Calibration: RMSE (m ³ /s)	8.13	12.1	12.0

Consider the strengths and weaknesses that are shared by all three methods. First, they are all able to estimate two-directional channel discharge at Delta Marsh in some capacity. This is a favourable outcome, and suggests that reasonable assumptions were made regarding flow behaviour as a function of friction slope, wind, and storage. Second, none of the calibrated coefficients are temporally or spatially transferable. This is more or less an expected outcome. However, temporal and spatial validation of the methods has given insight into potential pathways of method redevelopment. Third, all three methods were vulnerable to peak overestimation during 2014. There are several possible explanations for the disparity between VIM and simulated peak discharges, including: clogging of the DUC control structures by suspended debris, causing drastic increases in head loss during storms; short-term increases in the effective roughness of a channel during a storm; or the introduction of error in the extrapolation of the VIM rating curves. Fourth, there are practical advantages and disadvantages to all three methods. However, it is important to note that these observations are not all weighted equally.

Consider the RSMM; the advantages – physical basis and simplicity – are relatively important, while the disadvantages – equipment requirements and the non-transferability of β_1 – are less crucial. Regarding equipment requirements, note that all three methods require an ADCP and submersible ADV, which come at relatively high costs. Depth gauges are relatively less expensive, so the proportional differences in total cost between methods are small. These favourable observations are supported by the findings obtained during testing. The RSMM consistently had the best calibration statistics, and had the smallest drops in performance during validation. These findings imply that the RSMM had the most realistic and most complete approach to estimating two-directional flow.

Now, consider the PRM; the disadvantages – lack of physical basis and vulnerability to overfitting – are relatively important, while the advantages – cost and equipment requirements – are less crucial. These negative observations are supported by unexceptional test results. The PRM consistently performed worse than the RSMM, and could not be validated temporally or spatially.

Finally, consider the RLMM; prior to testing, this method could be described in two very different lights. From one perspective, the method strikes an elegant balance between the RSMM and the PRM; channel geometry is considered and estimated using nearby water levels, and less equipment is required. From another perspective, the method is a poor compromise of the others; friction slope is not estimated directly, but depth gauges are still required, while free data from second-hand sources are neglected. Unfortunately, testing seemed to indicate that the latter description was more apt. Coefficients are not transferable, peak overestimation can significantly impact calibration, and the performance statistics are consistently the poorest of all three methods.

Thus, the calibrated RSMM appears to be the most accurate and robust of the three novel methods. That being said, there is certainly room for the improvement of all three methods, and recommendations are highlighted in Section 8.3.

7. Conclusions

This section summarizes the findings presented in Chapter 6, and revisits the thesis objectives and hypotheses, described in Section 1.5.

7.1. Hydrodynamic Modelling

The objectives and hypotheses of numerical modelling have been revisited in Table 7:2.

Table 7:1 – Hydrodynamic Modelling: Objectives and Hypotheses Revisited

Objective		Hypothesis	Supported?
1.1	To develop a numerical model of Delta Marsh and Lake Manitoba	Not Applicable	YES – The MIKE 21 model worked was constructed and calibrated successfully
1.2	To establish a baseline understanding of the water movement phenomena in the marsh	Not Applicable	YES – modelling provided insight into hydrodynamic behaviour; summarized on the following pages
1.3	To rank the relative hydrodynamic influences of wind set-up, the Portage Diversion, and natural lake inflows	Wind is the main governing force, followed by the Portage Diversion (during wet years), followed by natural inflows	YES – the impacts on water composition, short-, and long-term storage are summarized on the following pages
1.4	To estimate the hydrodynamic impact of expansions to existing flood diversion infrastructure	Expansion of the diversion will accelerate spring inflow to the marsh; creation of an outlet channel will hasten drawdown	YES – expansion influences short-term storage, an outlet influences hastens drawdown and alters water composition
1.5	To test the hydrodynamic sensitivity of the marsh to a variety of watershed runoff scenarios (from Schellenberg)	Variability in tributary inflow will be insignificant compared to changes in marsh flux due to wind, the Portage Diversion, and natural lake inflows	Objective Not Met – MIKE 21 and MIKE She models were not used in tandem due to modelling schedules, but can be in the very near future

MIKE 21 model setup, calibration, and validation were deemed successful. That being said, several suggestions for further model development and improved calibration have been highlighted in Section 8.2. MIKE 21 modelling allowed for the qualitative interpretation of water movement mechanisms in the study area. Model results confirmed many existing hypotheses of flow behaviour, but also challenged several common assumptions of the physical behaviour of the marsh. Findings for the completed objectives are summarized as follows:

- Flow through a great majority of the marsh is controlled by discharges through Clandeboye Channel. Delta Channel plays a comparatively small role in governing overall flow behaviour. Discharge signals through Clandeboye Channel appear to reach The Gap. Discharge through The Gap does not correlate at all with discharge through Delta Channel. This is likely due to capacity; Clandeboye Channel carries 85% of the inflow into Delta Marsh
- Although flux between the marsh and lake can change direction frequently, it is likely not the same parcel of water passing back and forth between the two. Incoming lake water disperses to a low concentration, and remains in the marsh even during periods of net outflow. A burst of water from the Portage Diversion will enter Cadham Bay at a relatively high concentration, but the subsequent outflow from Cadham will be mostly marsh water.
- Wind friction across Lake Manitoba is the most significant physical control on marsh hydrodynamics. Wind-driven changes in flow direction cause short-term fluctuations in marsh level on the order of 1-1.5 meters. Moreover, since inflows disperse rapidly, the repetitive changing of flow direction due to wind results in the frequent inflow and dispersion of “new” water into the marsh.

- The Portage Diversion delivers massive quantities of Assiniboine River water to the marsh. This water can account for an enormous fraction of the net inflow. In fact, due to the dispersion of inflowing water, the marsh may experience a net gain of diversion water during a season of net total outflow. This may have countless implications on marsh function, depending on how the composition of this water varies from that of Lake Manitoba Water.
- The resulting increase in discharge intensity through the expanded Portage Diversion will not have a long-term impact on marsh storage or water composition, assuming that it is used to divert water faster, not to divert more total water. This assumption is likely invalid, given the historical use of the marsh as a reservoir.
- During years that the Lake St. Martin Emergency Channel is put into operation, the gradual drawdown in lake level in the north basin will cause marsh outflow, concentrating the diversion water that has already entered the marsh.
- Natural inflows to Lake Manitoba account for a consistently large fraction of marsh storage, but they do not have an impact on the composition of inflows (as they do not directly enter the marsh in any significant quantity). Discharge through The Narrows is heavily controlled by the balance in the north basin. When the outflow at the FRWCS exceeds the inflow from Waterhen River, the resulting drawdown in the north basin forces a steep flow gradient through The Narrows.
- Most of the water from the Portage Diversion that enters the marsh does so through Delta Channel. This is likely due to the proximity of Delta Channel to the diversion outlet. If, hypothetically, Delta Channel becomes silted-in, or is dammed, the amount of diversion water entering the marsh would reduce by half, but the hydrodynamic behaviour across most of the marsh would not change noticeably.

- Discharges across the marsh (from The Gap to Clandeboye Channel) are highly correlated, and can be estimated from each other. Continuous discharge measurement (or estimation) at one location (such as Waterhen Creek) can be used to estimate discharges at nearby flow cross-sections.
- The marsh was not observed to reach hydrologic steady state in either of the open water monitoring seasons.
- Short-term water level fluctuation damps further and further into the marsh, but the general water level trend is fairly uniform across the domain.
- Portage Creek is arguably an extension of the marsh (as opposed to a standard stream), as it can ebb and flow with changes in marsh level throughout the year.

These conclusions make up a fraction of the potential conclusions that can be drawn from the MIKE 21 model. The calibrated model can be used for any number of future simulation schemes. The same is true of the MIKE SHE model provided by Schellenberg (in progress).

The major takeaway from all of the conclusions listed above is that Delta Marsh is definitely a responsive, sensitive system. Changes to the regulation of The Portage Diversion and the Lake Manitoba water level can have tremendous impacts on water movement behaviours within the marsh. As such, the welfare of the marsh must be considered during the planning and design of water control mechanisms within the area.

7.2. Simplified Methods of Discharge Estimation

The objectives and hypotheses for the development of simplified methods of discharge estimation have been revisited in Table 7:2. Note that all objectives were met and that none of the hypotheses were wholly unsupported.

Table 7:2 - Discharge Estimation: Objectives and Hypotheses Revisited

Objective		Hypothesis	Supported?
2.1	To confirm the applicability of the VIM	The VIM is expected to work extremely well for all monitoring years	YES – The VIM regressed very well for all applications
2.2	To develop and test the RSMM	The RSMM is expected to work well, and will be repeatable from year to year, given its physical basis	Somewhat – The RSMM calibrates very well, but coefficients are not transferable
2.3	To develop and test the RLMM	The RLMM is expected to work moderately well, but may not be repeatable from year to year, given its vulnerability to regression error	Somewhat – The RLMM calibrates acceptably, but coefficients are not transferable
2.4	To develop and test the PRM	The PRM will work acceptably, but will not be repeatable from year to year, given its vulnerability to regression error	Somewhat – The RLMM calibrates moderately well, but coefficients are not transferable
2.5	To select the most balanced method	The RSMM will be the ideal method	YES – The RSMM can recreate the VIM results reliably

The RSMM is the most promising of the three tested methods. It recreated the VIM discharge records accurately, and had only small drops in performance during temporal and spatial validation. Peak overestimation was the main source of error during temporal validation. Accurately simulating peak events is currently a limitation of the method, but

future validation attempts may improve if the numerical method can be expanded in order to better represent rapid influxes. Spatial validation may improve if the method is expanded to include characteristics of the channel, namely length. Finally, the method is limited by the beta factor, which is unique for each season and location. This limitation can be avoided if all gauges are corrected to a datum with sub-centimetre accuracy. Finally, the RSMM is likely vulnerable to the same limitations that afflict a stage-discharge rating curve, such as shift, hysteresis, and extrapolation uncertainty.

Given the lack of limiting assumptions made during its development, the RSMM can likely be applied to two-directional channels in a variety of coastal wetland settings; since friction slope is estimated as a function of water levels, the RSMM should be able to simulate discharge driven by wind setup, tide, precipitation, or a large point source (e.g. a diversion channel). While these applications seem reasonable on paper, they must be tested; this thesis only attests to the successful application in a discontinuous inland coastal wetland.

The PRM recreated the VIM discharge records reasonably; this method can provide estimates of discharge within the correct order of magnitude, and can simulate cumulative volume fairly well. Unfortunately, since this method entirely neglects the physical characteristics of the channel, it will be difficult to validate spatially, if not altogether impossible. The RLMM failed to make a strong impression, and has thus been abandoned. It is less physically based than the RSMM, requires more effort and capital than the PRM, and performs worse than both.

To illustrate the potential impact on discharge estimation in coastal wetlands, consider a situation where researchers are interested in estimating the hydrographs through four channels at Delta Marsh over a 16-week surveying season. If four ADVs are available, one can be installed in each channel. Discrete discharge and area measurement can be taken by ADCP at all sites on a regular basis, and the VIM can be used to accurately estimate channel discharge. Instead, the field crew can install depth gauges at either end of each channel (8 gauges total), and can deploy only one ADV, moving it from site-to-site every month. ADCP measurements can be performed as above, and the VIM can be used to obtain four one-month hydrographs, one at each channel. The RSMM can be calibrated to each partial hydrograph, and expanded to cover the full four-month period, yielding four reasonably estimated four-month hydrographs. This process can be repeated annually. Since the method is recalibrated at each site every year, the non-transferability of β_1 is no longer an issue. In the example above, the researchers have effectively increased their data-to-capital ratio fourfold. Not too shabby.

8. Recommendations

Recommendations for ongoing fieldwork, further hydrodynamic modelling, and further development of the discharge estimation methods are discussed below. Appendix C lists practical recommendations for performing hydrographic research.

8.1. Field Work

1. Continue to collect discharge, velocity, geometry, and depth data for further hydrodynamic modelling and testing of the discharge estimation methods
2. Obtain discharge measurements at The Gap and Portage Creek to develop a broader understanding of marsh connectivity
3. Collect continuous depth data at the lakeside mouth of Delta Channel for improved discharge estimation → enacted in the summer of 2015

8.2. Hydrodynamic Modelling

1. Consider reforming and recalibrating the model in the following ways:
 - a. Try changing the Fairford outlet condition from a specified discharge series to a rating curve. While this may decrease the accuracy in the baseline storage simulation, it will allow for reflexive discharge simulation.
 - b. Regenerate the triangular mesh with more detail across Lake Manitoba, especially at The Narrows. Try to incorporate the marsh overbank area without severely diminishing the model runtime.
 - c. Recalibrate the model using a much wider range of Manning's M values. There is room for improvement in the calibration of channel flow, and this

may be improved by applying roughness values that are outside of the traditionally accepted range of values.

- d. Recalibrate the model using spatially variable coefficients of eddy viscosity
- e. Apply unique tracers to Lake Manitoba water, precipitation, etc.

2. Apply the model to the following scenarios:

- a. 2015 and 2016 baseline conditions
- b. The hydrodynamic impact of land use changes across the Delta Marsh Watershed: baseline watershed conditions, pre-development conditions, and maximum development conditions (from Schellenberg, in progress)
- c. Adjustments to the operating policy at the Fairford River Water Control Structure: allow the WSE at Steep Rock to fluctuate between 247.05 and 247.65 m ASL. This could not be performed for 2013 and 2014, as the gates have been wide open since 2011 in an attempt to flush water out of the lake. This can be simulated once the inflow to Lake Manitoba has decreased for an extended period.
- d. Storm simulation for use in the inspection and design of DUC structures within the marsh: based on design storms obtained from frequency analyses of meteorological data, coupled with design discharges through the Portage Diversion
- e. Wind effects directly over Delta Marsh: apply wind over the lake, but not the marsh (and vice versa), in order to assess the relative impacts on water movement within the marsh by lake seiching and marsh seiching.
- f. Extreme flooding scenarios, pending the inclusion of the overbank area

8.3. Simplified Methods of Discharge Estimation

1. All methods:
 - a. Expand to account for changes in behaviour during peak events; attempt to numerically represent screen clogging or changes in channel roughness
 - b. Expand to incorporate channel length (L) as an input, and test the impact of the proximity of the gauge to the mouth of the channel
 - c. Continue testing with 2015 and 2016 data
2. Regressed Slope Manning Method (RSMM):
 - a. Use data collected at the lakeside mouth of Delta channel
3. Polynomial Regression Method (PRM):
 - a. Expand parameter space to include non-linear terms
4. Test the general applicability of the methods in a variety of settings, such as:
 - a. In a continuous inland coastal wetland like the Netley-Libau Marsh, to test the impact of a major bisecting channel
 - b. In a tidal coastal wetland
 - c. Directly at any WSC discharge site along a one-directional channel, to compare against the traditional rating curve method
 - d. At a meander along the Red River in Winnipeg, to test the influence of streamwise irregularity
 - e. In the Assiniboine River, slightly upstream of The Forks, to test the impact of dynamic backwater effects
 - f. In a straight channel during the winter, to test the impact of ice-cover
 - g. Any other settings where traditional rating curves are not applicable, or where they are prone to error or shift

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Appendix A: Supplementary Hydrographic Results

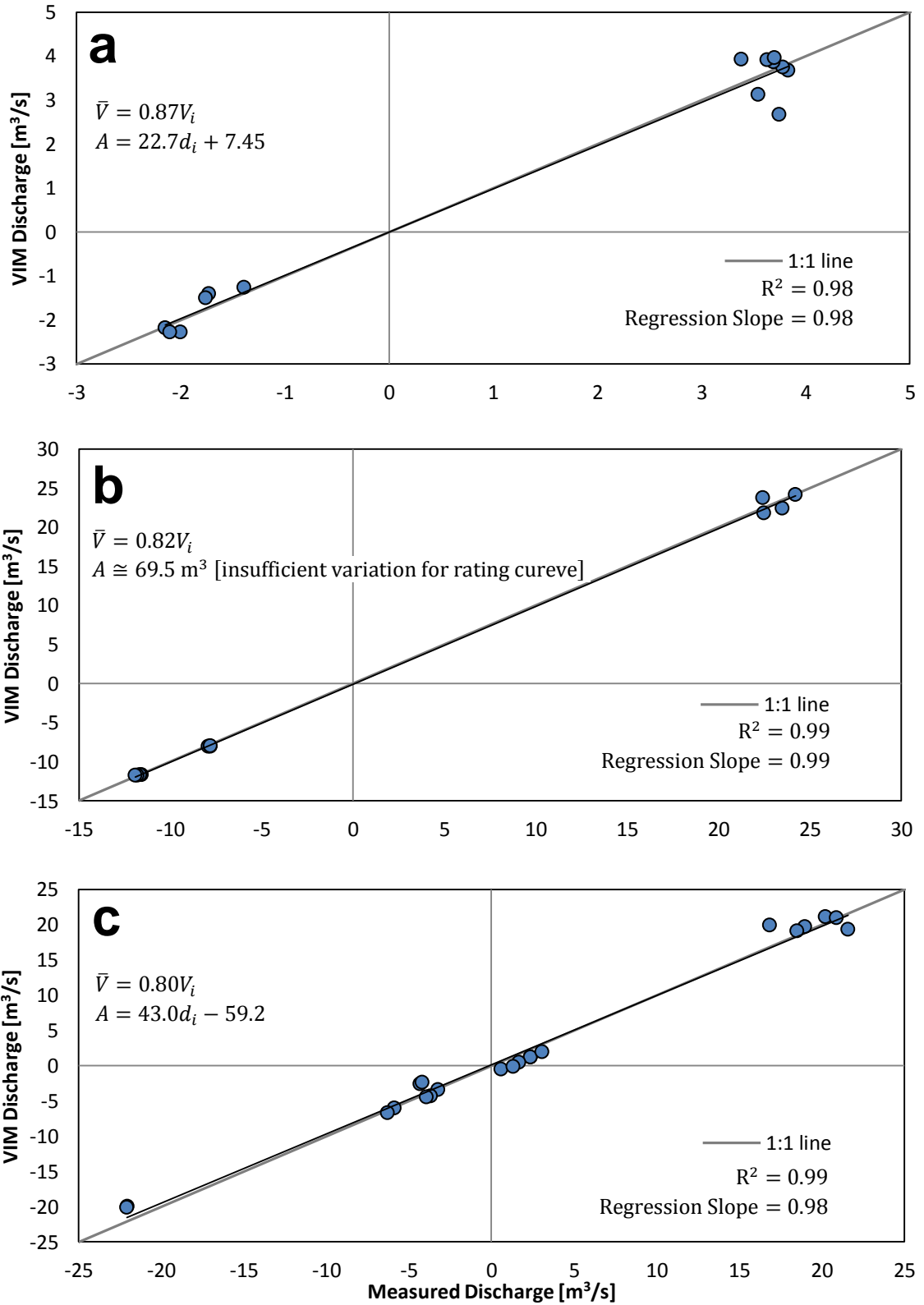


Figure A:1 – VIM Calibration Results & Rating Curve Coefficients

a) Delta Channel, 2013; b) Waterhen Creek, 2013; c) Waterhen Creek, 2014

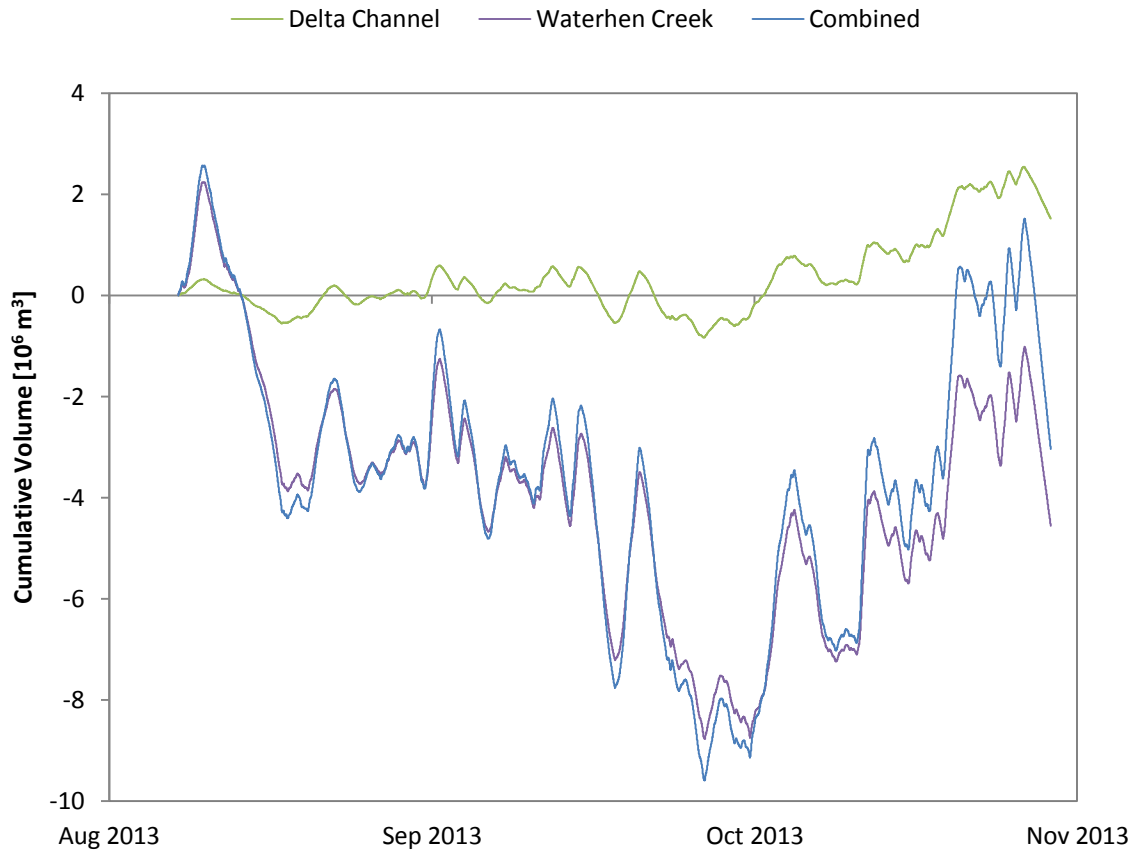


Figure A:2 – Comparison of Delta Channel and Waterhen Creek Capacities, 2014

Appendix B: Supplementary Numerical Modelling Results

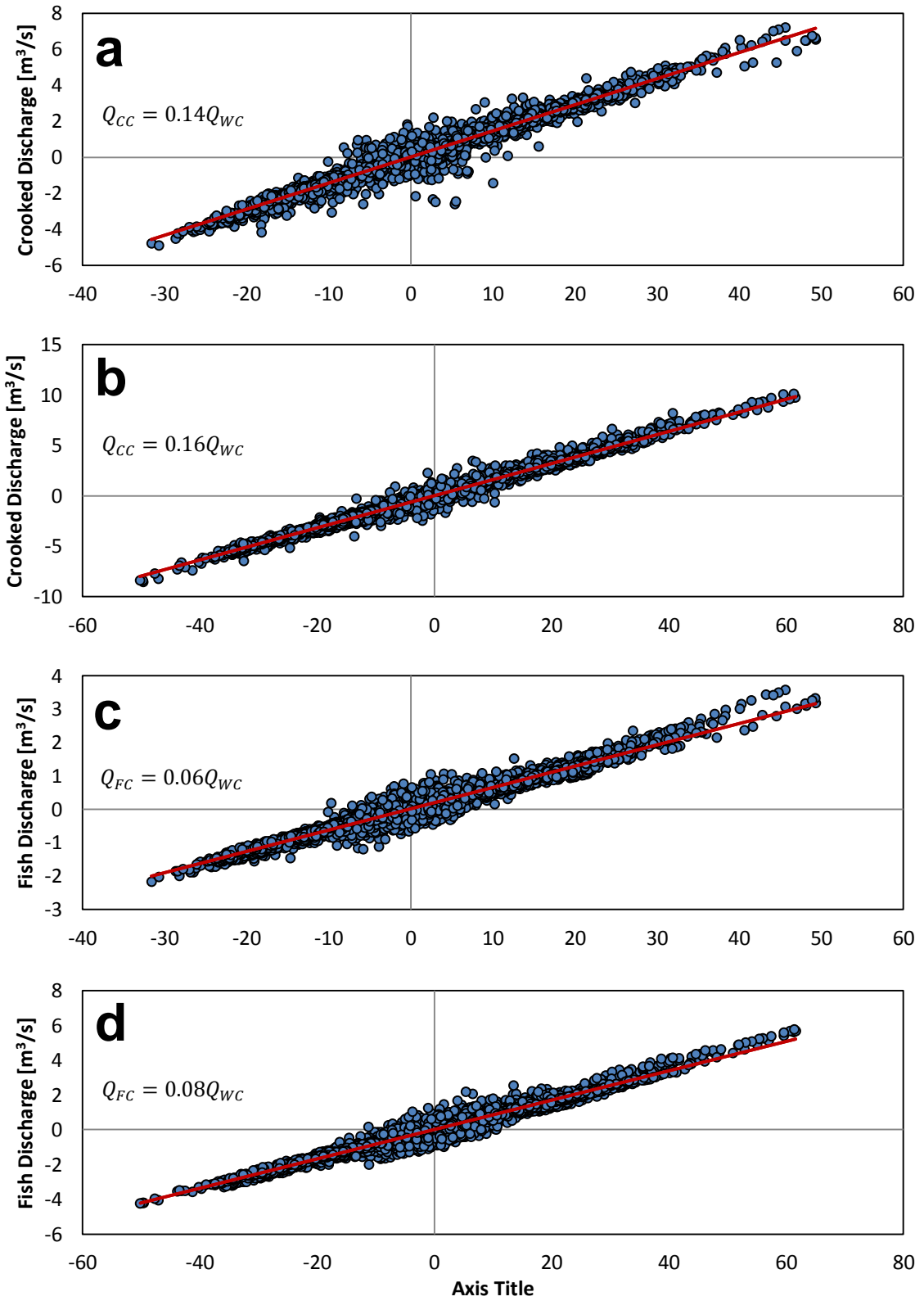


Figure B:1 – Modelled Baseline Capacity Comparisons at the East-Side of the Marsh

a) Crooked Creek, 2013; b) Crooked Creek, 2014; c) Fish Creek, 2013; d) Fish Creek, 2014

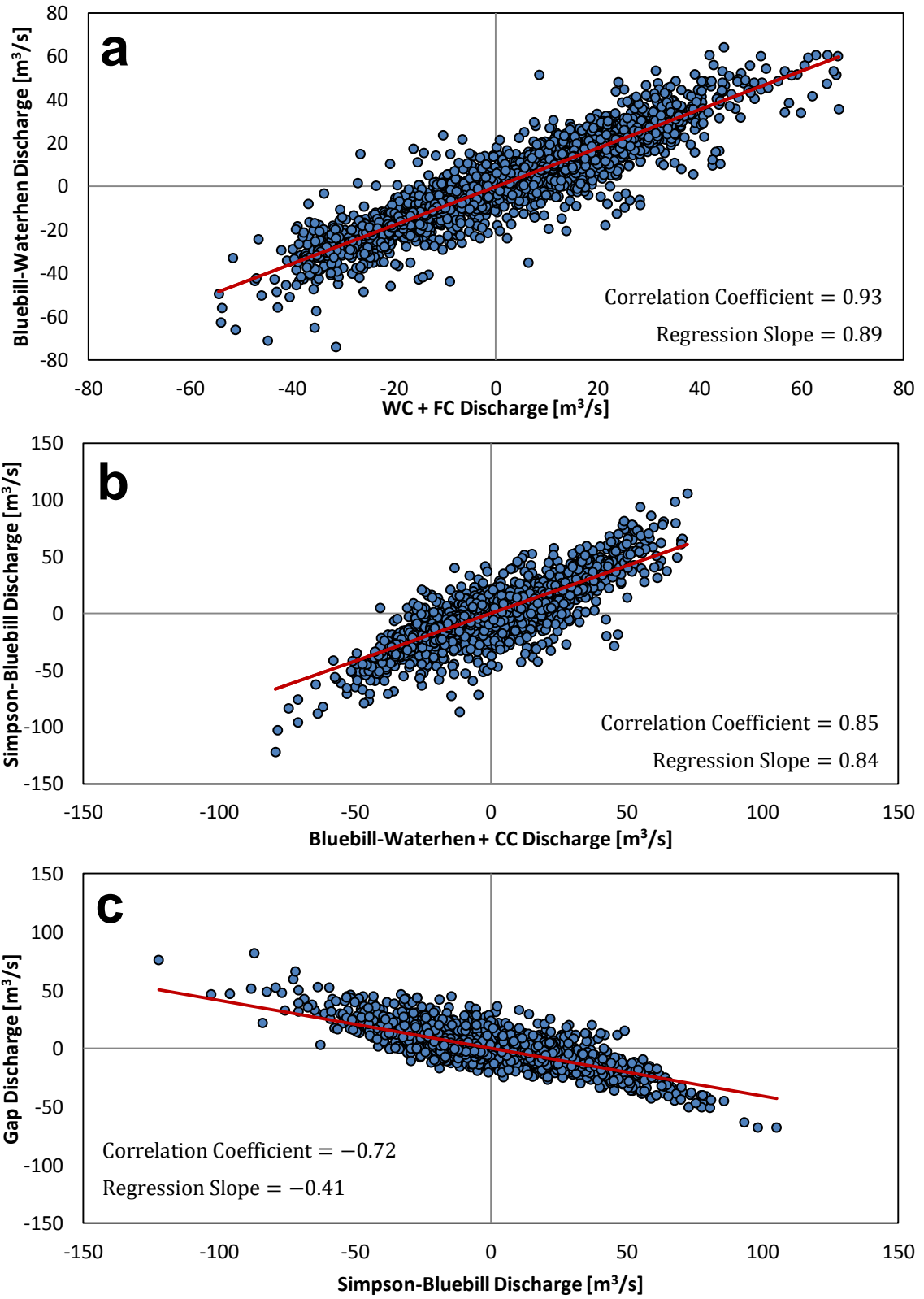


Figure B:2 – Internal Baseline Discharge Comparison, 2014

a) Bluebill-Waterhen / WC+FC; b) Simpson-Bluebill / Bluebill-Waterhen; c) Bluebill-Waterhen / Gap

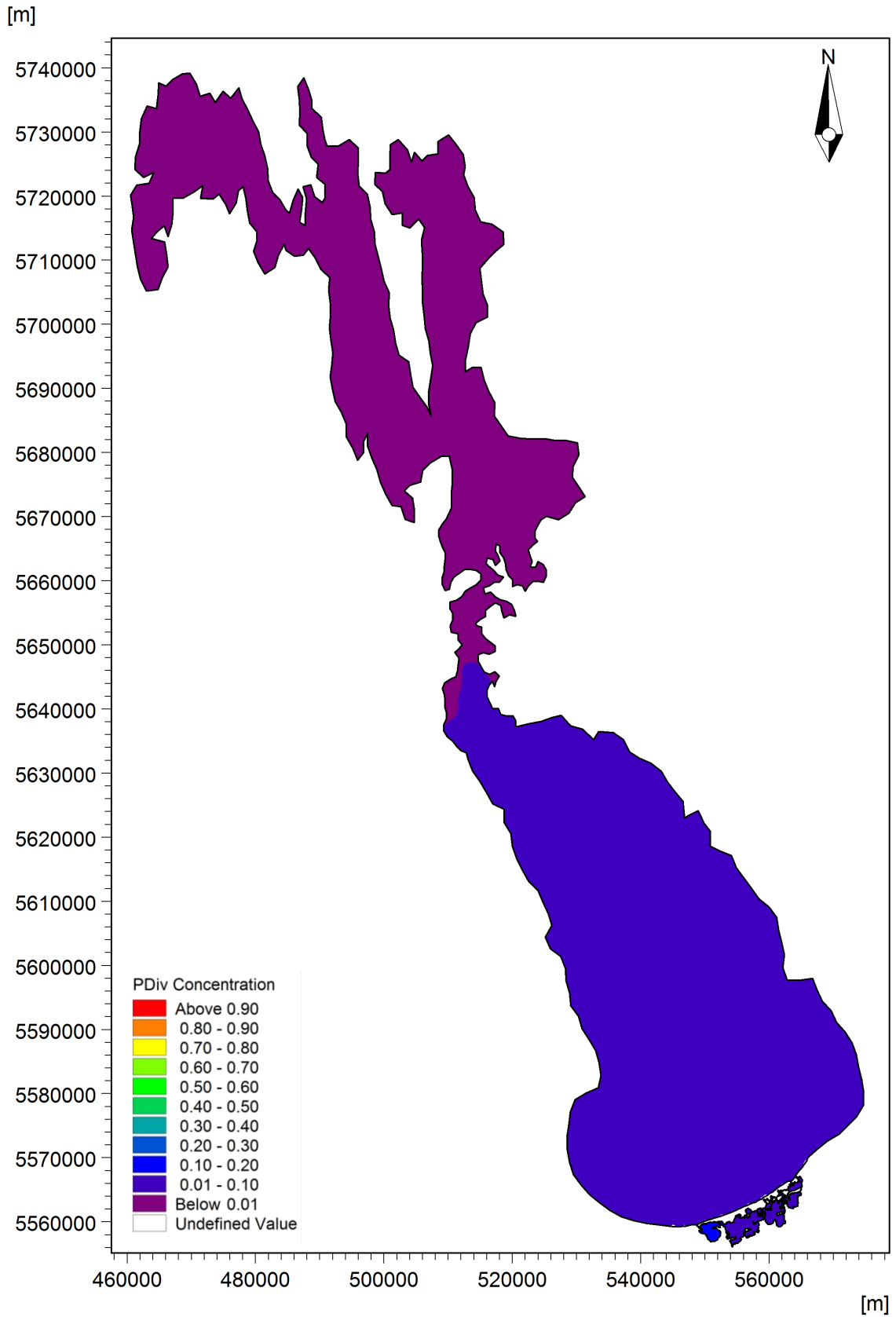


Figure B:3 – Portage Diversion Water Concentration, 00:00 01/11/2013

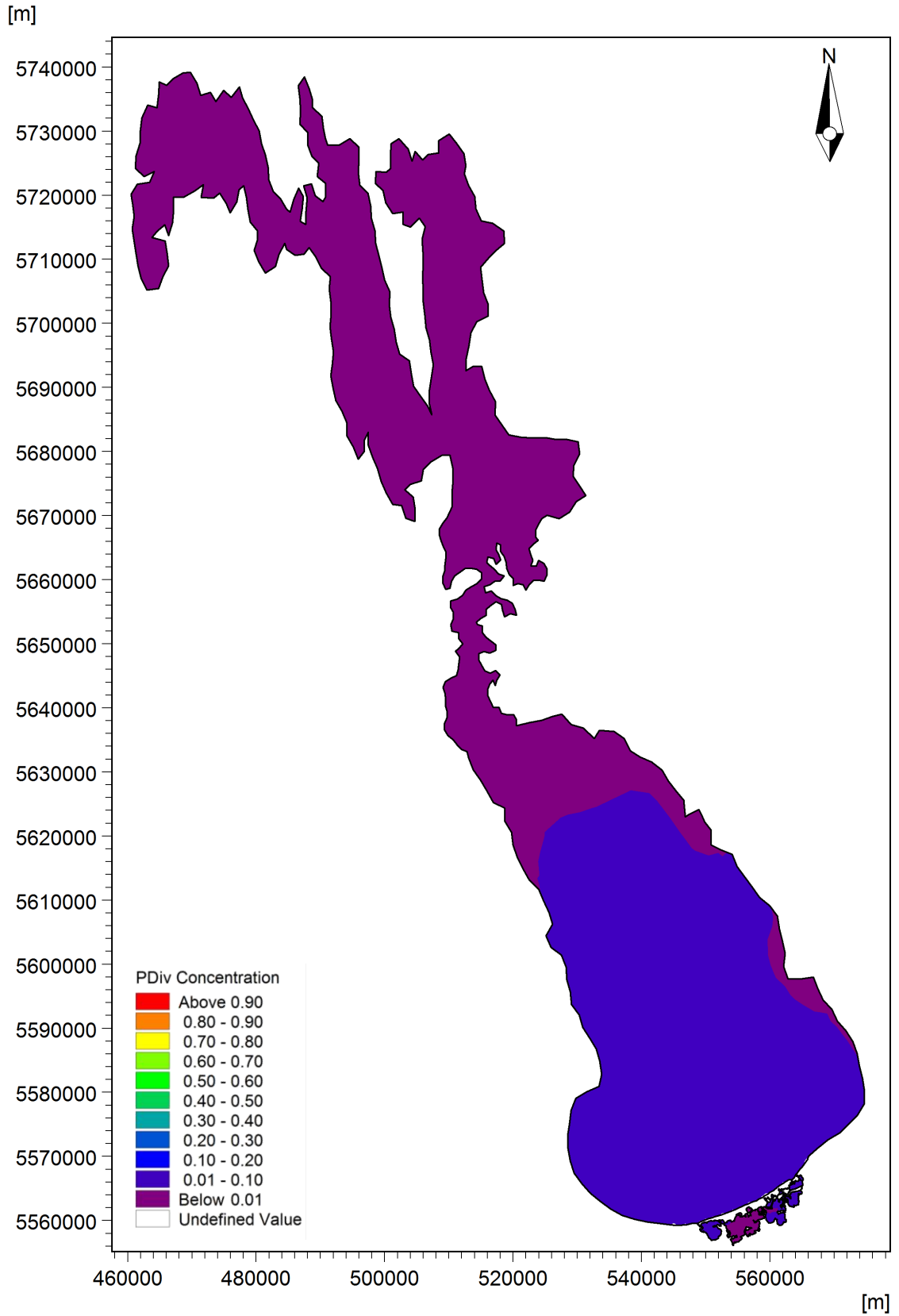


Figure B:4 – Whitemud River Water Concentration, 00:00 01/11/2013

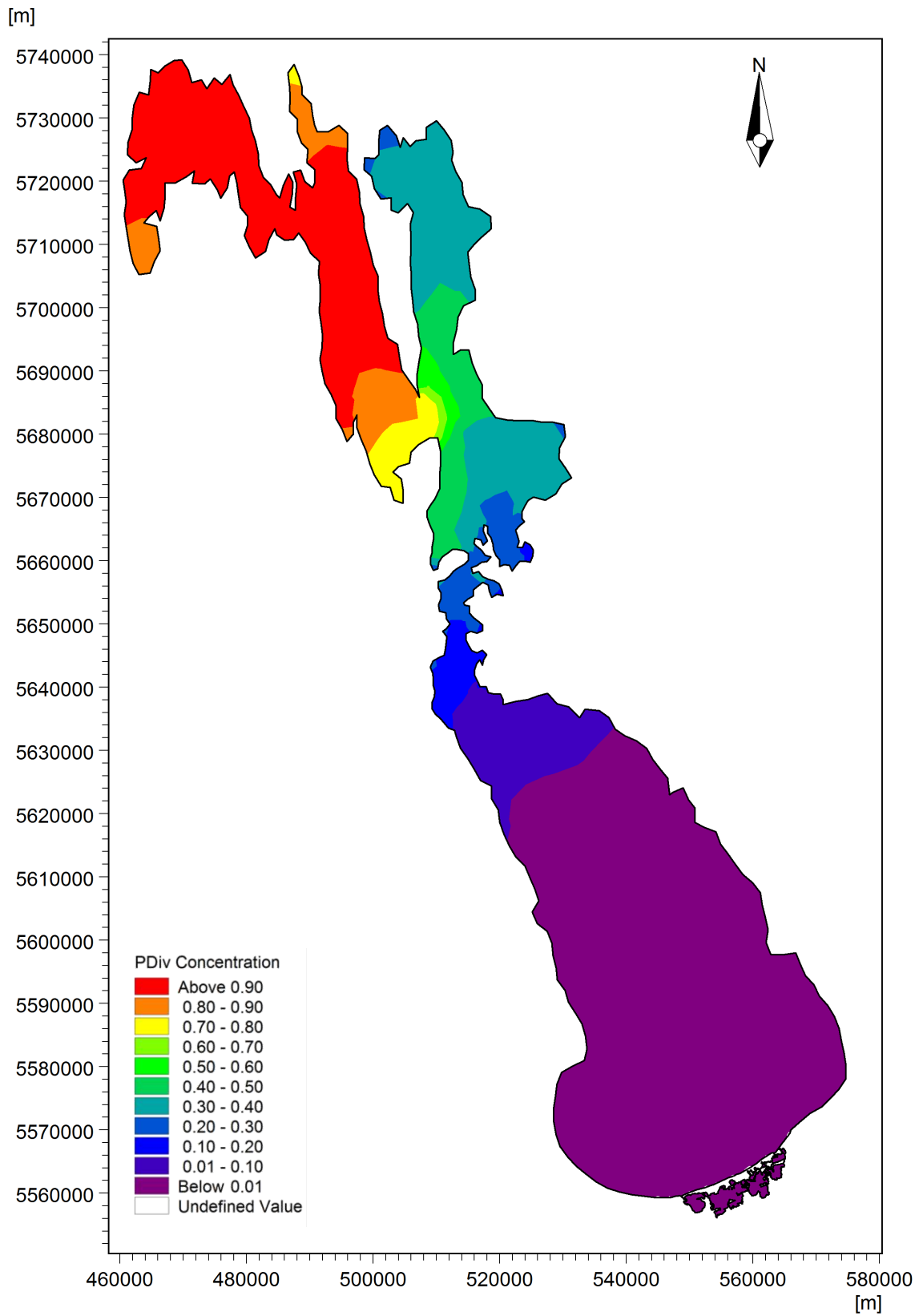


Figure B:5 – Waterhen River Water Concentration, 00:00 01/11/2013

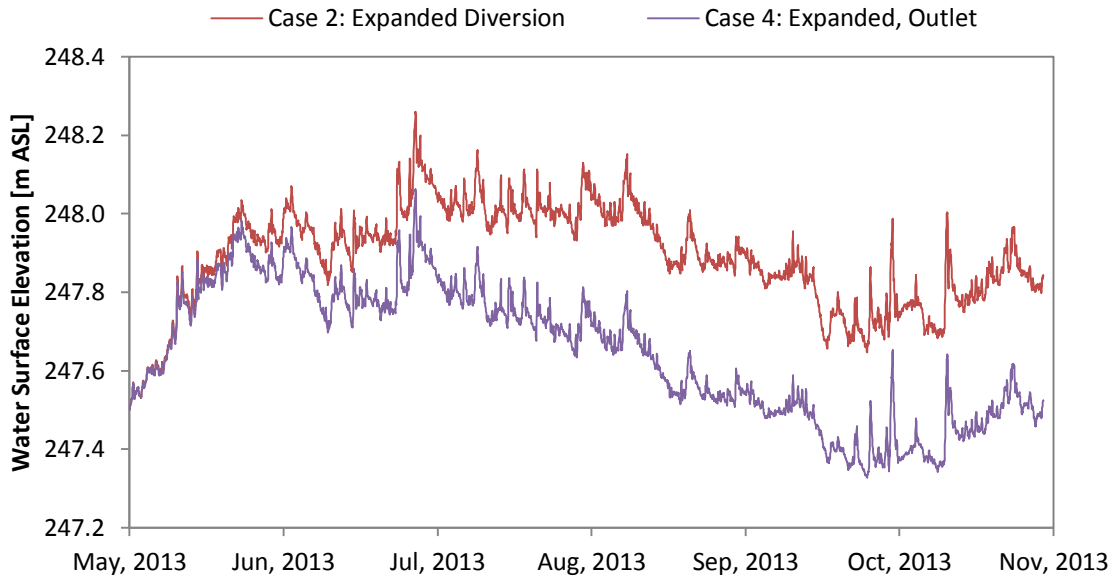


Figure B:6 – Clandeboye Bay WSE: Impact of Outlet Channel at High Inflow, 2013

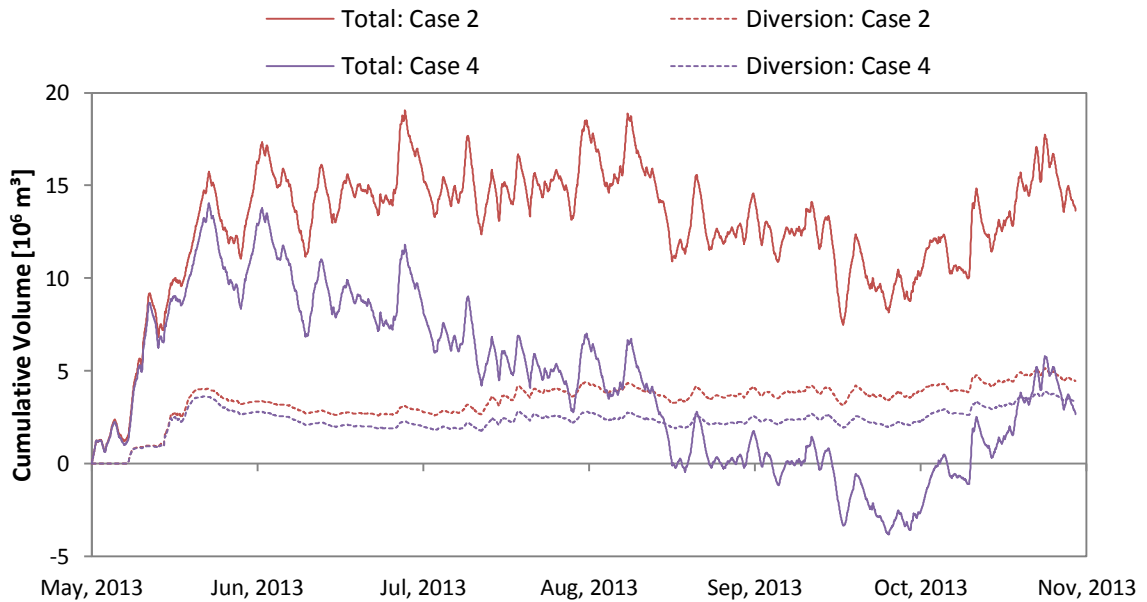


Figure B:7 – Clandeboye Channel Discharge: Impact of Outlet Channel at High Inflow, 2013

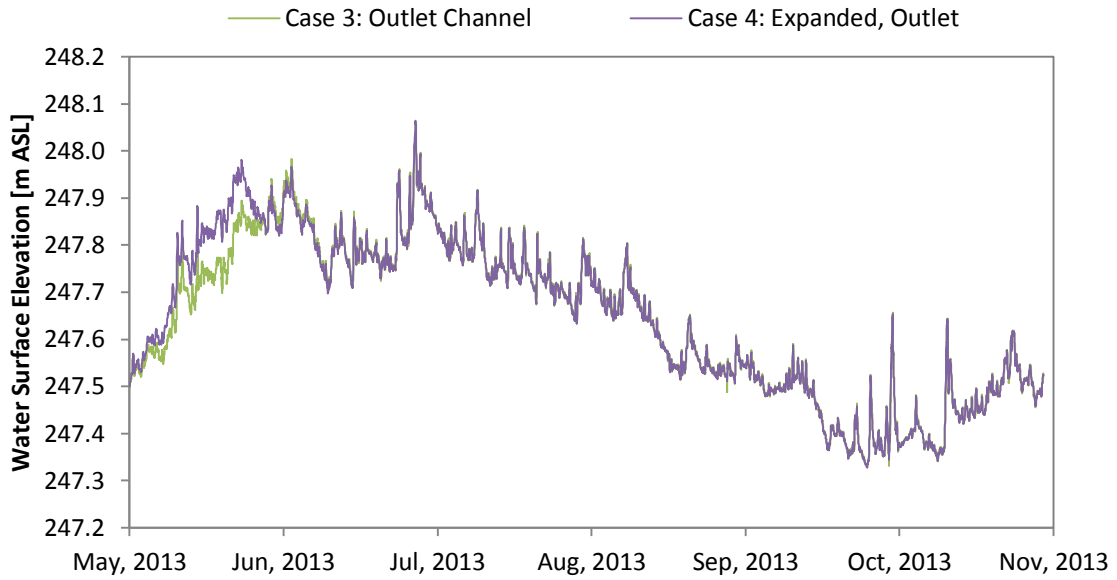


Figure B:8 – Clandeboye Bay WSE: Impact of Diversion Capacity with Outlet, 2013

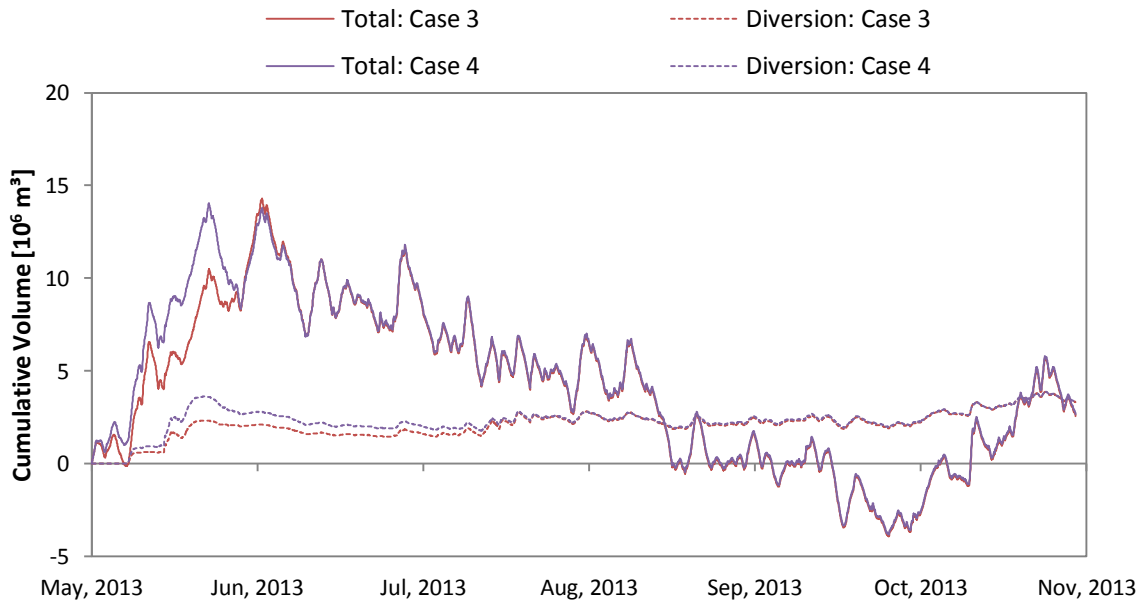


Figure B:9 – Clandeboye Channel Discharge: Impact of Diversion Capacity with Outlet, 2013

Appendix C: Practical Recommendations for Ongoing Field Research

Motivation:

Over the course of this project, the author of this thesis has compiled a list of suggestions regarding planning, preparing for, and conducting field research. This appendix is presented with the intention of passing on established methods to future field crews, and reducing the risk of repeating mistakes.

Regarding planning wetland hydrographic research:

1. Rehearse, from start to finish, the installation of each piece of equipment prior to heading out into the field. This will allow everyone to get comfortable with their roles, and will help you identify potential practical issues. Ask skeptical questions:
 - a. Can everyone complete their tasks without obstructing others?
 - b. Is there a simpler/lighter/cheaper/safer way to do this step?
 - c. Do we have enough rope/cable/material, and then some?
 - d. Does everyone have a manageable amount of work?
 - e. If something goes wrong, will we know, and can we fix it?
 - f. What can go wrong after installation, and how can we prevent it?
2. Remember that your study area may change dramatically over the season.
 - a. Install wet equipment (e.g. depth gauges) meters below the surface.
 - b. Install dry equipment (e.g. battery boxes) meters above the surface. Secure dry gear atop a table that has been hammered into the soil.
 - c. Mark each piece of equipment with flagging tape, and/or fluorescent paint, and/or pill floats, even if it is perfectly visible at the time of installation.
 - d. Document the locations of all field equipment in a GPS and a field book.
 - e. Vegetation can quickly overgrow your equipment. Pack a machete.

3. Develop a detailed packing list (sample list attached).
4. Planning is an ongoing process. Revisit your methods after every trip, and adjust them as you learn what works and what does not. During brainstorming sessions, there is no such thing as a bad idea. Dumb jokes have led to innovations.

Regarding preparing for a field trip:

5. If you are planning to head out on a Thursday, start checking the forecast on Monday. It will change.
6. When checking the forecast, remember that wind is worse than rain. Rain will leave you wet; wind will leave you wet, cold, and on choppy water.
7. Bring a variety of clothing that will allow you to be prepared for the warmest, coldest, wettest, and driest conditions.
8. Bring clothing that can get wet or muddy. Leave your designer sunglasses and silver wristwatch at home. Fashion has no utility on the marsh.
9. Invest in a multi-tool. You will use it every time you head into the field – and at home too! This cannot be overstated. Leatherman and Gerber make great tools.
10. Invest in 100% UV-blocking sunglasses (\$20 at Mark's, spring 2015). Dollar store sunglasses will reduce brightness, but will not shield your eyes from UV damage.
11. Invest in moisture-wicking socks (wool, or a synthetic blend).
12. Invest in a cheap but durable waterproof watch.
13. Pack double the water you think you need.
14. Pack redundant communication gear: cell phones, two-way radios, sat phone, etc.
15. Confirm the availability of lodging, vehicles, and equipment as early as possible.
16. Write as much as you can in the field book prior to getting on the boat.

Regarding conducting field research by boat:

17. Figure out how much gas you need for a round trip, and then pack twice as much.
18. Mark landmarks in the GPS to help navigate.
19. Keep in mind that GPS base maps are not perfect. Mark errors in the GPS.
20. There is no better way to learn the layout of your study area than to drive around.
This is especially true of large wetlands without landmarks. Make sure all core team members take turns driving and navigating.
21. Place heavier equipment at the front of the boat. This will help the boat become level, and will help you move faster and with better fuel efficiency.
22. Outboard motors are loud. Earplugs go a long way to preserving your sanity.

Regarding conducting winter field research:

23. Minimizing exposure is the key to safe and successful winter fieldwork. Try to prepare all field equipment as much as possible in advance to reduce the amount of time you will be fumbling with tiny screws during a blizzard.
24. Temperature affects the function of equipment. Everything will move slowly, parts will become stuck, and plastic is more brittle. Expect to troubleshoot everything.
25. Channels still convey water during the winter. As a result, the ice cover may be considerably thinner than on a bay. Inspect the ice cover of a channel before crossing it with your equipment. This should be done visually, and by drilling holes.
26. Have a detailed emergency plan for dealing with a team member who has fallen through the ice. Rehearse building a shelter and starting a fire.
27. Wear two layers of moisture-wicking socks inside well-fitting, insulated boots. Your feet will be warm and dry.

Regarding fieldwork in general:

28. Your priorities in the field should be as follows, in decreasing order of importance:

- a. Maintaining personal safety
- b. Maintaining the safety of other team members and of the public
- c. Avoiding or minimizing the impact to the existing environment
- d. Conducting research effectively
- e. Conducting research efficiently

In other words, never compromise the quality of data collection in favour of timeliness, for bad data is (are?) a waste of time. Never harm the environment to collect data, be it through poor planning or carelessness, for you have damaged that which you are trying to preserve and understand. Never compromise your own safety in an attempt to aid others, for you will become the newest casualty.

29. Safety and respect go hand-in-hand. Do not ask someone to do something that you would not feel comfortable doing yourself. If you feel that you have entered an unsafe situation, be honest with your team and voice your concerns.

30. Communicate your actions, movements, and needs to your team at all times.

31. Frustration can be motivating; anger is always impairing.

32. If you are not generally having a great time, try to identify and address the reason(s) why. Fieldwork should be a blast.

33. It does not have to be warm for you to get sunburn. Remember that sunlight hits you twice out on open water (directly and reflectively). Apply sunscreen often.

34. Chest-waders make for great rain/wind wear.

35. Seriously, invest in a multi-tool.

Date(s) of Field Trip: _____

Crew: _____

FIELD EQUIPMENT					
Item	Quantity	Container	Depart	Return	Comments
GENERAL					
Truck Key	1	---	<input type="checkbox"/>	<input type="checkbox"/>	In binder
Shovel / Pickaxe	1	---	<input type="checkbox"/>	<input type="checkbox"/>	
Rubber Boots	1 per	---	<input type="checkbox"/>	<input type="checkbox"/>	with insoles, if cold
Emergency Dry bag	1	---	<input type="checkbox"/>	<input type="checkbox"/>	emergency gear
FIELD BAG					
Field bag	1	---	<input type="checkbox"/>	<input type="checkbox"/>	
Field book	1	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	ensure copies have been made
Pencils	3+	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	sharpened, top outside pouch
Sharpies (fine-tipped)	2+	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	top outside pouch
Flagging tape	1	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	top outside pouch
GPS	1	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	put in Pelican case; check for extra batteries
Spare AA batteries	10+	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	in ziploc
Sigg bottles	2	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	filled with water, put in front pouch
First aid kit	1	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	ensure complete inventory, put in top inside pouch
Ear plugs	6+ pairs	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	
Sunscreen	1	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	in ziploc
Bug spray	1	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	in ziploc
Hand sanitizer	1	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	in ziploc
ACTION PACKER					
Action Packer	1	---	<input type="checkbox"/>	<input type="checkbox"/>	
Field laptop(s)	1 or 2	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	ensure fully charged; power cords, mouse
Back-up battery for Dell	1	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	put in Pelican case
Serial Adapter	1	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
Optical sensor	1	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	For Levellogger
Laminated protocols	1 set	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	SI sampling, LeveLogger, Argo, emergency contacts
TP	1	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	in ziploc
Rain gear	1 set per	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	jacket, pants, waterproof gloves
Bright hats & vests	1 per	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	caps or toques
Rope	1 spool	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
Machete	1	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
Hip-waders	2	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
Life jackets	1 per	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
Spare charge controller	1 or 2	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	

TOOLBOX					
Toolbox	1	---	<input type="checkbox"/>	<input type="checkbox"/>	blue field toolbox
Spare Steel Wool	2+	Toolbox	<input type="checkbox"/>	<input type="checkbox"/>	
Zipties	20+	Toolbox	<input type="checkbox"/>	<input type="checkbox"/>	Different sizes
Mallet	1	Toolbox	<input type="checkbox"/>	<input type="checkbox"/>	
Leatherman	1+	Toolbox	<input type="checkbox"/>	<input type="checkbox"/>	Or on person
SI SAMPLING					
30 mL bottles	As needed	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	taped, labelled if possible, in labelled ziplocs
Electrical tape	3+	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	not white or yellow, top outside pouch
Sampling pole	1	---	<input type="checkbox"/>	<input type="checkbox"/>	Only when sampling LM or PD
Manual pumps	3+	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	for piezometers
Spare ziploc bags	2+	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	
Oil	1+ jug	---	<input type="checkbox"/>	<input type="checkbox"/>	for precipitation buckets
ARGONAUTS					
Keys for padlocks	2	On person	<input type="checkbox"/>	<input type="checkbox"/>	with Alex and/or Parsa
ADCP					
M9 Case	1	---	<input type="checkbox"/>	<input type="checkbox"/>	with M9, GPS, and cables
Floater board	1	Sleeve	<input type="checkbox"/>	<input type="checkbox"/>	
Spare batteries	4	M9 case	<input type="checkbox"/>	<input type="checkbox"/>	fully charged
Battery chargers	2	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
Short Rope	2 lengths	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
ISCO					
ALS bottles	As needed	Field bag	<input type="checkbox"/>	<input type="checkbox"/>	
Coolers	2	---	<input type="checkbox"/>	<input type="checkbox"/>	1 for samples, 1 for ISCO supplies
Latex gloves	1 box	Cooler	<input type="checkbox"/>	<input type="checkbox"/>	
Acid solution	As needed	Cooler	<input type="checkbox"/>	<input type="checkbox"/>	At Delta
Sodium bicarbonate	As needed	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	At Delta
DI Water	As needed	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
Spare batteries	2	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
Voltmeter	1	Action Packer	<input type="checkbox"/>	<input type="checkbox"/>	
OTHER					
			<input type="checkbox"/>	<input type="checkbox"/>	
			<input type="checkbox"/>	<input type="checkbox"/>	
			<input type="checkbox"/>	<input type="checkbox"/>	
			<input type="checkbox"/>	<input type="checkbox"/>	
			<input type="checkbox"/>	<input type="checkbox"/>	
			<input type="checkbox"/>	<input type="checkbox"/>	
			<input type="checkbox"/>	<input type="checkbox"/>	
			<input type="checkbox"/>	<input type="checkbox"/>	