

**A historical analysis of the changes in connectivity and  
plant cover in Netley-Libau Marsh, Manitoba,  
Canada:**

**Distinguishing the effects of Lake Winnipeg and Red River  
hydrology on coastal marsh emergent macrophyte areal  
extent**

By

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## **Abstract**

Netley-Libau Marsh in Manitoba, Canada is a 26 000 hectare coastal, freshwater marsh located at the mouth of the Red River on the south shore of Lake Winnipeg. Shoreline erosion and loss of emergent vegetation since 1929 has resulted in large expanses of open water and an overall degradation to the marsh ecosystem. Six coastal marshes of similar size and all connected to the south basin of Lake Winnipeg were selected for comparison to determine if marsh vegetation loss is widespread in Lake Winnipeg coastal marshes or limited to Netley-Libau Marsh. As a measure of degradation, open water area measurements of the study marshes were digitized from aerial and satellite images taken between the years of 1929 and 2015. Distinguishing the effects of Red River discharge into the west side of Netley-Libau Marsh from that of Lake Winnipeg regulation was confounded by the finding that direct river connection to the marsh was not firmly established until approximately 1970, just six years prior to the commencement of lake regulation. Red River discharges upstream of Netley-Libau Marsh did not significantly account for variation in open water areal extent within the two Netley-Libau Marsh study areas, nor did modelled Netley Cut discharges. Between 56-95% of the variation in open water areal extent within the six study marshes was explained by two growing seasons of average May-October Lake Winnipeg water levels. Variation in open water areal extent was not comparable in all six study marshes, and the frequency and duration of low-water periods decreased after 1976. My findings show that the loss of habitat complexity and emergent vegetation in Lake Winnipeg coastal wetlands has been ongoing since the early 20<sup>th</sup> century and is attributed most heavily to the decrease in low-water periods in Lake Winnipeg levels. The greatest loss of open water area within Netley-Libau Marsh occurred in years when average Lake Winnipeg water surface elevation decreased to 217 metres above sea level during typical ice-free

months (May-October). These findings highlight the importance of periodic lowering of Lake Winnipeg water levels in promoting coastal marsh vegetation growth and future habitat restoration efforts.

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# **1 Introduction**

## **1.1 Wetlands**

Wetlands are highly complex, dynamic ecosystems that provide several beneficial services to flora, fauna, and humans alike. With an estimate of at least 1280 million hectares (ha) of wetlands worldwide (MEA 2005), Canada alone accounts for approximately 24% (NWWG 1988). These are some of the most biodiverse ecosystems in the world, consisting of vegetation that is uniquely adapted to hydric soil conditions, and serving as important foraging and breeding habitat for many species of birds, mammals, fish, amphibians, and invertebrates (Weller 1999; Mitsch & Gosselink 2007; MEA 2005; and Batzer and Boix 2016). Wetlands also decrease the impact of flooding and erosion of land downstream by slowing runoff and increasing water holding time and are also able to improve water quality downstream as nutrient pollution is sequestered in sediments and tissues of some aquatic plant species (Mitsch et al. 2009; Mitsch & Wang 2000; Krieger 2003; MEA 2005; and Grosshans et al. 2012). Other benefits of wetlands include food sources, recreation, and cultural/historical significance for humans (Batzer & Sharitz 2006; Voora & Venema 2008; MEA 2005). Even with the many recognized benefits of wetlands, their global degradation and loss is ongoing due in large part to human development and land use changes, nutrient loading, and the introduction of invasive plant and animal species (MEA 2005).

The defining features of wetlands are hydric (water saturated) soil and the hydrophilic (water loving) vegetation which thrive in these areas (NWWG 1988; Keddy & Fraser 2000; and Tiner 2017). In some wetlands, soils may simply stay saturated with water while in others the ground surface may be completely submerged under shallow water ephemeraly or all year round. These hydric surface conditions are caused by the combination of a number of factors

such as the climate, topography, geology, and soil type (Batzner & Sharitz 2006). The Canadian Wetland Classification System (NWWG 1988) recognizes five wetland classes: freshwater marshes, fens, bogs, swamps, and shallow open water which have their own unique flora and faunal communities as well as soil and water characteristics and chemistry defining them from one another. In this thesis, I will be discussing coastal freshwater marshes in particular.

## **1.2 Coastal Freshwater Marshes**

Out of approximately 23 334 000 ha of total wetlands covering the entire province of Manitoba, Lake Winnipeg coastal wetlands account for 140 400 ha (Halsey et al. 1997; Watchorn et al. 2012). Coastal freshwater marshes are typically located inland along the fringes of freshwater lakes, rivers, and streams. They are often subjected to similar hydrological, biological, and chemical conditions of the water body to which they are connected. The effects of these conditions often vary with the level and type of connection these wetlands have to other water bodies. This connection can be described as being part of a wetland's hydrogeomorphology. Three basic coastal marsh hydrogeomorphologies going from most connected to least are: open coastal wetlands, drowned river-mouths or deltas, and protected or isolated wetlands (Keogh et al 1999; Albert et al. 2005).

Barriers such as dykes and beach ridges can provide some degree of isolation, and in many cases, protection from the hydrological processes of other water bodies (Keogh et al 1999; Kowalski & Wilcox 1999; Trebitz et al. 2002; Wilcox et al. 2008; Bayley & Guimond 2009). These barriers are subject to change through the processes of erosion or sedimentation which are affected by water levels, wave action, ice scour, and direction and magnitude of water flows.

Watershed hydrology is an important factor when considering coastal marsh ecosystem processes as it can affect sediment deposition, habitat quantity and quality, species composition,

and nutrient cycling (Keough et al. 1999; Mitsch & Gosselink 2007; Batzer & Sharitz 2006). Hydrology determines the water holding time, affecting the magnitude and time of flooding (Mitsch et al 2009; Batzer & Sharitz 2006; Grosshans et al. 2012). Short-term water level fluctuations in coastal marshes are driven by seiches or ‘wind tides’ which may last for only a few hours (Einarsson and Lowe 1968). Seasonal and interannual variations are subject to the climate cycles of a particular region (Keough et al. 1999; Trebitz et al. 2002).

### **1.3 Hydrological Effects on Emergent Vegetation**

Freshwater marshes are characterized by having emergent aquatic plants such as *Scirpus* spp. (bulrush), *Typha* spp. (cattails), *Carex* spp. (sedges), and *Phragmites* spp. (reed grass) (Mitsch et al 2009). There is a general consensus that moist, but not flooded soil conditions in marshes are ideal for emergent seed germination, although other variables such as soil type and nutrient composition and concentration are also contributing factors to seed germination and seedling growth (van der Valk and Davis 1978; Keddy & Reznicek 1986; Mitsch et al. 2009; and Farrell et al. 2010). van der Valk and Davis (1978) describe a four-phase vegetation cycle driven primarily by water level conditions that has been widely accepted as a model to prairie marsh emergent vegetation growth and succession. Low to no standing water in the dry marsh phase allows emergent vegetation seeds to germinate and become established on mudflats exposed by low water levels. The dry phase then gives way to the regenerating marsh phase as water levels rise, allowing emergent vegetation to thrive in hydric conditions. The regenerating marsh phase eventually transitions to the degenerating marsh phase when emergent vegetation begins to die off due to sustained high water levels (limiting oxygen) and herbivory. The degenerating marsh then enters a lake marsh phase once most of the emergent vegetation has died off due to anoxic

(oxygen lacking) soil conditions caused by water saturation. This cycle then begins again once water levels are naturally or artificially lowered (van der Valk and Davis 1978).

The response of emergent vegetation growth and species composition to water level fluctuations has been the subject of many wetland studies (Lyon et al. 1984; Williams & Lyon 1997; Gottgens et al. 1998; Bailey & Bedford 2003; Trebitz et al 2005; Hudon 1997 and 2004; Chow-Fraser 2005). Not only is length of hydroperiod (flooding time period) important, but so too is the depth of flooding, or lack thereof, to the germination of emergent vegetation seeds, thus ultimately affecting species richness, vegetation growth, and zonation (van der Valk 1978; Keddy & Reznicek 1986; Baldwin et al 2001; Wilcox & Nichols 2008; Farrell et al 2010; Chapin & Paige 2013; Hudon et al 2005; and Wilcox et al. 2008). Marshes made up of a patchwork mosaic of open water and vegetation tend to be the most biodiverse, providing a greater number of micro-habitats for both flora and fauna (Weller 1999; Keddy & Reznicek 1986; Murkin et al. 1997).

The freshwater coastal marshes of the Great Lakes provide some of the best examples of how freshwater coastal marsh vegetation growth and communities can be affected by the water bodies to which they are connected. Gottgens et al. (1998) analyzed the areal extent of emergent vegetation to lake levels in southwestern Lake Erie marshes with differing degrees of connection to the lake. They showed that emergent vegetation cover remained at 50% average cover over the course of 119 years (1872-1991) in wetland areas isolated from the hydrological processes of Lake Erie by dykes and with independently managed water levels that allowed for water level drawdowns. This contrasts with the 95% loss of emergent vegetation in marsh areas openly connected to Lake Erie and thus subjected to the same above average, stabilized water levels that are a result of water level regulation of Lake Erie. Emergent vegetation area in the openly

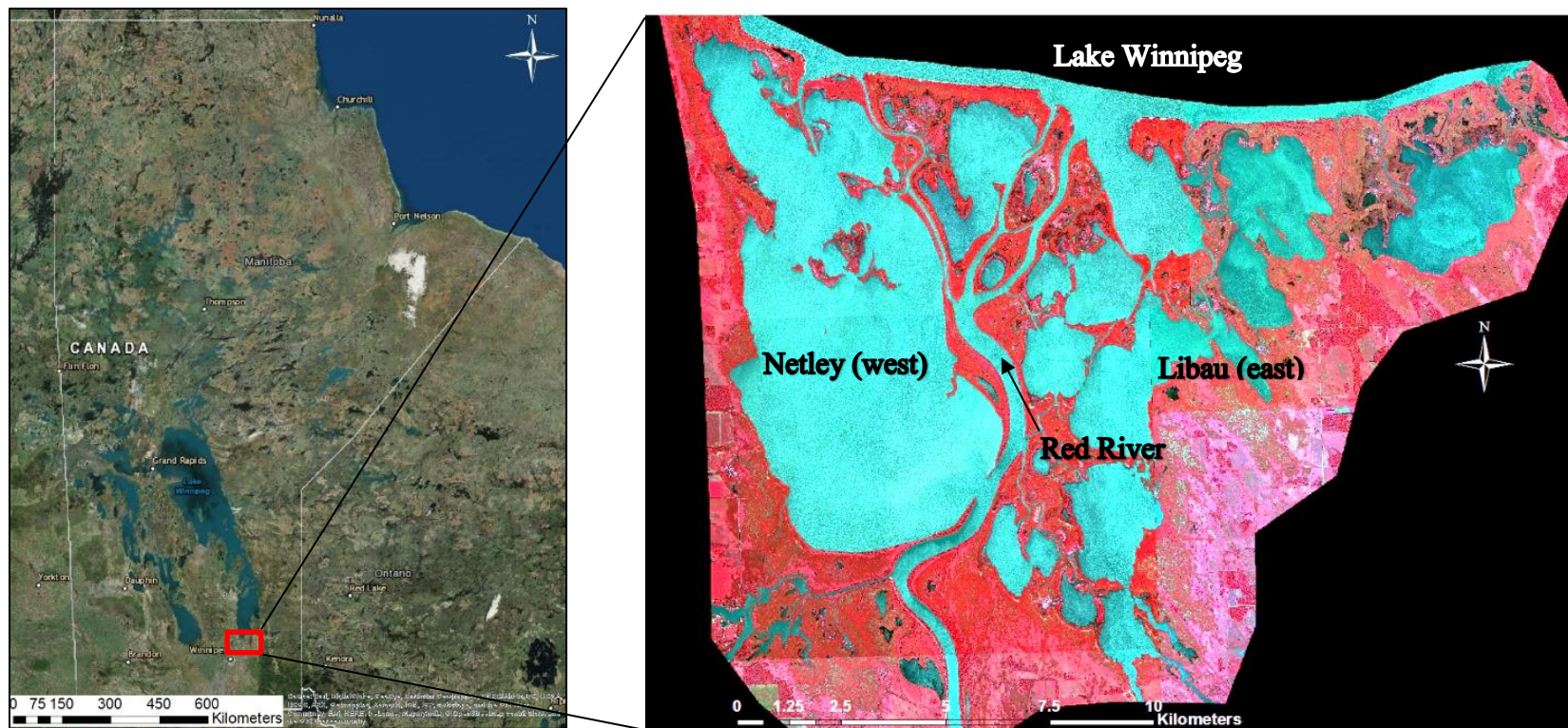
connected, non-regulated marshes fluctuated with lake levels and then decreased rapidly since the 1970s, during which there has been a period of sustained high Lake Erie levels (Gottgens et al. 1998). Chow Fraser (2005) investigated the relationship between percent of emergent vegetation cover and water levels at Cootes Paradise Marsh at the west end of Lake Ontario. She found there was a strong, statistically significant relationship tying together long-term historical vegetation extent and water level. When water levels were low, vegetation extent was high and vice versa (Chow Fraser 2005).

The close relationship between extent and growth of emergent vegetation and hydrology was further demonstrated by Wilcox and Nichols (2008) at Saginaw Bay, Lake Huron. Percent cover of emergent vegetation was estimated in transects at varying elevations along the shoreline of the coastal marsh to assess vegetation response to water level fluctuations. They showed that transects that remained flooded over the entire five-year study were much less species rich than transects that went from flooded to dry (exposed), demonstrating the need for water level fluctuations for promoting vegetation biodiversity. Transects that were flooded briefly or were within the shoreline zone affected by seiches had lower species richness, possibly due to the scouring of waves along exposed shorelines (Wilcox and Nichols 2008).

#### **1.4 Netley-Libau Marsh**

Lake Winnipeg has 140 400 ha of coastal wetlands (Watchorn et al. 2012). One of these wetlands is Netley-Libau Marsh, which is located at the mouth of the Red River (Figure 1) where it drains into the south end of Lake Winnipeg. The marsh straddles the Red River near its outlet, with the Netley portion of the marsh on the west side of the Red River and the Libau portion located on the east side. Channels and bays connect Netley-Libau Marsh to both the Red River and Lake Winnipeg, subjecting the marsh to the hydrologys of these two water systems.

**Figure 1.** Location of Netley-Libau Marsh, Manitoba, Canada. Source: Base image on left obtained from ESRI ArcMap Version 10.2.2 with Netley-Libau Marsh outlined in red. Netley-Libau Marsh image on right is WorldView 3 satellite imagery purchased by the University of Manitoba and acquired on August 15, 2015 (DigitalGlobe 2015). Locations of Lake Winnipeg and Red River have been labelled in relation to Netley-Libau Marsh.



#### **1.4.1 Hydrogeomorphology**

Netley-Libau Marsh has been categorized as a barred drowned river mouth (Watchorn et al. 2012) and, at 26 000 hectares in size, it is believed to be the largest coastal freshwater marsh in North America (Grosshans et al. 2004; Watchorn et al. 2012). The hydrology of Lake Winnipeg and the Red River act as driving forces on the hydrology of Netley-Libau Marsh. The Red River flows through the Netley-Libau Marsh complex, acting as a natural division between the west (Netley) and the east (Libau) marshes before it finally discharges into Lake Winnipeg.

The marsh is separated from Lake Winnipeg by a 21.7 km barrier beach ridge that is interrupted by channels and bays (Verbiwski 1986). The number of these connections to Lake Winnipeg varies over time between eight and eleven depending on lake level (Watchorn 2015). Water levels within the marsh can fluctuate up to two metres depending on Lake Winnipeg levels and wind set up (Nielsen 1998). With the predominant winds coming from the northwest, this wind set up pushes Lake Winnipeg waters to its south end, flooding the flat, low-lying Netley-Libau Marsh and its surrounding upland areas. Inland flooding from wind set up can be extensive, due to the low topography of the Netley-Libau Marsh area which, according to the Canadian Digital Elevation Model, sits below 218 metres asl (above sea level) (Aquatics Environmental Services Inc. 2011; Natural Resources Canada 2017).

#### **1.4.2 Vegetation**

Past vegetation studies of Netley-Libau Marsh describe communities of submerged, emergent, wet meadow, and upland plants (Verbewski 1986; Grosshans et al. 2004; Watchorn 2014 and 2015). Since the 1970s, researchers have noted a degradation of the marsh ecosystem in the form of erosion of shorelines, loss of emergent vegetation, expansion of open water area, and decreased habitat for flora and fauna (Verbiwski 1986; Lindgren and the Netley-Libau

Marsh Foundation Inc. 2001; Grosshans et al. 2004). Notice in Figure 2 the replacement of dense patches of emergent vegetation by non-vegetated open water, increased surface water connections between water bodies, and eroded shorelines within Netley-Libau Marsh. Concerns of local landowners and researchers over this loss of vegetation have prompted several vegetation and land cover studies of Netley-Libau Marsh. Aerial infrared photography was used by Grosshans et al. (2004) to create vegetation maps of Netley-Libau Marsh in 1979 and 2001. Between these years, open water areas increased from 39% to 51% (+12%) while emergent vegetation decreased from 38% to 22% (-16%) of Netley-Libau Marsh area (Verbiwski 1986; Grosshans et al. 2004). In the most recent vegetation study conducted at Netley-Libau Marsh the most common macrophytes were *Typha* spp. (Cattail), *Scirpus* spp. (mixed bulrush), *Carex* spp. (sedges ), and *Phragmites australis* (giant reed grass (Watchorn 2015)).

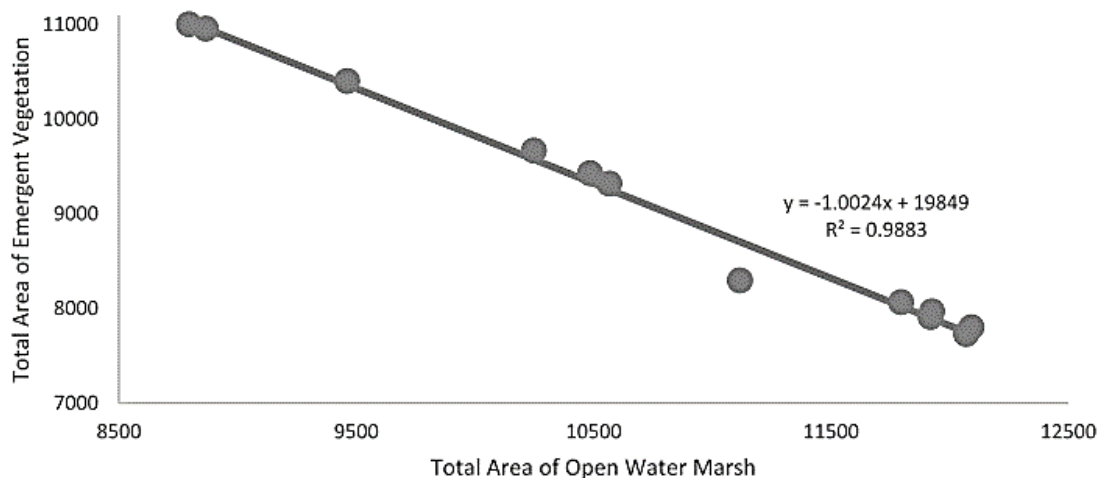
**Figure 2.** Historical aerial images of the Netley-Libau Marsh from 1923 (top) and 2003 (bottom). These aerial photos were taken near the mouth of the eastern most branch of the Red River with the camera oriented southwest. In the background is the southern half of Netley Lake. Source: 1923 image obtained from Archives of Manitoba, FA23/07, C10 Box 15, 1960-2. Air photos of Red River from Lake Winnipeg to Winnipeg, 72 photos, 9x8, 1923. 2003 image obtained from Goldsborough unpublished data 2003.



The dominant vegetation classes in 1979, from highest percent cover to lowest, were *Typha* spp. (cattails, 20.8%), *Scirpus* spp. (hard- and soft-stemmed bulrush, 13.3%), *Scirpus fluviatilis* (river bulrush, 4.0%), *Carex* spp. (sedges, 7.0%), and *Phragmites australis* (giant reed grass, 2.9%) (Verbiwski 1986). The 1979 vegetation study also identified that water accounted for 38.5% percent cover in Netley-Libau Marsh and that the remaining 13.5% was uplands, agriculture, trees, willow, and human dwellings. The 1979 vegetation classes still existed for the most part when vegetation mapping was done again in 2001, although percent covers had changed and the river bulrush and emergent sedge classes were combined into one class. Dominant emergent vegetation classes in 2001, from highest percent cover to lowest, were: cattails (17.9%), giant reed grass (2.8%), hard and soft stemmed bulrush (1.2%), and *Scirpus fluviatilis* (mixed river bulrush) and sedges (0.6%) (Grosshans et al. 2004). In 2001 water accounted for 50.9%, and the remaining 26.4% was wet meadow, low prairie, and upland cover. Caution must be used in making these temporal comparisons. One must take into account differences in water surface elevations when comparing the vegetation community between these two years. In the five years preceding 1979, mean May-October wind-smoothed water levels in Lake Winnipeg fluctuated by 1.71 metres between the highest and lowest average levels, while in the five years preceding 2001 fluctuations were far smaller at only 0.30 metres. As discussed previously in Chapter 1.3, inter-annual water level fluctuations often increase floral biodiversity in marshes. Therefore, differences in the Netley-Libau Marsh vegetation community between 1979 and 2001 should not be attributed solely to a general loss in emergent vegetation through time, but rather the response of the vegetation community to environmental conditions leading up to these years of study. A vegetation map created from Landsat 7 imagery of the marsh in 2001 identified five main marsh zones: water, non-vegetated, emergent wetland vegetation, wet

meadow, and upland (Watchorn 2014). Similar cover classifications were used in a Netley-Libau Marsh vegetation time series analysis (1990-2013) conducted by Watchorn (2015), who found that there was an almost perfect negative correlation between open water areal extent and the areal extent of emergent vegetation (Figure 3). As open water areas increased, emergent vegetation areas decreased. This finding justifies the use of open water areal extent as a measure of potential emergent vegetation area decline in Netley-Libau Marsh (Figure 3).

**Figure 3.** Least squares linear regression relationship between open water area and area of emergent vegetation in Netley-Libau Marsh (Watchorn 2015, Figure 9.10).



Marsh vegetation growth is affected by the current growing season water levels and previous growing season water level conditions. Several Great Lakes coastal marsh studies suggest that the lag time length in vegetation response to water levels is a period of two to five growing seasons (Gottgens et al. 1998; Keddy & Fraser 2000; and Wilcox et al. 2008). No significant relationship was found between change in open water area between mapped years and Red River spring discharges ( $\text{m}^3/\text{s}$ ), meaning Red River discharge through Netley-Libau Marsh

may not be the driving force of open water area expansion and emergent vegetation loss (Watchorn 2015).

### **1.4.3 Wildlife and Resource Use**

Netley-Libau Marsh was declared an Important Bird Area (IBA) by the Canadian IBA Program in the late 1990s as it is a major staging ground for migrating bird species. Gulls, terns, grebes, and herons rely heavily on Netley-Libau Marsh as a breeding/nesting area due to the abundance of small fish species, deep channels, and emergent vegetation stands. Many species of waterfowl, as well as Franklin's gulls, Forster's terns, black-crowned night-herons, swallows, and blackbirds use the marsh as a staging or nesting area during migration (Verbiwski 1986; Lindgren and the Netley-Libau Marsh Foundation Inc. 2001). Since the 1970s there has been a marked decline of wildlife in the area attributed to the degradation of nesting, brood rearing, and foraging habitat via the erosion of islands and shorelines (Verbiwski 1986).

Fish species such as bullhead, northern pike, carp, sauger, and yellow perch use the Netley-Libau Marsh for foraging and spawning. Small fish species like emerald and spottail shiner are also abundant; helping support Manitoba's commercial bait fish industry (Verbiwski 1986). Fish species requiring shallow water and flooded vegetation areas for spawning and nursery habitat such as northern pike and perch would be most heavily impacted by the loss of emergent vegetation and increase in open water area, as there is more wave action and the possibility of predation in open water areas (Verbiwski 1986).

Netley-Libau has cultural historical significance as an area for hunting, fishing, trapping, and agriculture and it's because of this significance that it is a Manitoba Heritage Marsh (Lindgren and the Netley-Libau Marsh Foundation Inc. 2001). In the past, waterfowl hunters took advantage of the exceptional populations of waterfowl utilizing Netley-Libau Marsh as a

staging area. An area of the northwest portion of Netley-Libau Marsh, between the main and west channels of the Red River mouth, was declared a Game Bird Refuge in 1966 to increase waterfowl numbers (Lindgren and the Netley-Libau Marsh Foundation Inc. 2001). Since the 1970s, the number of hunters utilizing Netley-Libau has gone down in response to decreasing waterfowl populations (Verbiwski 1986). Traditionally, upland areas were used to grow and harvest hay (Verbiwski 1986; Public Works Canada 1907). Agricultural land has decreased in size within the Netley-Libau Marsh as shorelines continue to erode and many locals no longer live within the marsh complex.

#### **1.4.4 Hydrological Factors Influencing Netley-Libau Marsh Degradation**

Grosshans et al. (2004) identified two hydrological factors that are likely driving the land cover changes seen in Netley-Libau Marsh: 1) increased water flow via hydrological connection to the Red River and 2) marsh water level stabilization due to Lake Winnipeg regulation. In this thesis, I analyzed the change in open water area and thus emergent plant cover in Netley-Libau Marsh over time compared to changes in other coastal marshes connected to the south basin of Lake Winnipeg. I also investigate the two hydrological factors suggested by Grosshans et al. (2004) that may be having an influence on areal extent of emergent vegetation and open water.

##### **1.4.4.1 Red River Connectivity**

In 1913, a channel called the Netley Cut was dredged by the federal government to connect the Red River with the Netley-Libau Marsh to allow easier access to hay lands and to possibly alleviate Red River flooding upstream (Public Works Canada 1907). The Netley Cut was originally dredged to a width of 27.5 metres (Public Works Canada 1915), but over time it has eroded and, in 2003, it was measured to be 400 metres wide (Grosshans et al. 2004). After its

dredging, it was soon realized that the Netley Cut did not provide flooding relief as intended and federal government engineers speculated on how to close it again.

“Re: My letter of April twentieth last and my telegram of yesterday stop the Netley Cut was evidently a mistake in the first place as it did not relieve the settlers from the flooding of hay lands stop what is your final report stop should bridge be maintained or should original condition be restored and cut closed entirely” [telegram from J. E. St. Laurent, District Engineer to A. St. Laurent, Chief Engineer at Ottawa. June 14<sup>th</sup>, 1922. (Public Works Canada 1922)]

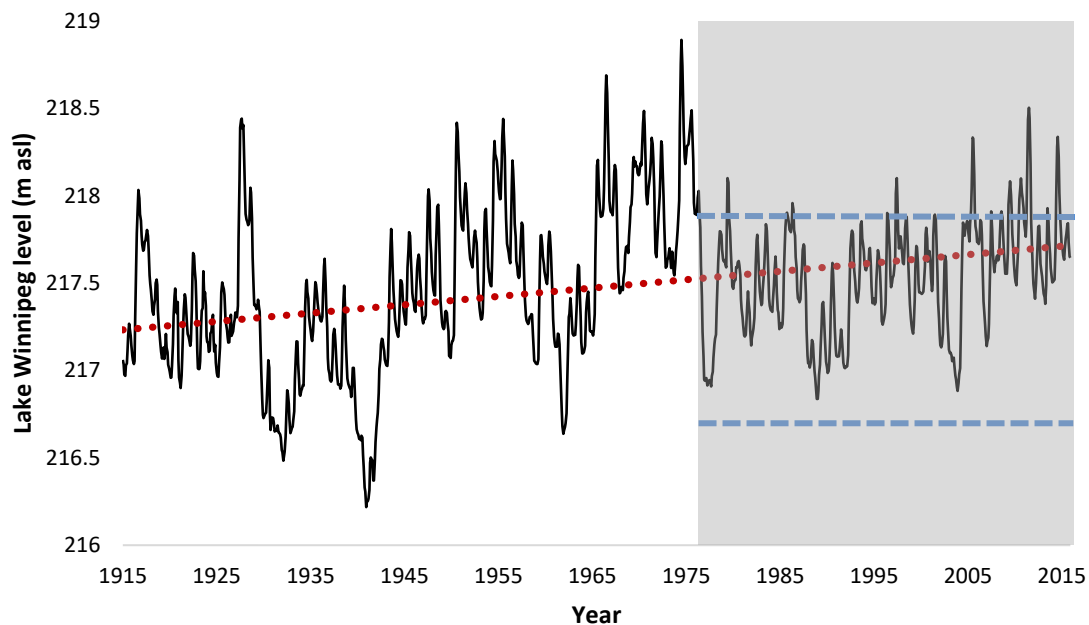
This connection to the Red River led to river water being diverted through the marsh; on average 37% of Red River flow from measurements taken in 2009 and 2014 (Shawn Clark. 2014 unpublished data). There has been speculation that river connection via the Cut has led to the erosion of islands and shorelines, and a decrease in emergent macrophyte growth due to increased water flow through the marsh (Grosshans et al. 2004). Connections between marshes and rivers can have a beneficial role in marsh vegetation growth by promoting nutrient cycling and allowing water levels to fluctuate with river flows. However, vegetation growth can be limited by disturbance during extreme flood years (Bayley & Guimond 2009). High water discharge through Netley-Libau Marsh could also potentially erode bottom sediments, causing long-term water depth to be too deep for the growth of emergent marsh macrophytes.

#### **1.4.4.2 Water Level Stabilization**

Regulation of Lake Winnipeg water levels by Manitoba Hydro started in 1976 for the purposes of hydroelectric energy production, with the added benefit of flood control for shoreline property owners. Prior to regulation, natural May-October mean Lake Winnipeg levels fluctuated widely between 216.2 and 218.9 m asl (2.7 m), but with the commencement of regulation, the Lake Winnipeg level range was narrowed to a Manitoba Hydro operating range of 216.7 and 217.9 m asl (1.2 m) (Figure 4). Although the regulated range in water levels has decreased from the natural range, the overall mean Lake Winnipeg level after regulation began (217.4 m asl)

(herein referred to as post-regulation) has increased by only 0.10 metre from years prior to regulation (herein referred to as pre-regulation) (217.5 m asl). Lake levels are kept within this range by controlling the outflow of water via a series of hydroelectric dams along the only outlet, the Nelson River located at the north end of Lake Winnipeg. When Lake Winnipeg levels are low, outflow is restricted at these dams to store Lake Winnipeg water. When lake levels are above 217.9 m asl Manitoba Hydro is required under its operating license to discharge Lake Winnipeg water through dam spillways to stay within its operating range. In this way, Lake Winnipeg has effectively become a large reservoir.

**Figure 4.** Wind-smoothed monthly mean Lake Winnipeg water levels from 1915 to 2015. The grey shaded portion of the graph represents the years that Lake Winnipeg levels have been regulated (1976-present). The blue dashed lines represent the operating range of 216.7-217.9 metres above sea level and the red dashed line is the Lake Winnipeg trend line over the entire 90-year period. Source: Raw data provided in 2015 by Manitoba Hydro.



Water levels in coastal marshes are heavily impacted by Lake Winnipeg conditions, and so it has been suggested that the sustained stable water levels caused by regulation are disrupting the natural water level fluctuations of the Netley-Libau Marsh (Verbiwski 1986; Grosshans et al. 2004). As stated previously, the disruption of historical water level fluctuations within Netley-Libau may have had a negative impact on the growth of emergent macrophytes. Without periods of low water, marsh emergent vegetation seeds in the sediment bank are less likely to germinate and become established as seedlings; conversely, prolonged high-water levels can cause emergent vegetation to die (van der Valk and Davis 1978; Keddy & Reznicek 1986). The

importance of low water periods was demonstrated during the 2003 drought when average May-October Lake Winnipeg level reached only 217.02 m asl. During the 2003 growing season open water decreased by 20.7% compared to 2002. Large expanses of sediment in Netley-Libau Marsh were exposed, allowing the growth of emergent macrophytes in much of the marsh that had not been vegetated for many years, some of which also persisted for ten years after 2003 when average water levels were at non-drought levels ( $>217.1$  m asl) (Grosshans et al. 2004; Watchorn 2015). This demonstrates the importance of lowered water levels in the reestablishment and growth of emergent macrophytes in Netley-Libau Marsh.

Although Lake Winnipeg's water levels have overall become more stabilized through limiting its fluctuation range, there is also reason to believe that the water level trends in this lake have become less stable in terms of water level trend duration. This means that periods of extended high water levels and, more important to emergent vegetation recruitment, low water periods have become shorter and less predictable year to year. Nearby Lake Manitoba, which has been regulated for flood control since 1961, was shown to have undergone lowered water level trend duration when analyses of pre- and post-regulation yearly water levels were compared (Kenkal 1995). Shorter trends coupled with narrower fluctuations in water levels were speculated to have a negative impact on the growth of emergent vegetation in Delta Marsh, a large coastal marsh located at the south end of Lake Manitoba. As Lake Winnipeg is also a large regulated lake located near Lake Manitoba it is likely that decreases in trend duration is also occurring there as well as in its associated coastal marshes.

Evidence from other aquatic and shoreline macrophyte studies conducted on regulated lakes also suggest that regulating levels may have negative impacts on the vegetation community and growth. Nilsson and Keddy (1988) found that species abundance and richness of emergent

macrophytes in a regulated hydroelectric reservoir in Sweden were most strongly predicted by reservoir levels and the length of flooding time in the previous year growing season. Long periods of sustained flooding correlated negatively with species abundance and richness in the following year, whereas frequent short periods of flooding (frequent fluctuations) was correlated positively with these variables. Farrell et al. (2010) concluded that regulation of water levels along the upper St. Lawrence River in drowned river mouth wetlands led to a decrease in diversity of the emergent plant community and increased dense, monodominant stands of cattail. Similar results were obtained in an earlier study by Wilcox et al. (2008) conducted on Lake Ontario and upper St. Lawrence wetlands, where higher than average water levels allowed for the expansion of invasive *Typha X glauca* (hybrid cattail) stands. It is possible that a decrease in emergent plant community diversity is occurring in coastal marshes around Lake Winnipeg due to the presence of the invasive hybrid cattail, which is known to be one of the dominant species of emergent vegetation at Netley-Libau Marsh (Grosshans et al. 2004 and 2012). Field and laboratory studies conducted in the Laurentian Great Lakes (Boers et al. 2008) and at Delta Marsh, MB (Shay et al. 1999; Grosshans 2001) have shown that hybrid cattail is able to thrive and out-compete other emergent species in conditions where water levels have been stabilized and where eutrophication is occurring.

## **1.5 Tracking Long-term Vegetation Changes Using Remote Sensing and Photointerpretation**

Vegetation sampling can be used to characterize the land cover and vegetation communities of a particular area. Having multiple years of sampling data is valuable when assessing changes in vegetation through time in response to abiotic or biotic variables such as low water levels or herbivore grazing. The challenge of examining changes over a broad time

scale where field data may be inconsistently collected or simply does not exist can be addressed by using remotely sensed data. Photointerpretation of remotely sensed (aerial or satellite) images can provide a literal snapshot of the conditions of a site at a particular moment in time.

Geometrically corrected (ortho-rectified) images are valuable in wetland surveys and inventories, as well as wetland boundary delineation and change through time analyses (Lyon et al. 1984; Williams & Lyon 1997; and Tiner 2017) as is also the case in this study.

Images can come from two sources: 1) aerial photographs, taken from a fixed-wing airplane, helicopter, or even drone and 2) images taken from satellites (e.g., Landsat 1-8, WorldView 3, QuickBird 1-2). Digital formats of these images can then be used for photointerpretation in a Geographic Information System (GIS). A computer based Geographic Information System allows the operator to manipulate and analyze geographic data in many ways. Many coastal marsh historical vegetation studies have used photointerpretation techniques using either aerial photographs (Gottgens et al.1998; Kowalski &Wilcox 1999; Wilcox et al. 2008; and Farell et al. 2010), satellite imagery (Leahy et al. 2005 and Watchorn et al. 2014), or a combination of the two (Hudon et al. 2005; Wilcox et al. 1985). The advantages of using aerial photos are that they extend as far back as the 1920s and often are taken from low altitudes so spatial resolution is often high. Some disadvantages of aerial photos are that they have quite often been collected using a single sensor or camera to obtain images in the visible light spectrum only and historical images are in black and white. This can make delineation of vegetation by species or community challenging as photointerpretation must be based primarily on shading, contrast, and texture rather than true colour images or imagery obtained via several sensors to capture vegetation spectral reflections in non-visible spectral bands (Tiner 2017). Vegetation strongly reflects Near Infrared energy and thus delineation of vegetation types is now

commonly done using cameras that can pick up energy from that part of the electromagnetic spectrum. Automated and semi-automated tools can be used in a GIS to classify a landscape image into different land cover (water, vegetation, etc.) categories based off spectral characteristics of pixels and even groupings of pixel types. Unfortunately, historical images consist of pixels of many shades of grey, which can be misclassified by automated GIS tools; so it is often best for the GIS operator to manually (heads up) digitize boundaries because of the human eye's superior ability to detect changes in shading, contrast, and texture of pixel groupings.

Several vegetation studies have been conducted on Netley-Libau Marsh using remote sensing and photointerpretation techniques. Verbiwski (1986) used a combination of infrared colour aerial photographs and ground-truthing (on the ground sampling) of vegetation plots to classify twelve different vegetation communities in 1979. This vegetation map was later used in a study by Grosshans et al. (2004) to compare the changes in vegetation between 1979 and 2001. The 2001 vegetation map was created in a similar way, with 1979 vegetation classes reclassified to make comparisons easier. The most recent remote sensing vegetation classification study was conducted by Watchorn (2015) in which Landsat 5, 7 and 8 satellite imagery were used and the ground-truthed 2001 Grosshans et al. (2004) vegetation map was used to create a vegetation key for the obtained Landsat imagery. The Watchorn et al. (2015) study was the only other time-series analysis of vegetation in Netley-Libau Marsh prior to this one, covering the period from 1990 to 2013.

## 1.6 Objectives

This project was begun in May 2015 with the following three objectives:

1. Quantify, describe, and compare variation in the open water area, and thus emergent vegetation cover, of two large coastal marshes within the Netley-Libau Marsh complex and four other large coastal wetlands connected to the south basin of Lake Winnipeg to assess whether emergent vegetation extent changes within Netley-Libau Marsh are also reflected in other Lake Winnipeg coastal marshes. A similar expansion of open water areas in marshes outside of the Netley-Libau Marsh complex would indicate that marsh habitat degradation is linked to Lake Winnipeg hydrology. A dissimilar expansion of open water areas in marshes outside of the Netley-Libau Marsh complex would indicate that marsh habitat degradation is linked to Red River hydrology.
2. Estimate the total volume of water flowing over time into Netley-Libau Marsh from the Red River via the Netley Cut to test for any relationship between changes in Netley-Libau open water areal extent and Red River connectivity.
3. Examine historical Lake Winnipeg water levels as a possible factor affecting erosion and emergent vegetation cover in the Netley-Libau Marsh and four other coastal marshes around the south basin of Lake Winnipeg. Compare statistical relationships and trends in open water area and thus emergent vegetation gains and losses in the six study marshes in the years before Lake Winnipeg level stabilization (regulation) began (1915-1975) to the years after regulation came into effect (1976-2015) to assess whether marsh ecosystem degradation has been greater since regulation began

## **1.7 Rationale**

The first step to marsh restoration and the increase of biodiversity and valuable ecological goods and services will be to determine the main causes of degradation in the form of emergent vegetation loss. Measurements of open water areas will be used as a measure of marsh degradation; as open water devoid of islands and vegetation does not provide a complex habitat required for many species of marsh flora and fauna, nor does it provide other benefits of a healthy marsh such as erosion/flood control and pollution/nutrient sequestration (Weller 1999; Keddy & Reznicek 1986; Murkin et al. 1997; Grosshans 2001; Albert & Minc 2004).

There has not been a detailed long-term historical analysis that has quantified broad changes in land cover (e.g., water to vegetation and vice versa) within the Netley-Libau Marsh going as far back as the early twentieth century. In this study I used regression analyses to assess coastal marsh conditions before and after the commencement of Lake Winnipeg regulation to isolate from each other the impact that Red River and Lake Winnipeg hydrology may have had on marsh plant cover. Regression analyses have been commonly used in similar coastal marsh studies assessing hydrological factors impacting vegetation growth and community structure (Nilsson & Keddy 1988; Gottgens et al. 1998; Kowalski & Wilcox 1999; and Chow-Fraser 2005; and Watchorn 2015).

If Lake Winnipeg hydrology is the major factor affecting emergent vegetation growth in the Netley-Libau Marsh then we would also expect to see an expansion of open water areas in other coastal wetlands around the south basin. We would also expect to see a change in the amount of open water area, and thus emergent vegetation before and after Lake Winnipeg regulation began due to a response to the altered hydrology. If Red River connectivity is the main factor affecting the marsh ecosystem, an expansion of open water area will not be seen in

other coastal wetlands located away from the Red River. Results obtained by the regression analyses I have conducted will be used to further substantiate whether Lake Winnipeg regulation or altered hydrology via Red River connection is the main driving force of changes to the Netley-Libau Marsh emergent vegetation areal extent.

## 2 METHODS

### 2.1 Study Sites

The coastal marshes selected for study in this thesis are all large coastal marshes of a similar size and are also all connected to the south basin of Lake Winnipeg (Figure 5). The marshes of interest located within the Netley-Libau Marsh complex are: Hardman Lake (Figure 6), Folster Lake (Figure 7), and the area around the Netley Cut (Figure 8). The marshes of interest located outside of the Netley-Libau Marsh complex are: Willow Point (Figure 9), Balsam Bay (Figure 10), Grand Marais (Figure 11), and Hillside Beach (Figure 12).

Hardman Lake is located on the west side (Netley side) of the Netley-Libau Marsh complex. It is connected directly to the west and main channels of the Red River that meander through Netley-Libau before discharging into Lake Winnipeg. The elevation of the shorelines and islands of Hardman Lake is approximately 218 m asl (Natural Resources Canada 2017).

Folster Lake is located on the east side (Libau side) of the Netley-Libau Marsh complex. It is bordered by pasture and agricultural land to the south populated with number of cabins, farms, and homesteads. The Brokenhead Ojibway Nation community is also located just east of the marsh. It is not connected directly to the Red River but is still a part of the Red River mouth delta that is the Netley-Libau Marsh. Folster Lake is also connected via a channel to a much smaller tributary called the Brokenhead River to the east of Netley-Libau Marsh. Like Hardman Lake, the shorelines and islands of Folster Lake sit at approximately 218 m asl (Natural Resources Canada 2017).

The area around the Netley Cut is unique from the other study sites in that I did not create a set boundary to measure open water area. Aerial images of this site were used to measure the width of the Netley Cut and to qualitatively examine the amount of vegetation in each photo as

supplemental data. The Netley Cut was dredged in October 1913 by the federal government through the southeast shore of Netley Lake, located on the west side (Netley side) of the Netley-Libau Marsh complex. The shorelines on either side of the Netley Cut sit at approximately 218 m asl like much of the rest of Netley-Libau Marsh (Natural Resources Canada 2017)

The area around Willow Point was settled in 1875. Present-day communities in its vicinity are Gimli, located to the north, and Miklavik and Siklavik to the west of the marsh. The Willow Point marsh has been classified as a barrier-protected coastal marsh with a beach ridge separating it from Lake Winnipeg (Watchorn et al. 2012). In 1912, a channel was dredged through this barrier beach, connecting Willow Point to Lake Winnipeg to allow boat passage into the once isolated marsh, with the channel still open to this day (Goldsborough 2015). The shorelines and islands of Willow Point sit at approximately 216 m asl (Natural Resources Canada 2017).

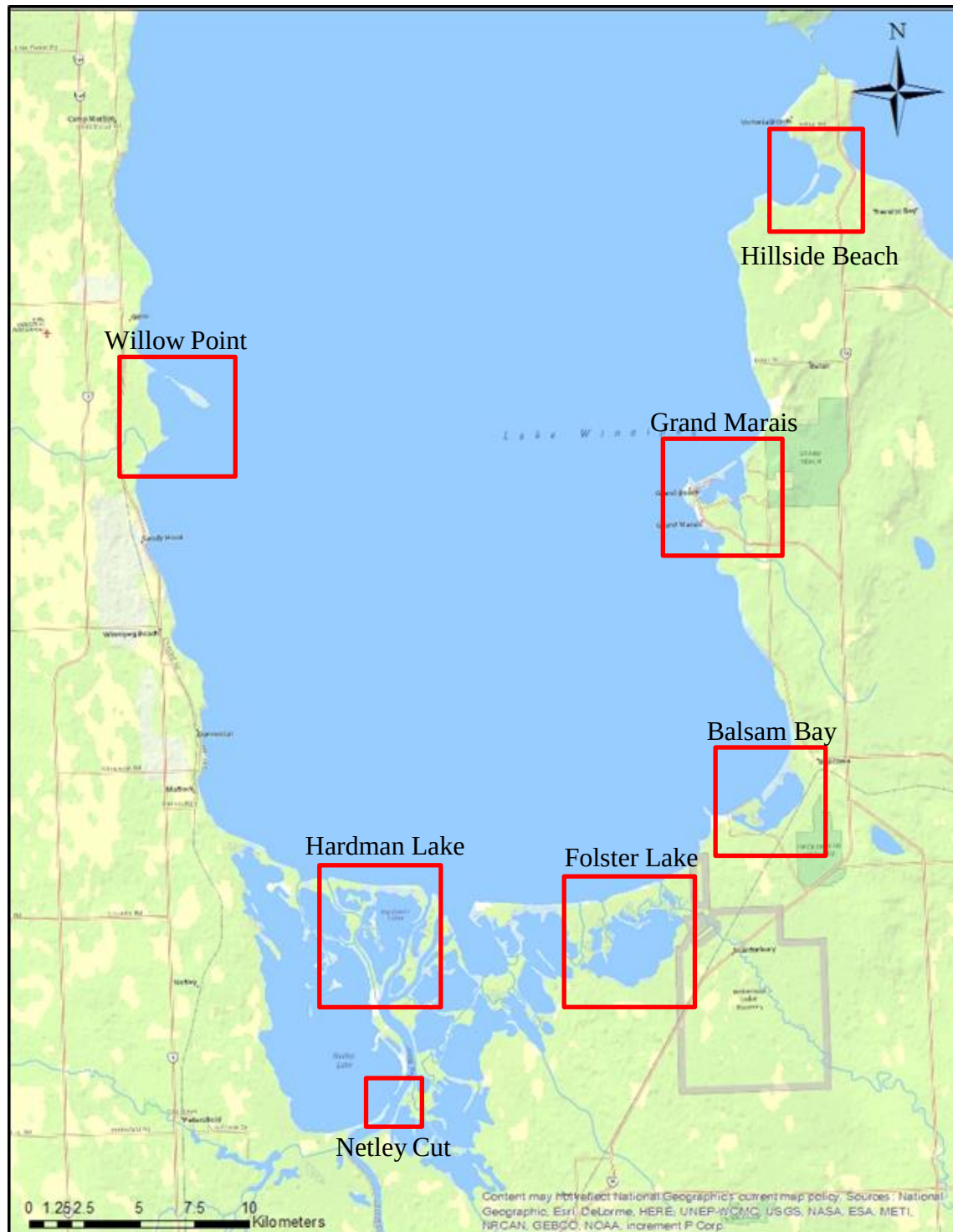
The area of Balsam Bay was settled in the early 1900s after the Canadian Northern Railway constructed a railway line to Grand Beach. A dyke, on which the railway line was built, still borders the Balsam Bay marsh on its east side, although no rails exist there now. The present-day community of Beaconia is located just northeast of the marsh. The Balsam Bay marsh is classified as a lacustrine coastal marsh (Watchorn et al. 2012). Located on the sandy ridge between this marsh and Lake Winnipeg is Patricia Beach Provincial Park and Beaconia Beach which are frequented by campers and beach-goers during the summer months. The shorelines and islands of Balsam Bay fall between 218 and 224 m asl (Natural Resources Canada 2017).

Grand Marais is a barrier-protected coastal marsh (Watchorn et al. 2012) located within Grand Beach Provincial Park. The marsh is sheltered from Lake Winnipeg by a beach ridge that has been a popular destination to campers and beach goers since the early 1900s when the

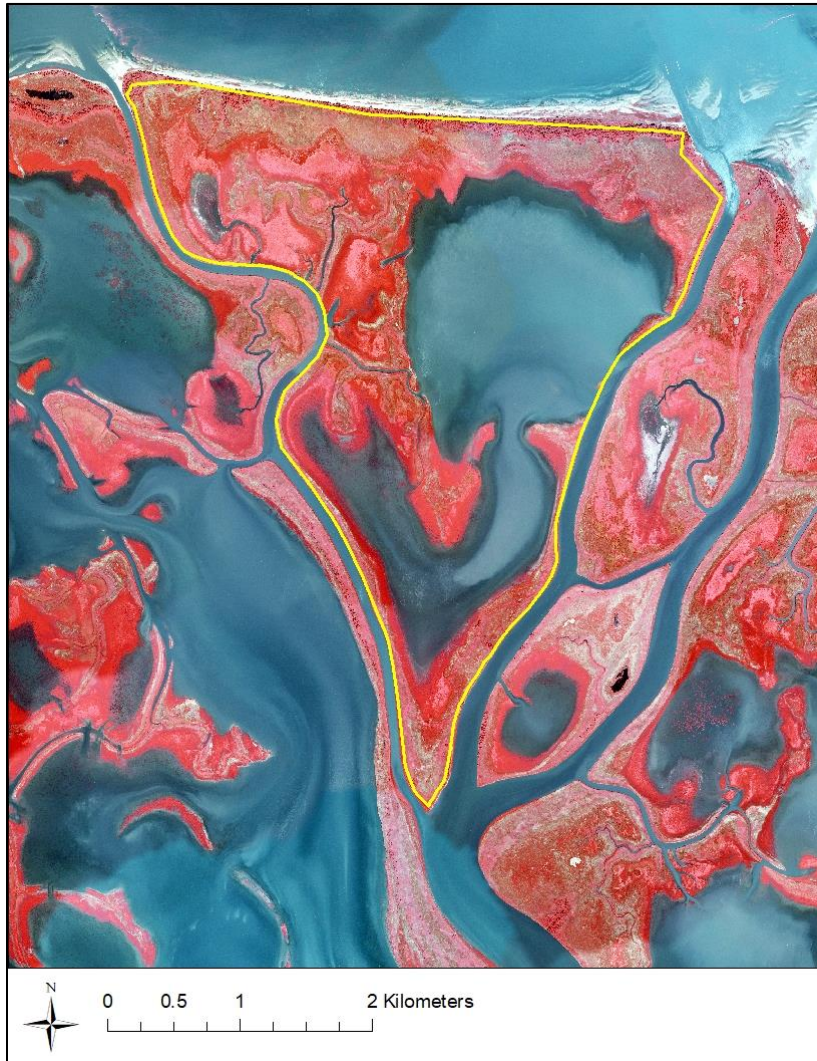
Canadian Northern Railway constructed a railway connecting the community of Grand Beach to Winnipeg. The communities of Grand Beach and Grand Marais are located just to the west and south, respectively of Grand Marais. The shorelines and islands of Grand Marais sit at approximately 216 m asl (Natural Resources Canada 2017).

The area of Hillside Beach was settled in the early 1900s. It became a popular tourist destination when the railway was constructed because of its long sand beach. Sheltered from Lake Winnipeg behind this sand beach is the marsh, classified as barrier-protected coastal marsh (Watchorn et al. 2012). The marsh is bordered by three small communities: Hillside Beach to the south, Albert beach to the east, and Victoria Beach to the north. The shorelines and islands of Hillside Beach sit at approximately 216 m asl (Natural Resources Canada 2017).

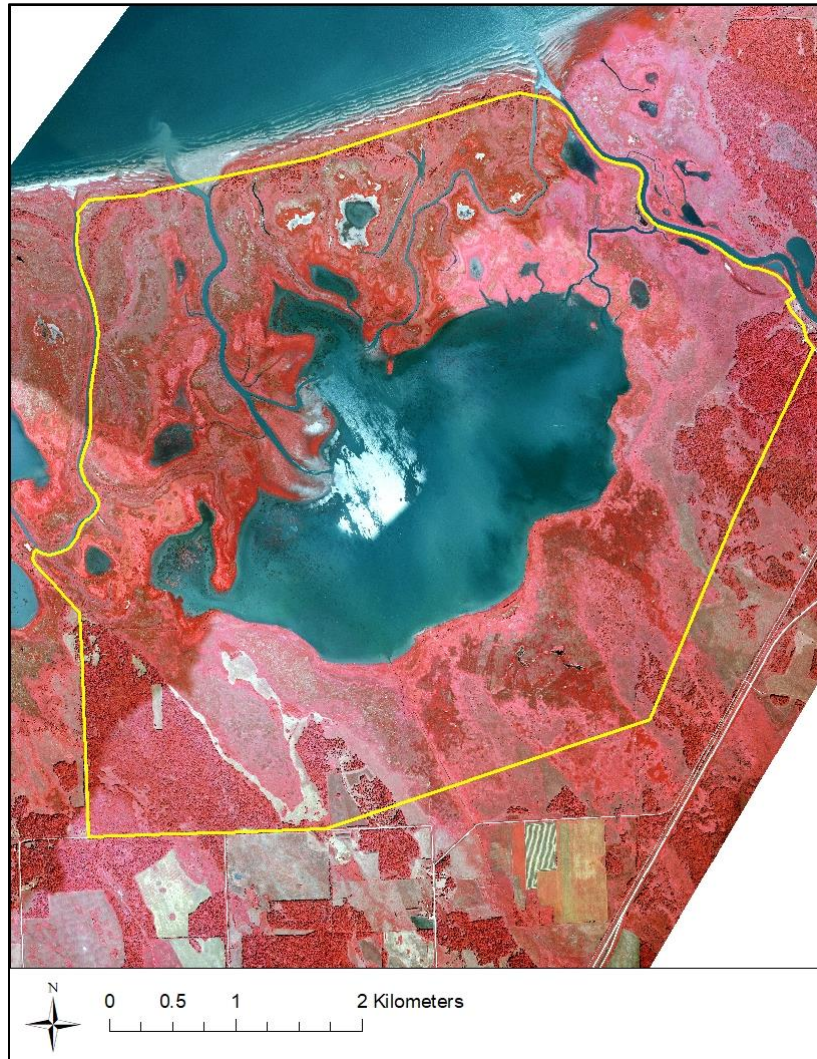
**Figure 5.** The south basin of Lake Winnipeg displaying all seven study sites outlined in red boxes. Source: Base image obtained from ESRI ArcMap Version 10. 2.2.



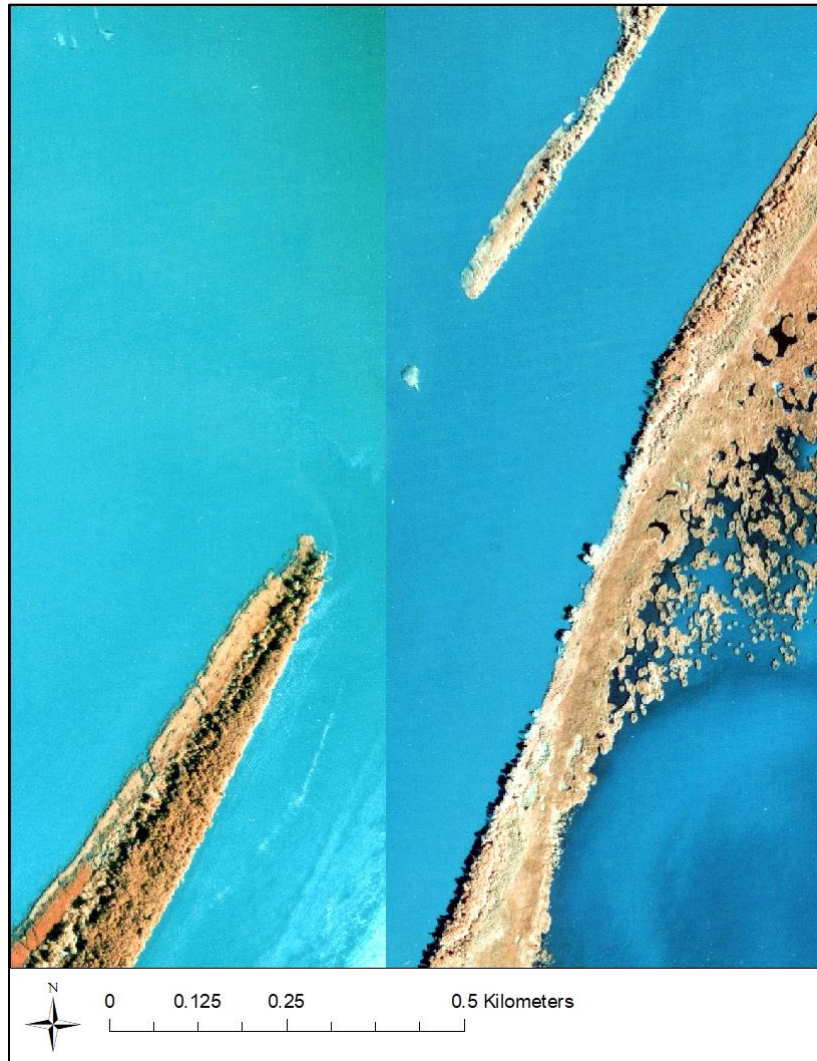
**Figure 6.** False-colour infrared image of Hardman Lake from August 16, 2003 (Goldsborough unpublished data 2003). Study site boundary is outlined in yellow. Study site centre: longitude 96° 50' 13" W, latitude 50° 22' 56" N.



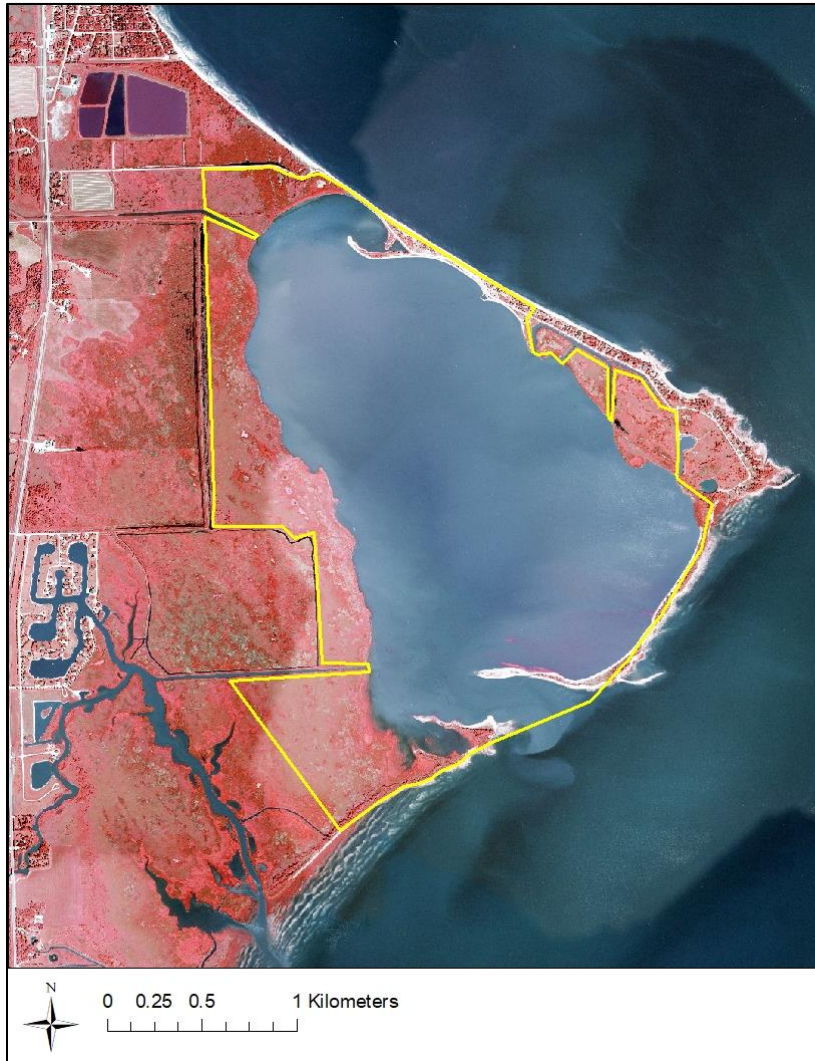
**Figure 7.** False-colour infrared image of Folster Lake from August 16, 2003 (Goldsborough unpublished data 2003). Study site boundary is outlined in yellow. Study site centre: longitude  $96^{\circ} 40', 29''$  W latitude  $50^{\circ} 22' 3''$  N.



**Figure 8.** False-colour infrared image of the Netley Cut from August 3, 2001 (Grosshans et al. 2004). Study site centre: longitude 96° 50' 7" W, latitude 50° 18' 39" N.



**Figure 9.** False-colour infrared image of Willow Point from August 16, 2003 (Goldsborough unpublished data 2003). Study site boundary is outlined in yellow. Study site centre: longitude  $96^{\circ} 57' 50''$  W, latitude  $50^{\circ} 35' 52''$  N.



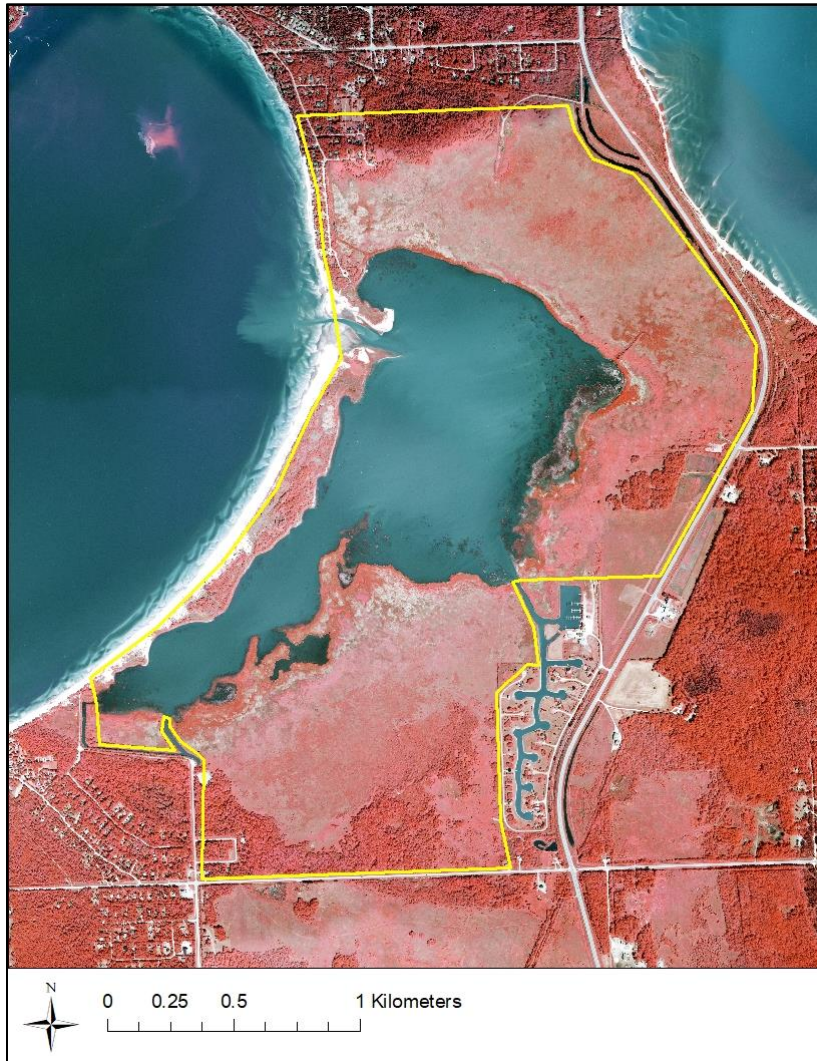
**Figure 10.** False-colour infrared image of Balsam Bay from August 16, 2003 (Goldsborough unpublished data 2003). Study site boundary is outlined in yellow. Study site centre: longitude 96° 34' 40" W, latitude 50° 25' 44" N.



**Figure 11.** False-colour infrared image of Grand Marais from August 16, 2003 (Goldsborough unpublished data 2003). Study site boundary is outlined in yellow. Study site centre: longitude 96° 36' 32" W, latitude 50° 33' 28" N.



**Figure 12.** False-colour infrared image of Hillside Beach from August 16, 2003 (Goldsborough unpublished data 2003). Study site boundary is outlined in yellow. Study site centre: longitude  $96^{\circ} 32' 23''$  W, latitude  $50^{\circ} 40' 49''$  N.



## **2.2 Image Acquisition**

In 2003, aerial images of the six coastal marsh sites I have selected for study were acquired and orthorectified. These orthorectified images were used to georeference all of the historical aerial photographs and one map used in this study (Goldsborough unpublished data 2003). In total, one hundred and forty-six images of these six marshes around the south basin of Lake Winnipeg were scanned at 300 dpi from photos archived at the Manitoba Air Photo Library in Winnipeg and the National Air Photo Library in Ottawa (Appendix E). These images are greyscale, single-band aerial photos of coastal marshes I selected for study, with the earliest ones taken in 1929 and the latest from 2003. Scales of obtained aerial images ranged between 1:10,000 and 1:80,000. Manitoba OrthoRefresh aerial color imagery (one metre resolution) taken on October 4<sup>th</sup> and 5<sup>th</sup>, 2010 were also used in this study (Manitoba Land Initiative. 2010).

Satellite imagery from 2009, 2011, and 2015 were also used to supplement the dataset. The 2009 QuickBird imagery (0.6 metre resolution) was taken on August 20 and September 7 (DigitalGlobe 2009). Landsat 5 imagery from 2011 (30 metre resolution) was taken on July 14 and August 22 (NASA Landsat Program 2016). WorldView 3 imagery (1.24 metre resolution) of the Netley-Libau Marsh was also acquired by the University of Manitoba on August 17, 2015 (DigitalGlobe 2015).

Only images acquired between July and October were used in the analyses to measure open water areas at times of maximum emergent vegetation cover. In the selected images the boundary between water and emergent vegetation had to be distinguishable, they had to be cloud free and contain the entire study sites. Using images captured during months of maximum vegetation cover allows for comparison of changes in emergent vegetation cover year to year.

Once suitable images were selected for analyses, it was evident that data were lacking between the years 1929 and 1950. A 1934 township survey map of the area including Netley-Libau Marsh and the Balsam Bay marsh, created by a Manitoba Land Surveyor of the Province of Manitoba (Canada Map Sales 1934), was also selected to supplement the timeline coverage of the dataset. This map was processed and visually delineated using those same techniques for aerial photographs outlined in the following sections. After the completion of this image selection process there were a total of twelve images between 1929 and 2011 of the Balsam Bay marsh, thirteen images between 1934 and 2015 of Folster Lake, seven images between 1948 and 2011 of Grand Marais, ten images between 1934 and 2015 of Hardman Lake, eight images between 1955 and 2011 of Hillside Beach, and ten images between 1950 and 2011 of Willow Point.

### **2.3 Image processing and analysis**

All the acquired images were projected in NAD\_1983\_UTM\_Zone\_14N and then georeferenced to orthophotos obtained in 2001 and 2003 (Grosshans et al. 2004 and Goldsborough unpublished data 2003) using ArcMap 10.2.2. In some years, multiple partial images were captured on the same dates for the same site and so these were combined using the Photomerge tool in Adobe Photoshop CS5 version 12.0 x32 prior to georeferencing in order to form one complete image of the entire study site boundary.

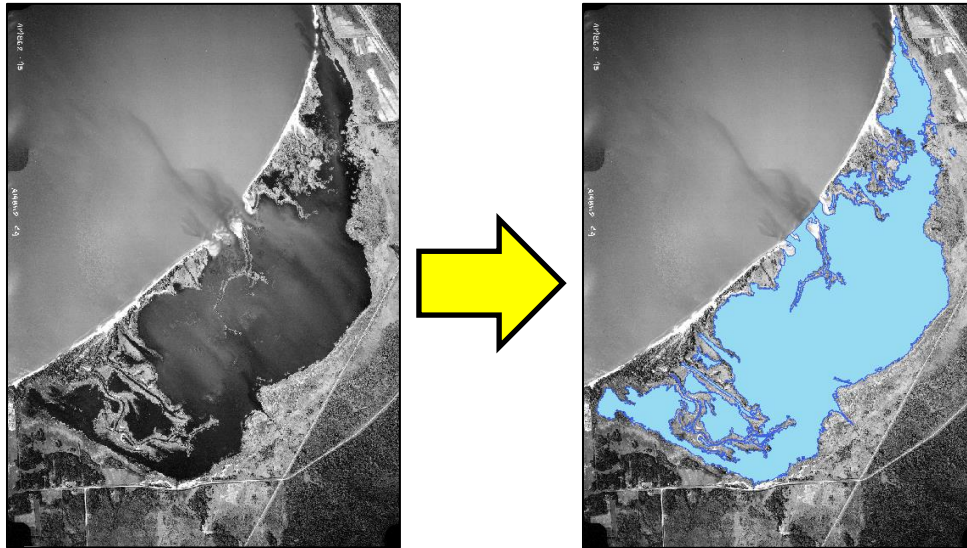
The acquired images were georeferenced using distinct landmarks in each image, such as large trees, road intersections, forks of permanent channels, and bridges in image to image registration. Ground control points (GCPs) at 2.5 metres accuracy were obtained at the distinct landmarks at each study site and then overlaid onto the georeferenced images to ensure spatial accuracy. The coordinates of over 25 ground control points were acquired using a Garman

60CSx handheld GPS receiver at each study site, with averaging to obtain spatial accuracy of 2.5 metres. Between 6 and 15 GCPs were used to georeference each of the obtained aerial images with root-mean-mean-square-error under  $\pm 1$  metre.

### **2.31 Visual Delineation**

The greyscale, single-band historical imagery that was acquired could not accurately be classified automatically or semi-automatically in GIS software. Maximum Likelihood Classification and Iso Cluster Unsupervised Classification automated classification tools were tried but they resulted in high degree of speckle which resulted in misclassification between land and water pixels. Following the approach used by Watchorn (2014) and the Manitoba Wetland Inventory Project (G. Leo, pers. comm.), open water areas (defined as areas from which emergent macrophytes were sparse or absent) were heads-up digitized as shapefile polygons in ArcMap 10.2.2 (for example, Figure 13). The areas of these open water polygons were then calculated in ArcMap using the Add Geometry Attributes tool.

**Figure 13.** This example of heads-up digitization of historical imagery of Balsam Bay, 1955, shows how open-water area was delineated using a GIS.



Potential uncertainties exist in exact open water delineation and areal extent measurements due to the multiple different resolutions of the aerial and satellite images used in visual delineations. Resolutions of the digital images used in analyses range from 0.5-30 metre pixels. To reduce the subjectivity of manual marsh delineation, a set of criteria was developed to make these measurements as reproducible as possible, as follows:

1. Study site boundaries were created and any open water area including ponds and channels within these boundaries were delineated and measured (see Figures 6 to 12 for study site boundaries in yellow). The study site boundaries were determined using fixed landscape features and barriers such as roads and rivers as the edges of the study sites.
2. Open water areas were digitized along the border between emergent vegetation and water.

3. If an area contained an intermingling of water and emergent vegetation, it was excluded from the open water measurements when most of the visually interpreted area was covered by emergent vegetation (>50%).
4. Only areas of open water with little to no vegetation were measured. Small, sparse patches of emergent vegetation only a few metres in size were excluded from the visual delineation as they were effectively a part of open water areas.
5. Human-made ponds and channels (eg., drainage ditches, the Siglavik subdivision of Gimli, MB) were not included in the measurements as they are not a true reflection of the effect that Lake Winnipeg or Red River hydrology may be having on these marshes.

To measure error due to the subjectivity of visual delineation, ten volunteers (including myself) were asked to delineate the open water area of a section of marsh located within the study site boundary of the Folster Lake marsh site (Figure 14). Volunteers were chosen based on their varied level of experience with freshwater marshes and GIS software, from expert to complete novice. The goal was to capture a broad skillset ranging from no experience to over several years of experience in wetland delineation. Volunteers were given the above set of criteria to review before they began delineation and were then left alone with no outside influence. After they finished delineation, each volunteer was given ten minutes to look over their work and make any corrections they felt were necessary. Volunteers were not able to observe others while they were delineating nor were they allowed to view the other volunteers finished results until after the delineation session was complete. Total areas of each volunteers delineated open water area and a standard deviation in delineated areas was calculated.

**Figure 14.** The section of marsh used for volunteer delineations located within the Folster Lake marsh site. Delineation boundary is in yellow.



## 2.32 Automated Classification

The more recent aerial and satellite imagery from 2001, 2003, and satellite imagery from 2009, 2011, and 2015 were high resolution multiband images, allowing for automated classification in ArcMap 10.2.2, with the exception of the 2003 Folster Lake and Grand Marais images, which had to be delineated manually due to reflections of light on the water surface causing complications in classification. Quickbird satellite imagery from 2009 also had to be delineated manually due to a reoccurring software error in automated classification processing.

The Iso Cluster unsupervised classification tool in the Classification toolset of ArcMap 10.2.2 was used to create between fifteen to twenty-five classes in each image. These classes were then reclassified as being either land/vegetation or water. After reclassification was

completed, the water classes were extracted and converted into polygons. These polygons were then merged into one polygon so its total area could be calculated.

Open water area measurements of marshes located outside the Netley-Libau Marsh complex (Willow Point, Balsam Bay, Grand Marais, and Hillside Beach) were compared to the ones within it (Hardman Lake, Folster Lake) to distinguish the effects caused by both Lake Winnipeg water levels and Red River connectivity. In addition to examining overall changes in open water area at each study marsh, I also calculated standard deviation as a measure of variation of open water area before and after Lake Winnipeg regulation began.

## **2.4 Lake Winnipeg water level data acquisition**

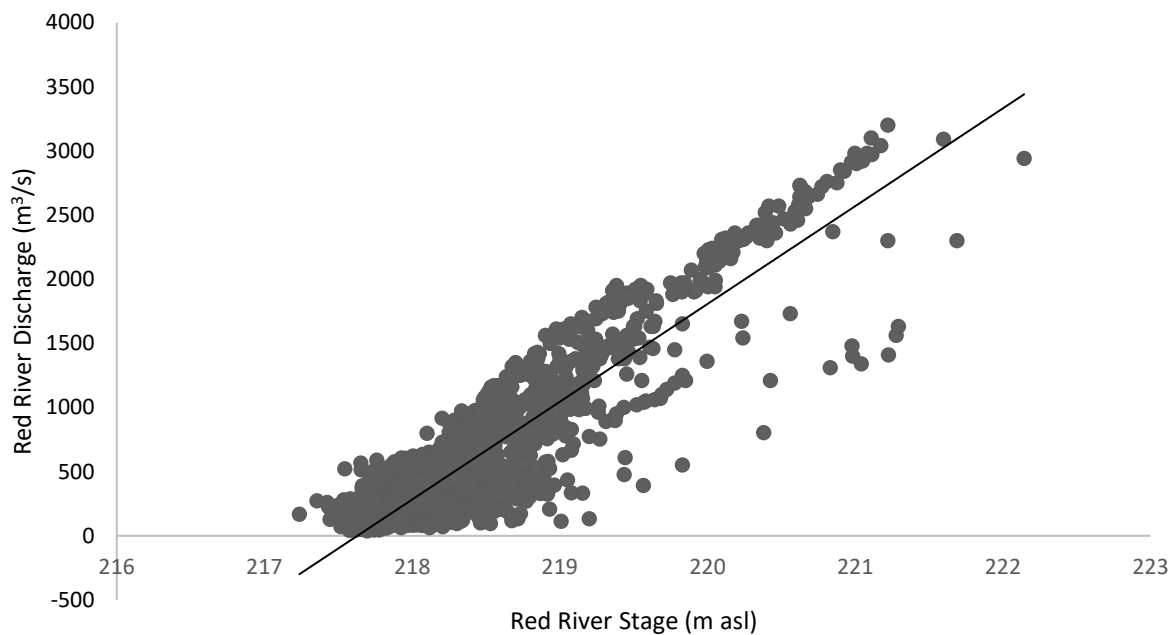
Daily Lake Winnipeg wind-smoothed levels asl (metres above sea level) from 1915 to 2015 were obtained from Manitoba Hydro and were used to determine mean May-October Lake Winnipeg levels in metres above sea-level during these typically ice-off months for each year. For a detailed explanation on how Manitoba Hydro calculates wind-smoothed lake levels refer to the Review of Lake Winnipeg Water Level Reporting Procedures prepared for the Lake Winnipeg Shoreline Erosion Advisory Group (Baird W.F. & Associates Coastal Engineers Ltd. 2000).

## **2.5 Red River flow data acquisition**

Daily Red River flow data ( $\text{m}^3/\text{s}$ ) were obtained from the Water Survey of Canada website from gauges located at Winnipeg, Lockport, and Selkirk to cover the same time period as the database of aerial photos, from 1928 to 2015. Unfortunately, flow data could not be obtained at all sites, nor for the entire period of study, so river level data were obtained when flow was not available (1913-1961). Overlapping flow and level data (2008-2014) at Selkirk were found to be highly correlated ( $R^2 = 0.83$ ,  $p < 0.05$ ). These data were used to create a rating curve (Figure 15)

of flow versus level fitted with a linear trend line. Using the equation of the line from the rating curve (Eq. 1), Red River flow at Selkirk was estimated from level measurements.

**Figure 15.** Rating curve of Red River flow versus level at Selkirk, MB fitted with a linear trend line.



Eq. 1  $y = 762.18x - 165872$   
 $R^2 = 0.8346$  ( $p < 0.05$ )

Where  $y$  = Estimate of Red River flow ( $\text{m}^3/\text{s}$ )  
 $x$  = Measured Red River level (m asl)

Level and flow measurements from the Meteorological Service of Canada gauge 05OJ005 at Selkirk (latitude  $50^\circ 16' 58''$  N, longitude  $96^\circ 51' 30''$  W) were available only sporadically during the timeline covered by the historical imagery. Level measurements at Selkirk that did exist were compared to level measurements taken at gauge 05OJ001 in Winnipeg from 1912 to 1977 (latitude  $49^\circ 55' 00''$ , longitude  $97^\circ 07' 30''$ ). Levels at both Selkirk and Winnipeg were

plotted against each other and a linear trend line was fitted to obtain equation 2. This equation was used to estimate Red River level at Selkirk from 1912 to 1961 using level measurements taken at Winnipeg. Red River level data at Selkirk was then used to calculate flow estimates at Selkirk from 1912 to 1961 using the Selkirk rating curve (Eq. 1). Around one-quarter of the calculated flows resulted in negative values suggesting that this model is unable to estimate river flow values when river level is very low. To replace the negative calculated flows at low river levels with realistic estimates it was important to first determine what the lowest positive calculated flow value ( $0.401\text{m}^3/\text{s}$ ) was and what its corresponding river level (217.627 m asl) was. Any Red River levels lower than 217.627 m asl consistently resulted in negative flow values which were then reassigned values of  $0.401\text{m}^3/\text{s}$  as it is the lowest positive calculated flow value. In reality, these flow values would most likely fall between  $0.000\text{m}^3/\text{s}$  and  $0.401\text{m}^3/\text{s}$  but, because the difference between these two values is so small I used  $0.401\text{m}^3/\text{s}$  as the lower threshold flow rate.

$$\text{Eq. 2 } y = 0.4916x + 107.83$$

$$R^2 = 0.7104 \text{ (} p < 0.05 \text{)}$$

Where  $y$  = Estimated Red River level at Selkirk (m asl)  
 $x$  = Measured Red River level at Winnipeg (m asl)

Red River flow measurements from 1962 to 2008 were obtained from the Water Survey of Canada gauge 05OJ010 near Lockport (latitude  $50^\circ 6' 28''$ , longitude  $96^\circ 55' 54''$ ), and were used with the Selkirk actual and estimated flows to form a complete flow record from 1913 to 2015 for the Red River upstream of the Netley Cut. Due to the lack of Red River data for the area around the Netley Cut, I assumed that Red River flow did not change significantly between the Cut and Lockport; with Selkirk being located approximately 20 kilometres upstream of the Cut and Lockport approximately 25 kilometres upstream with very little elevation change between these locations (Natural Resources 2017). To confirm this assumption, I plotted 2008 –

2014 Red River level at Selkirk against levels at Breezy Point (approximately 2-3 kilometers upstream of the Cut), which resulted in a strong relationship between Red River levels close to the Cut and Red River levels at Selkirk ( $R^2 = 0.86$ ,  $p < 0.05$ ).

## **2.6 Netley Cut Discharge Calculation**

Only eight discharge ( $\text{m}^3/\text{s}$ ) measurements of Red River water through the Netley Cut were available from 2009 and 2014 spring, summer, and fall (Clark unpublished data 2014). Due to the few Red River flow and level measurements at the Netley Cut and the widening of the Cut over time, a rating curve could not be constructed to estimate the amount of Red River water being discharged through the Cut at a given time. To estimate discharge, I assumed the Cut behaves as a broad-crested side weir and used a modified broad-crested side weir equation (Eq. 3; S. Clark, pers. comm.) to calculate Netley Cut discharge. A weir is typically a dam like construction used by hydrologists and engineers to modify stream or river flow. When a weir is constructed with a broad, flat bottom it is said to be broad-crested. A side weir is built on the side of a main channel to divert flow from that main channel. In this way, the Netley Cut functionally resembles a broad-crested side weir.

Eq. 3  $Q = C \times L \times H^{3/2}$

Where  $Q$  = Discharge ( $\text{m}^3/\text{s}$ )

$C$  = the weir coefficient

$L$  = Netley Cut width (m)

$H$  = weir head height (m)

The Netley Cut width measurements obtained from the image database were done in ArcMap 10.2.2 using the Distance Measure tool. The Cut widths were measured at the shortest distance from the edge of one bank to the other. In some cases, islands of shoreline were still present between the banks of the Netley Cut so these were excluded from the overall Cut width

measurements by measuring only lengths of open water between banks and then summing them as total Cut width.

The weir head height was calculated according to Eq. 4. The Netley Cut crest elevation used in all head height calculations was 215.5 m asl as this was the average Cut bottom elevation measured in 2009 by hydrologists from the University of Manitoba (S. Clark, pers. comm.). The average Netley Cut crest elevation in 1922 was determined to be 214.92 m asl using sheet pile dam blueprints from the Public Works Canada archival records at Library and Archives Canada in Winnipeg (Figure A1). The difference (0.58 m asl) in measurements obtained from the sheet pile dam blueprint and more recent measurements from 2009 tells us that the Cut bottom elevation has increased by roughly half a metre over the last century, most likely due to sedimentation over time. The average elevation in 2009 was used as it is the most accurate measurement available.

Eq. 4  $H = \text{Red River surface elevation (m asl)} - \text{Netley Cut crest elevation (m asl)}$

A weir coefficient was calculated for the eight Red River flow measurements taken at the Cut in 2009 and 2014 using Equation 3 (S. Clark pers. comm. 2014). After the weir coefficients were calculated using each of the eight inflow measurements, they were plotted with Red River discharge estimates at Selkirk. Using the equation of the line (Eq. 5) from this graph, the weir coefficient for each Red River discharge estimate at Selkirk was calculated and used in the modified broad-crested side weir calculation (Eq. 3) to calculate an estimate of the volume of Red River water flowing through the Netley Cut.

Eq. 5  $y = 0.0003x + 0.1204$   
 $R^2 = 0.7399$  ( $p = < 0.05$ )  
Where  $y$  = Weir coefficient  
 $x$  = Red River discharge

## **2.7 Open Water Area Change versus Time**

As the marshes in this study vary in size between sites it was important to compare changes in open water area relative to one another. Thus, changes in open water area from one year to another are expressed as a percent of the mean open water area of each marsh. Changes in the variation in open water areal extent at each study marsh were analyzed by calculating the standard deviation of open water area in pre- and post-regulation time periods.

Trends for Balsam Bay, Willow Point, and Hardman and Folster lakes open water area over time were calculated and plotted using pre-regulation years as well as post-regulation area data. The resulting pre- and post-slope of the lines were then compared based on slope steepness and direction. The direction of the line tells us if open water area has been on a decreasing (downwards slope) or increasing (upwards slope) trend through time, while slope steepness allows us to examine how rapidly these trends are increasing or decreasing. The slope of a line is described in the formula  $y = mx + b$ , where the magnitude of  $m$  gives us the steepness of the slope of the line while a positive or negative  $m$  value tells us the direction of the line (positive = downwards slope, negative = upwards slope).

## **2.8 Multiple Regression Analyses**

For each of the six marsh sites, all available open water area values were used to determine if they were related to Lake Winnipeg levels overall. For further insights, the time period of the study was split into two smaller periods: years prior to Lake Winnipeg regulation (1913-1975) and years after regulation began (1976-2015). This was to see if any differences arose in the relationships between marsh open water areas and Lake Winnipeg levels before and after they were stabilized between a range of 216.71 and 217.93 metres above sea level (m asl).

The lag time in vegetation response to water levels was chosen based on previous studies of marsh vegetation growth response to water levels, which suggested that a lag period of two to five growing seasons is required to observe the full response of emergent vegetation growth to a change in water levels (Gottgens et al. 1998; Keddy and Fraser 2000; and Wilcox et al. 2008). During the 2003 low water period following an extended period of high water, emergent vegetation grew back in many areas of Netley-Libau Marsh within a single growing season (Grosshans et al. 2004). Based on those observations by Grosshans et al. (2004) and literature research, I decided that averaging level and flow data for a period longer than two growing seasons was unnecessary and perhaps result in a lower goodness of fit in regression models. Means of May-October Lake Winnipeg levels and April-June Netley Cut discharges were calculated in the year prior to each aerial marsh image being taken. From the years the aerial and satellite images were taken, May 1<sup>st</sup> to date of photo capture lake level means and April-June Netley Cut discharge means were also calculated. These Lake Winnipeg level and Red River flow mean seasonal values were used as the independent variables in my stepwise regression analyses.

All statistical analyses were conducted using the software package R version 3.4.1. Multiple regression analyses were performed on each of the study site marshes to determine the relationship between open water areas and averaged Lake Winnipeg May-October levels. As there were only two to three aerial photos available prior to regulation, the relationship between open water areas and lake levels could not be compared pre-regulation to post-regulation years for the Hillside Beach and Grand Marais marshes. Thus, the regression analyses for Grand Marais and Hillside Beach were conducted using all available area (seven-eight measurements) and level data within the 1915-2015 time period.

First, multiple regression analyses were run both with and without an interaction term between both lake levels one growing season prior to photo capture year and of photo capture year to determine whether these two variables are acting together to form a stronger relationship to open water areas, or whether they must be considered exerting a unique effect from one another. Using the Information Theory Approach, multiple stepwise regression models were tested to determine whether including both lake levels from photo capture year growing season and the growing season of the year prior produced the most optimal model. The stepwise model with the lowest AIC (Akaike information criterion) value is determined to be the most optimal, as a relatively low AIC value indicates the least complex model with the best fit. The resulting  $R^2$  of the most optimal model was then used to examine the relationship between open water area and lake levels.

The resulting p-values from the stepwise regression analyses determined whether the regression relationships were statistically significant. A significance level of 0.1 was used in this study rather than the normally used 0.05 due to the small number of open water area measurements for each study site, as well as having to include estimated Red River discharge values for parts of the time series. Regression coefficients ( $R^2$ ) values with p-values of 0.1 or lower indicated relationships that were statistically significant. This approach was consistent with a suggestion by Watchorn (2015) that, due to small sample sizes, analyses with p-values less than or equal to 0.1 should be investigated further, even though a significance level of 0.05 was used in that study. A significance level of 0.1 will lower the possibility of making a Type II error, which would falsely assume there is no significant causal relationship between lake and river hydrological variables and marsh open water areas when in truth such a relationship may exist.

Stepwise regression analyses using Hardman Lake and Folster Lake open water areas and Red River and Netley Cut discharge were conducted as these two sites are within the Netley-Libau Marsh complex and the most likely to be affected by Red River connectivity. Analyses were done using the open water areas and the means (April-June) of Red River flow and Netley Cut discharges of the growing season a year prior and the year of image capture (April-date of image capture).

## **2.9 Autocorrelation and Hurst Re-scaled Range Analysis of Lake Winnipeg levels**

As coastal marshes connected to Lake Winnipeg are subjected to similar water surface elevations as the lake itself it is important to investigate whether any trends exist in Lake Winnipeg water levels, as the coastal marshes of this study would also be influenced by Lake Winnipeg hydrological trends. Trends in water levels can be especially important in determining the growth response and community assemblages of emergent vegetation. With a long-term high water trend we might expect emergent species to senesce. With a long-term low water trend we would expect an infilling of marsh areas that were previously too flooded and devoid of vegetation. Aquatic systems with no long-term trends in water levels may actually form a very chaotic habitat where only short-lived emergent vegetation species are able to colonize some areas.

Temporal autocorrelation analyses were conducted on average May-October Lake Winnipeg levels to produce autocorrelation profiles (correlograms) with one lag equal to one year. These correlograms plot the correlations of the dataset to itself at increasing lag to reveal persistence of trends in water levels over time. Autocorrelations that fall outside of the 95% confidence interval are deemed statistically significant. Separate analyses were conducted on lake levels pre- and post-regulation and the results compared to see if there have been any

changes in the persistence of trends before and after regulation began. All autocorrelations analyses were conducted using the “acf” function from the STATS package in the statistical software R version 3.4.1.

Additional time series analyses were also done using Hurst rescaled range analyses to obtain Hurst exponents as a quantitative measure of persistence for pre- and post-regulation Lake Winnipeg level trends. Hurst re-scaled range analyses were conducted on Lake Winnipeg level data prior to and after regulation began to provide a quantitative measure to the likelihood of long-term water level trends continuing (persistence of trends). Resulting Hurst exponent values can range between 0 and 1, with higher values indicating that the time series is positively correlated with itself, meaning there is a persistence of long-term trends in the times series, while values around 0.5 indicate that there is no persistence in trends and the data in the time series is completely uncorrelated with itself (no trends). All Hurst re-scaled range analyses were conducted using the “hurstexp” function from the pracma package in the statistical software R version 3.4.1.

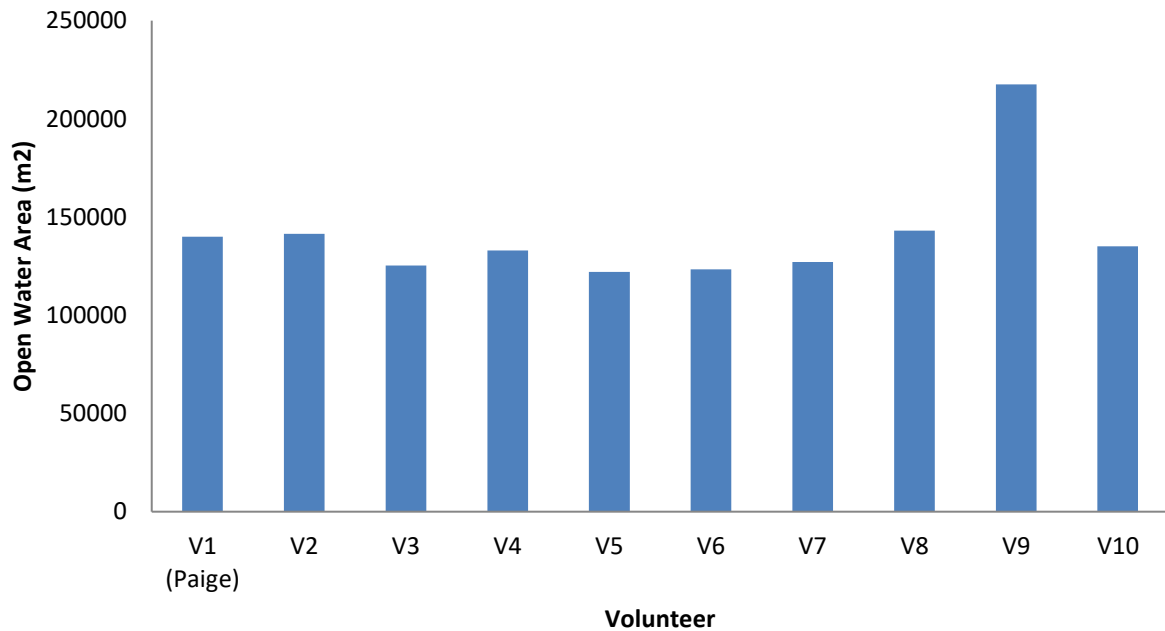
### 3 RESULTS

#### 3.1 Visual Delineation Variability

Open water area delineations among different volunteer GIS operators varied little, except for volunteer nine whose measurement was +55% higher (217581 m<sup>2</sup>) than the group mean (140769 m<sup>2</sup>) (Figure 16). Variation among all ten of the volunteer open water area measurements was 20% (28053 m<sup>2</sup>). Variation decreased to 6% (8119 m<sup>2</sup>) when the volunteer nine was removed from the analysis. The other nine volunteers varied considerably in their experience using GIS software and with wetland delineation so the large difference between most of the group and a single volunteer could not be attributed to level of skill or knowledge.

It is important to note that I was the first volunteer to carry out this sample delineation and that my measurement was within 845 m<sup>2</sup> of the 140769 m<sup>2</sup> mean ( $\pm 0.006\%$  error) of the other volunteers, excluding volunteer nine. I carried out all area measurements of the six studied marshes and the Netley Cut width to reduce the subjectivity and thus variability in delineation. In addition to having experience in boundary delineation using ArcMap software, I had visited and done field work at each study site.

**Figure 16.** Open water area (m<sup>2</sup>) measurements of a pre-selected area of the Folster Lake marsh done by ten volunteers ranging in skill from no experience to extensive GIS and delineation experience. Volunteers were assigned a number in the order that they conducted their measurements.



## 3.2 Overall changes in six coastal marshes

### 3.2.1 Open Water Area

Mean open water area measurements over the entire time period of this study (1913-2015) for the six study marshes were as follows (in descending order): Folster Lake = 9127245 m<sup>2</sup>, Hardman Lake = 5656815 m<sup>2</sup>, Willow Point = 4053308 m<sup>2</sup>, Balsam Bay = 3403735, Grand Marais = 263484 m<sup>2</sup>, and Hillside Beach = 1428676 m<sup>2</sup>. Folster Lake and Hardman lakes showed the largest overall temporal change in open water areas over the entire time period of this study (1913-2015) with a 48% and 70% of mean increase, respectively, in open water area between the 1934 and 2015 measurements. Between the 1929 and 2011 measurements at Balsam

Bay, there was a 4% increase in open water area. Between the 1950 and 2011 measurements at Willow Point, there was a 3% increase in open water area. Between the 1948 and 2011 measurements at Grand Marais, there was a 3% decrease in open water area and in between the 1955 and 2011 measurements at Hillside Beach there was a 10% net decrease in open water area.

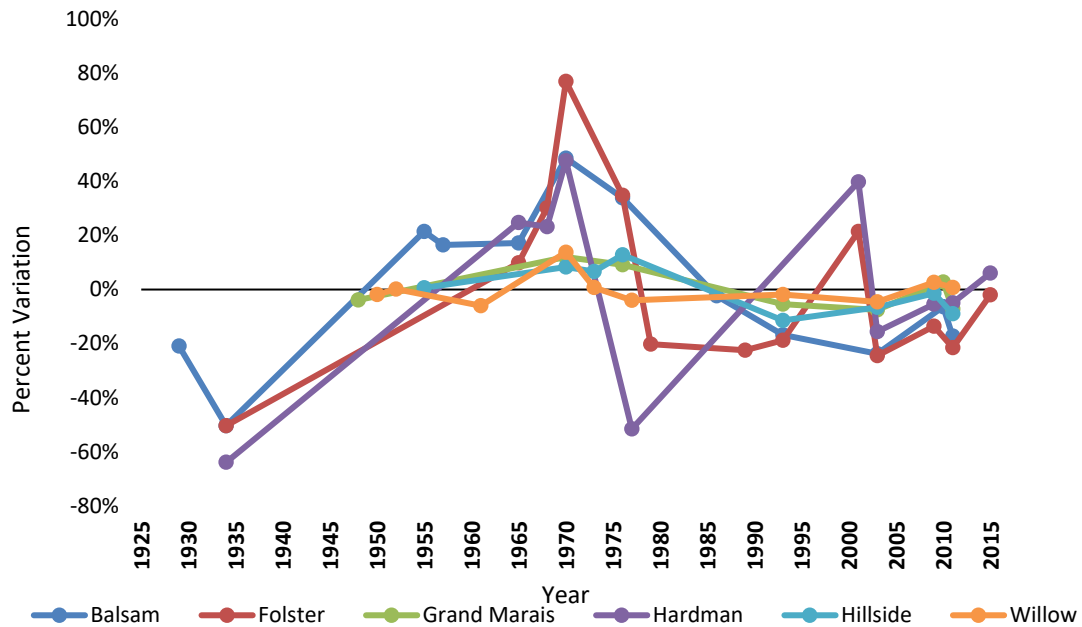
The two marshes located within the Netley-Libau Marsh complex (Hardman and Folster) not only showed the highest overall temporal (1934-2015) increase in open water area out of all six marshes but also had the largest variation from their mean open water areas between the lowest and highest open water measurements, with a difference of 127% for Folster Lake and 112% for Hardman Lake.

Although its overall temporal (1929-2011) increase in open water area was small (4%), the Balsam Bay marsh showed the third-highest open water area change out of all six marshes, with a difference of 70% between its highest and lowest open water area measurements. In Folster and Hardman lakes and Balsam Bay, the lowest open water area occurred in 1934 while the highest area was measured in 1970. In comparison, the Willow Point, Grand Marais, and Hillside Beach marshes showed relatively narrower ranges of change between highest and lowest area measurements at 18%, 20%, and 24%, respectively (Figure 17). Like Folster, Hardman, and Balsam the highest open water area measurements for Willow Point and Grand Marais were also obtained from the 1970 aerial photos, while the lowest at both these marshes were obtained from the 2003 photos. In contrast, the highest open water area measurement at Hillside Beach was obtained from the 1976 aerial photo with the 1970 measurement being a close second, and the lowest measurement obtained from the 1993 aerial photo.

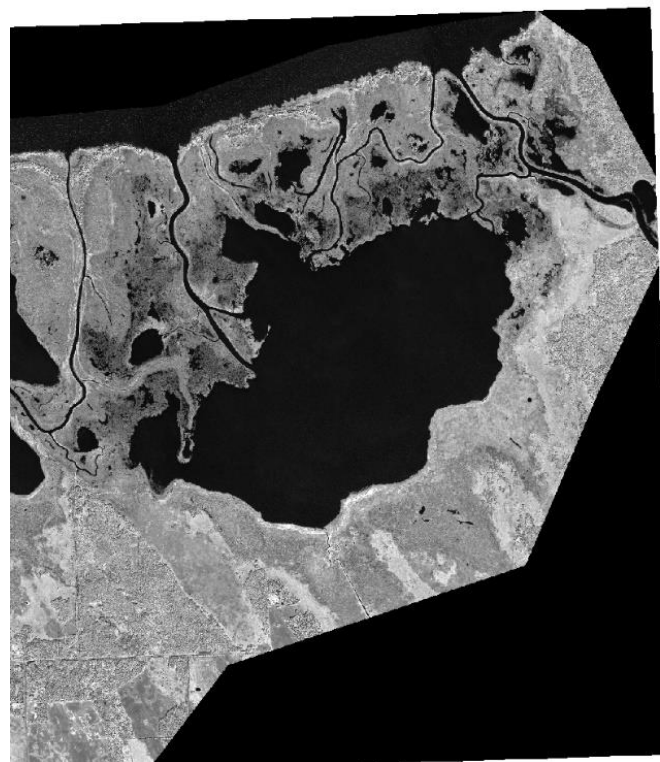
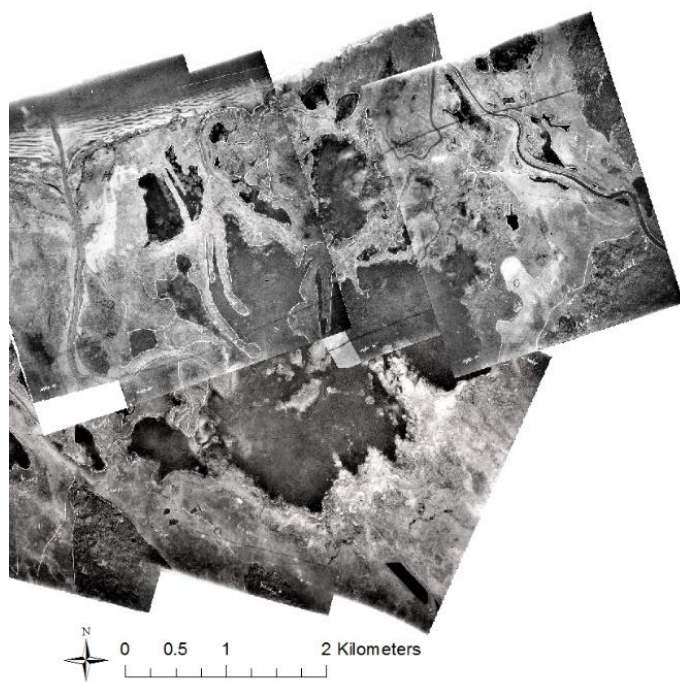
When the earliest imagery of Hardman and Folster lakes and Balsam Bay obtained from September 1929 was compared to satellite imagery of these marshes from August 2015, I saw a

marked difference in shoreline positioning and habitat complexity. Visual inspection of the Hardman, Folster, and Balsam Bay marshes shows a reduction of emergent vegetation patches and an increase in connections between water bodies (Figures 18-20). Aerial images from 1929 showed how the physical layout of these marshes changed over time (Figures 18-20). Where once the open water area of these marshes were interrupted by islands, patches of emergent vegetation, and winding channels, they are now wide-open expanses of water with dense stands of cattail around the shoreline. Many of the small secluded ponds had become directly connected to the main “bays” via new formed channels or by complete washout of the shoreline. These marshes had also become increasingly connected to Lake Winnipeg and neighboring waterbodies by channels and direct connections. There has been a clear landward progression of the Balsam Bay marsh as the open water boundary has retreated landward by approximately 125 metres and now abuts the dyke where the old railway line used to be located (Figure 20). In the case of Folster Lake, open water measurements could not be quantified from the 1929 photo due to a lack of ground control points which prevented accurate georeferencing. The 1929 aerial imagery of Hardman Lake did not include all of the study area and so open water measurements for this year could not be obtained.

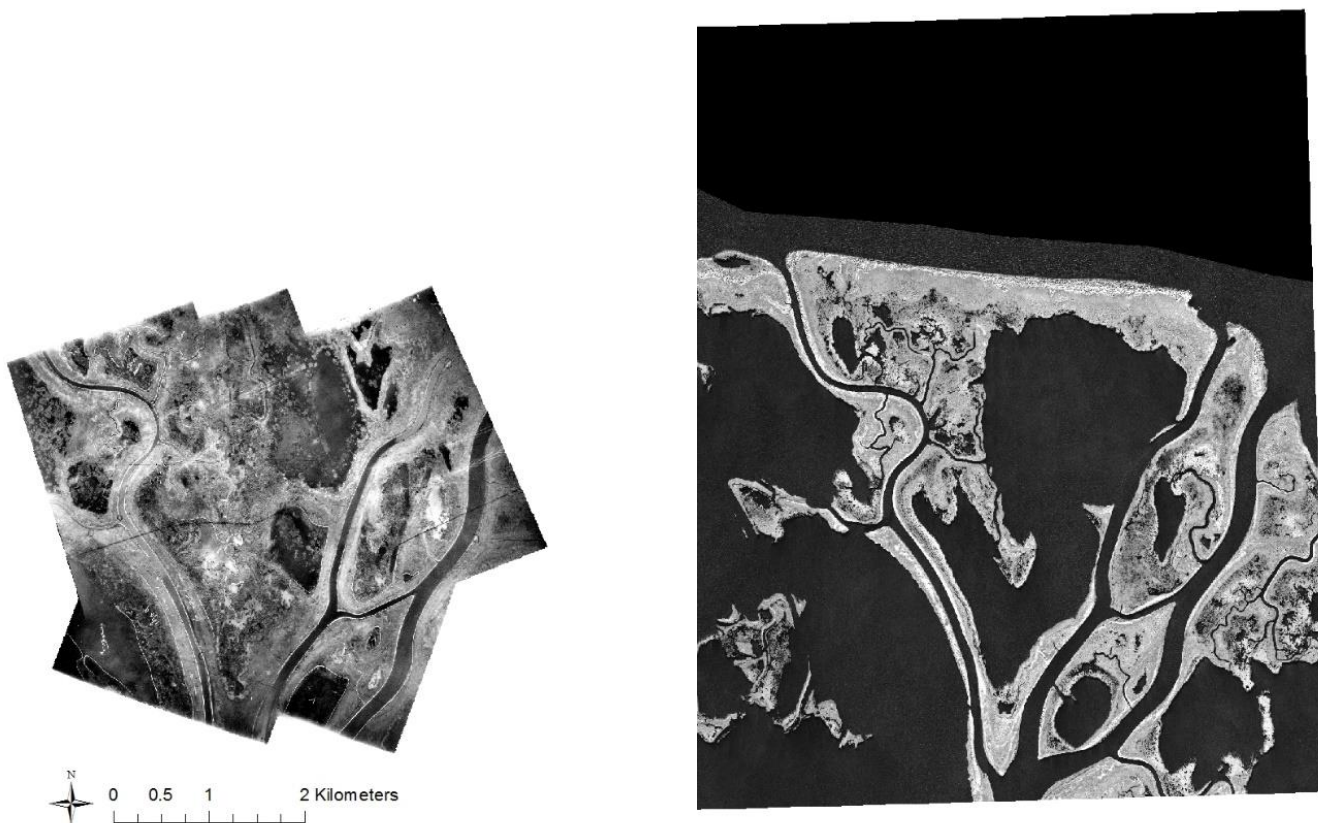
**Figure 17.** Percent deviation from the mean of open water area in six Lake Winnipeg coastal marshes plotted over time.



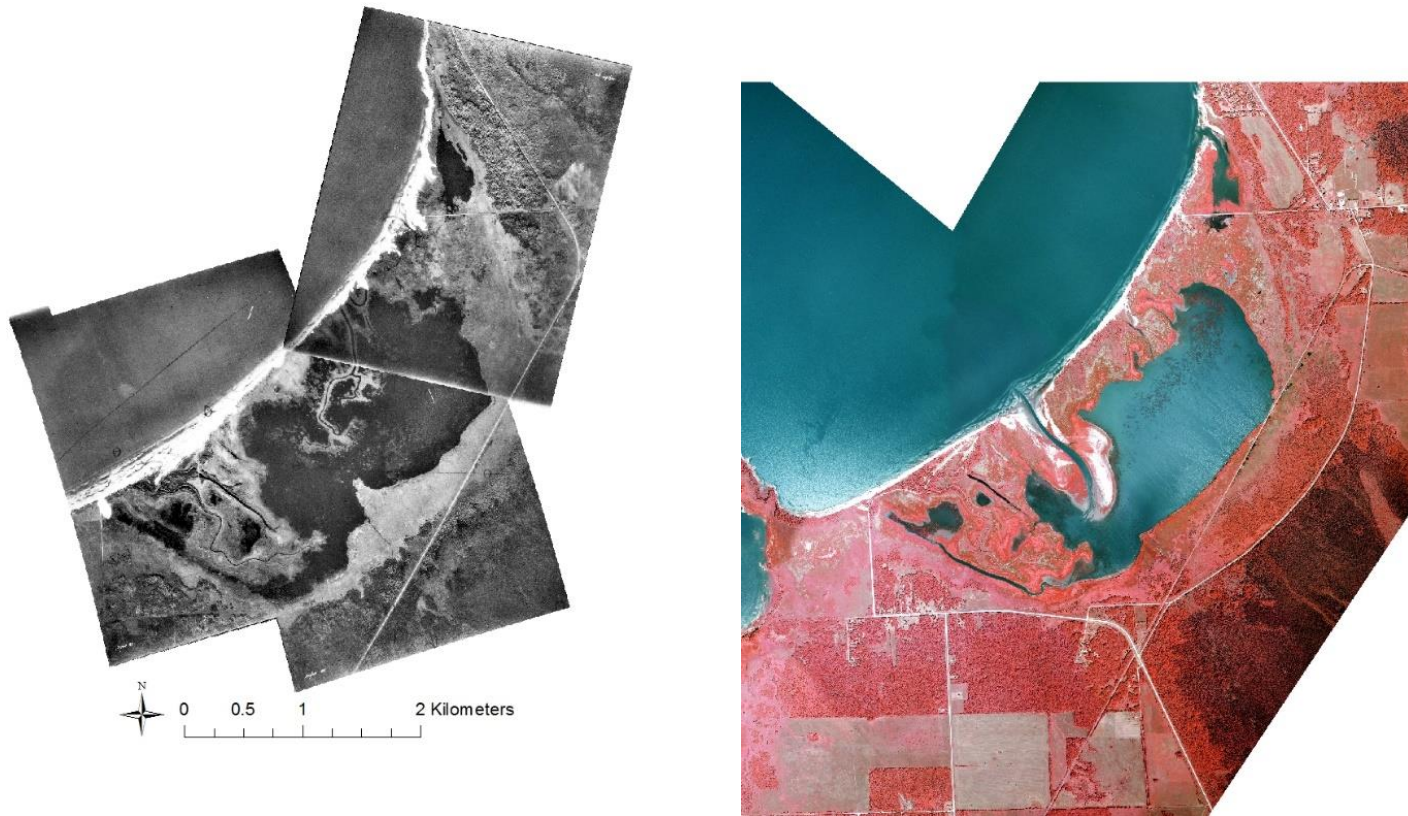
**Figure 18.** Remotely sensed images of Folster Lake with the earliest taken in September 1929 (left) and August 2015 (right).



**Figure 19.** Remotely sensed images of Hardman Lake with the earliest taken in September 1929 (left) and August 2015 (right).



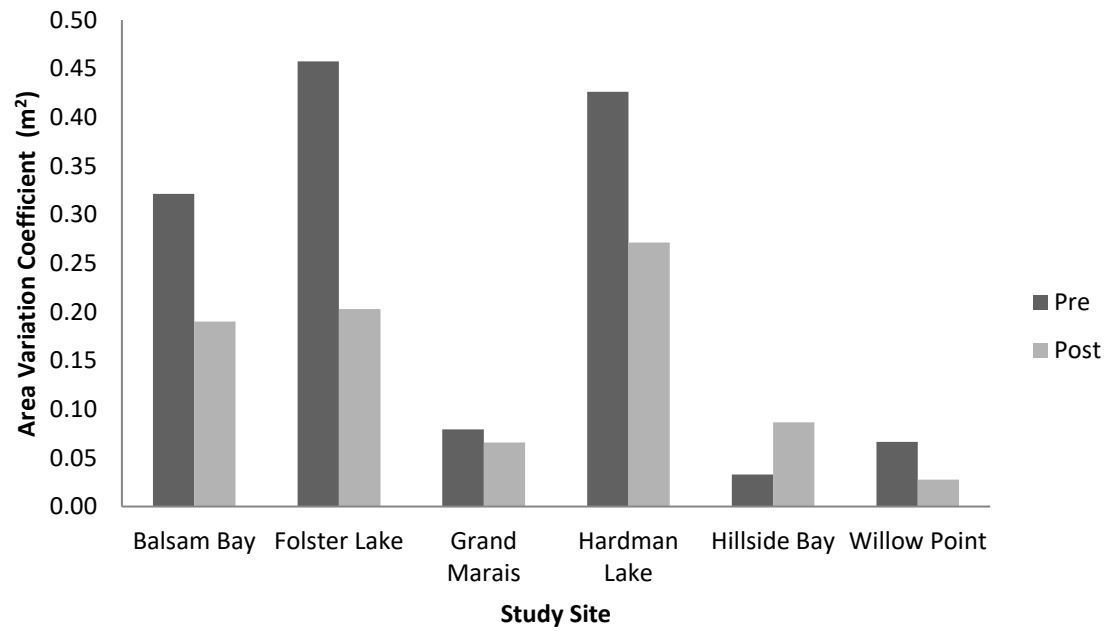
**Figure 20.** Remotely sensed images of Balsam Bay marsh with the earliest image taken in September 1929 (left) and August 2003 (right). Note the change in marsh shoreline proximity to the railway line between these years. This marsh has moved gradually landward over time.



In five out of the six study marshes, variation in open water area decreased after the commencement of lake level regulation. Expressed as coefficients of variation (standard deviation / mean), these decreases in variation between pre- and post-regulation years in descending order were: Folster Lake (-25%), Hardman Lake (-15%), Balsam Bay (-13%), Willow Point (-4%), and Grand Marais (-1%). The large variation decreases from the pre- to post-regulation time periods at the Folster, Hardman, and Balsam sites can be explained by the earlier aerial photos (Balsam;1929) and survey map (Folster and Hardman; 1934) providing a much earlier marsh open water area record than that of Willow Point, Grand Marais, and Hillside Beach. The 1920s and 1930s represented a period of lower Lake Winnipeg levels and Red River flows than the years after 1950, and so marsh open water area would vary more as Lake Winnipeg levels and Red River discharges increased over time.

Expressed as a coefficient of variation, Hillside Beach was the only site to increase (+5%) in open water area variation after regulation began (Figure 21). This increase in Hillside Beach variation in the time period after regulation began is most likely due to having only three pre-regulation open water area measurements. These three area measurements were obtained from photos taken in 1955, 1970, and 1973; years that occurred after the extreme flood events of 1950 and 1970 when emergent vegetation was likely drowned and regrowth limited.

**Figure 21.** Open water area (m<sup>2</sup>) variation coefficients (open water area standard deviation / mean open water area) of each of the six study marshes of both the pre and post Lake Winnipeg regulation time periods.



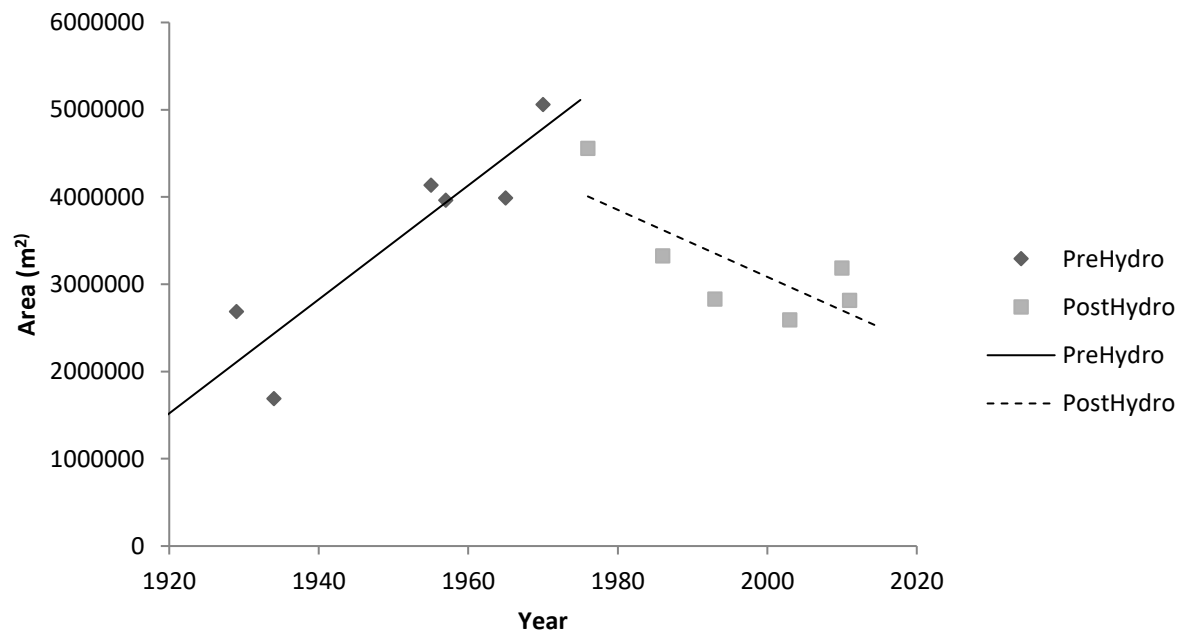
Over the entire time period covered by this study (1913 – 2015), open water area was at its largest (and thus emergent vegetation area at its smallest) in 1970, with the exception of Hillside Beach with its second largest open water area measurement in 1970 (1547006 m<sup>2</sup>) and largest in 1976 (1612113 m<sup>2</sup>). The expansion of open water areas in all of the study marshes during the 1970s may be attributed to higher than average Lake Winnipeg levels during typical ice-free months (May-October). Between 1965-1975, average mean May-October Lake Winnipeg levels were 0.5 metres above the 1915-2015 average level of 217.6 m asl. Three of the ten highest mean May-October Lake Winnipeg levels occurred in 1966, 1969, and 1970 (218.47, 218.19, and 218.28 m asl). Between 1965 and 1975, mean April-June Red River discharges were also higher (+232.0 m<sup>3</sup>/s) than the 1913-2015 average of 496.9 m<sup>3</sup>/s, with the tenth-highest average flow occurring in the spring of 1966 (1114 m<sup>3</sup>/s).

Open water area was at its smallest in 2003 at Grand Marais (2436270 m<sup>2</sup>) when mean May-October Lake Winnipeg levels reached their eighth-lowest value of 217.02 m asl, 0.57 metres below the 1915-2015 average (217.59 m asl). Out of the five years preceding 2003, 2002 was the only year where mean May-October Lake Winnipeg level was below average (-0.11 m asl). Willow Point's smallest area (3810577 m<sup>2</sup>) occurred in 1961 when mean May-October Lake Winnipeg levels reached their ninth-lowest value of 217.04 m asl. Out of the five years preceding 1961, 1958 was the only year where mean May-October Lake Winnipeg level was below average (217.26 m asl). Hardman Lake, Folster Lake, and Balsam Bay reached smallest open water area size in 1934 when mean May-October average Lake Winnipeg level was 0.19 metres below the 1915-2015 average. Average seasonal Lake Winnipeg levels in the five years prior to 1934 (216.93 m asl) were well below the 1915-2015 average (-0.66). Four out of those five years were among the ten lowest mean seasonal May-October levels. The Red River reached its sixth-lowest spring mean flow (April-June) of 70.89 m<sup>3</sup>/s in 1934, with the five preceding years also being below the 1913-2015 average (496.86 m<sup>3</sup>/s). Hillside Beach reached its smallest open

water area of 1265210 m<sup>2</sup> in 1993 when Lake Winnipeg mean May-October levels were 0.07 metres above the 1915-2015 average; Hillside's open water area reached its second-smallest areal coverage in 2011 when mean May-October Lake Winnipeg levels were 0.67 metres above average and at the fifth highest they have ever been between 1915-2015.

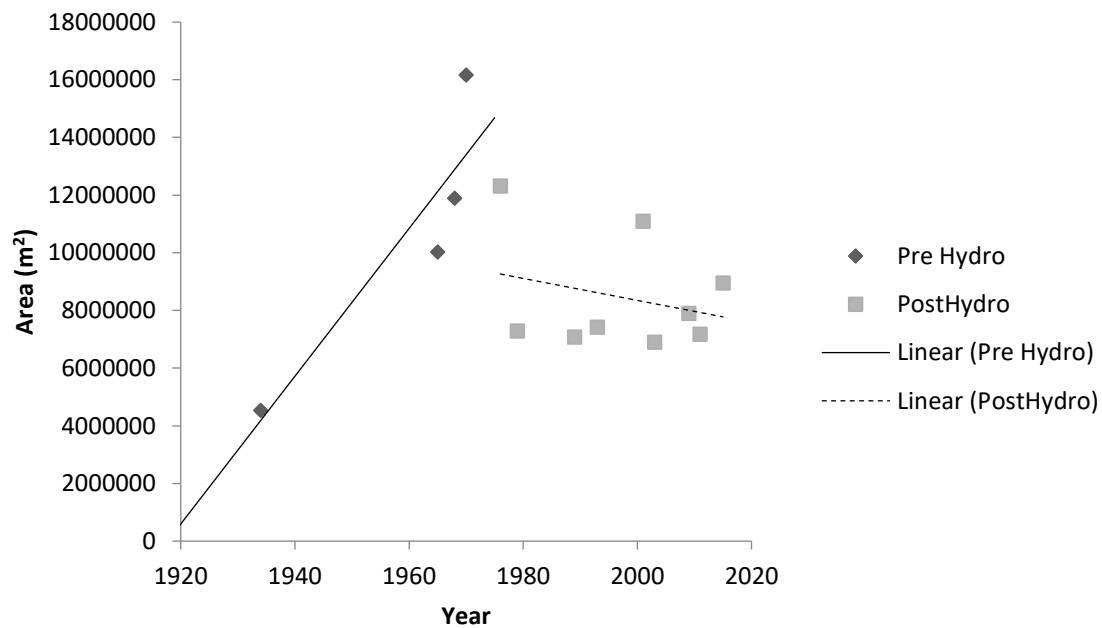
In the years prior to regulation, there was a strong, significant linear trend ( $R^2 = 0.82$ ,  $p = 0.01$ ) of increasing open water area over time in the Balsam Bay marsh ( $y = 65302x - 1 \times 10^8$ ). Open water area decreased significantly ( $r^2 = 0.57$ ,  $p = 0.08$ ) in post-regulation years ( $y = -38407x + 8 \times 10^7$ ). The slope of the line in pre-regulation years was steeper than that of post-regulation years, indicating a slightly higher rate of change prior to regulation (Figure 22).

**Figure 22.** Trends of Balsam Bay open water areas from 1929 to 2011. Trend lines were calculated using pre-regulation years of area data (solid line) and post-regulation years of area data (dashed line).



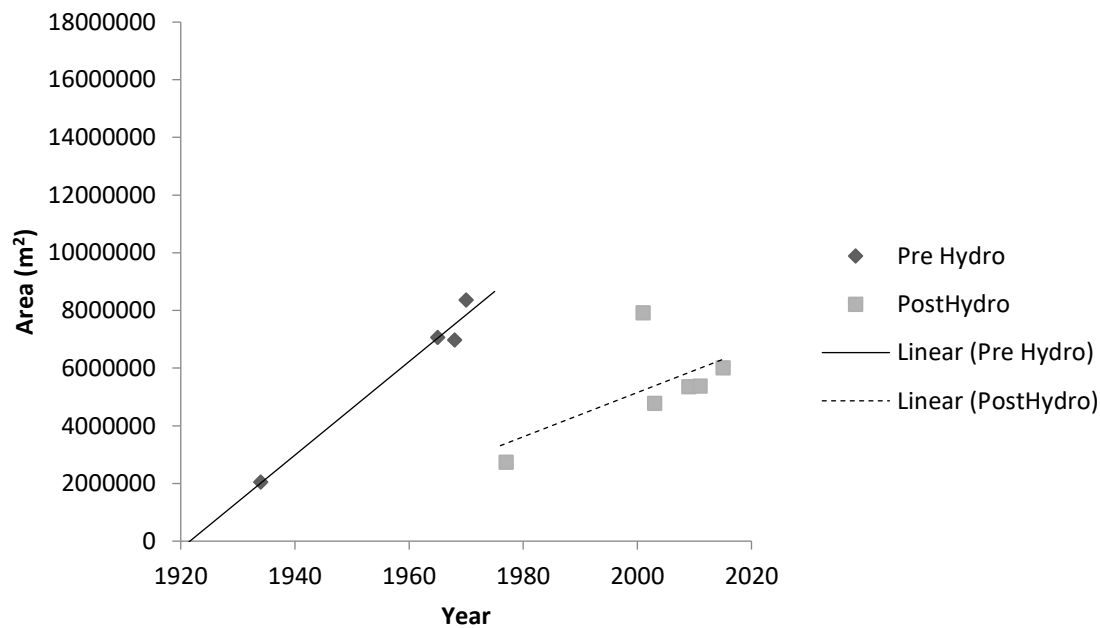
There was a statistically significant increasing trend ( $r^2 = 0.81$ ,  $p = 0.1$ ) of increasing open water area over time in the pre-regulation period in Folster Lake ( $y = 256165x - 5 \times 10^8$ ) and in post-regulation years there was no significant trend ( $r^2 = 0.07$ ,  $p = 0.48$ ) in open water area over time existed ( $y = -38087x + 8 \times 10^7$ ). The slope of the line of pre-regulation years was steeper than that of post-regulation study years; indicating that the rate of change was higher in pre-regulation years (Figure 23).

**Figure 23.** Trends of Folster Lake open water areas from 1934 to 2015. Trend lines were calculated using pre-regulation years area data (solid line) and post-regulation years of area data (dashed line).



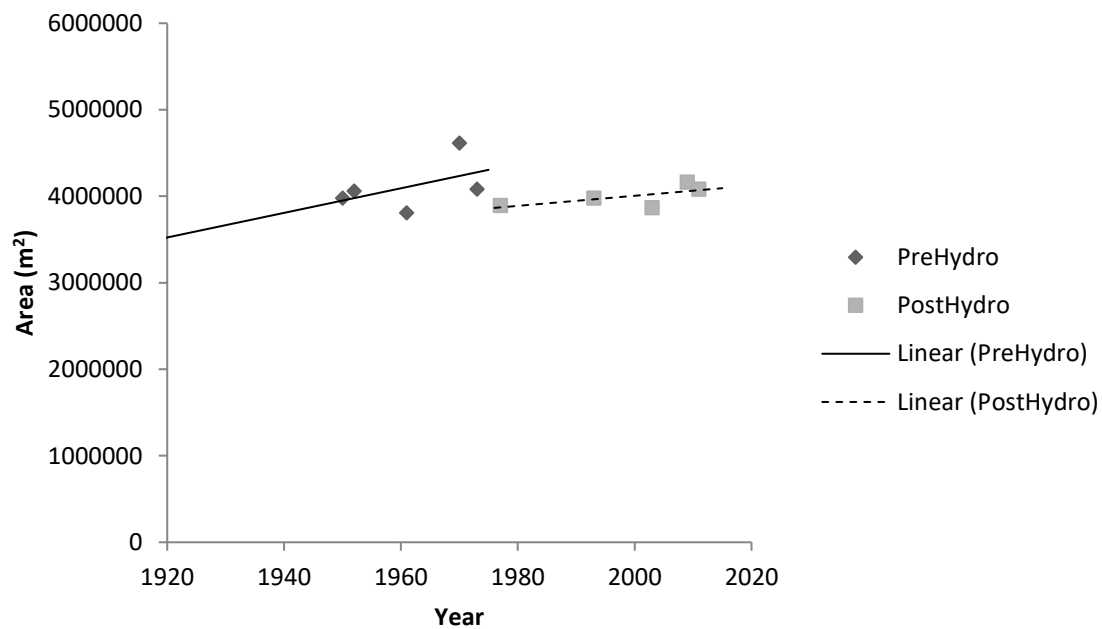
Open water area increased significantly ( $r^2 = 0.98$ ,  $p = 0.01$ ) over time in the Hardman Lake pre-regulation data ( $y = 162145x - 3 \times 10^8$ ) and no trend existed in post-regulation years ( $y = 76766x - 1 \times 10^8$ ) ( $r^2 = 0.38$ ,  $p = 0.19$ ). The slope of the line with pre-regulation years was steeper than the slope of post-regulation years, indicating that marsh rate of change was slightly higher in pre-regulation years (Figure 24).

**Figure 24.** Trends of Hardman Lake open water areas from 1934 to 2015. Trend lines were calculated using pre-regulation years of area data (solid line) and post-regulation years of area data (dashed line).



No trend in open water area of the Willow Point marsh existed over time ( $r^2 = 0.24$ ,  $p = 0.40$ ) in both the pre-regulation ( $y = 14215x - 2 \times 10^7$ ) and post-regulation periods ( $y = 5835x - 8 \times 10^6$ ) ( $r^2 = 0.43$ ,  $p = 0.23$ ).

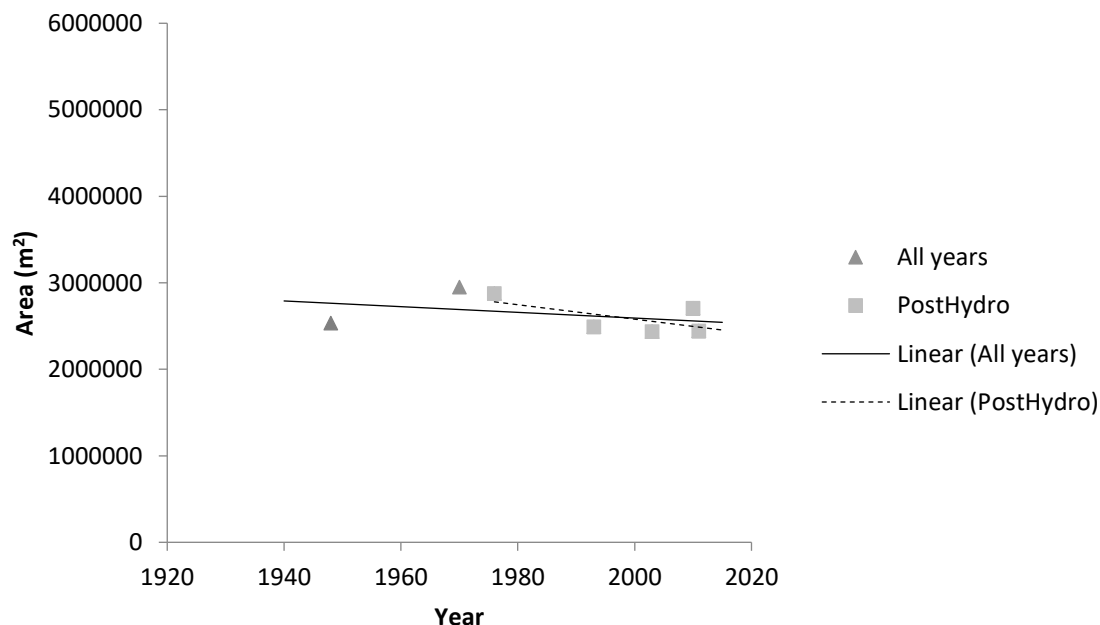
**Figure 25.** Trends of Willow Point open water areas from 1950 to 2011. Trend lines were calculated using pre regulation years of area data (solid line) and post regulation years of area data (dashed line).



The same approach of comparing pre- and post-regulation years that was used with Balsam Bay, Willow Point, and Hardman and Folster lakes could not be used with Grand Marais and Hillside Beach marshes due to the lack of pre-regulation open water area data. Instead, I compared the trends with all years included to the trends in only post-regulation years.

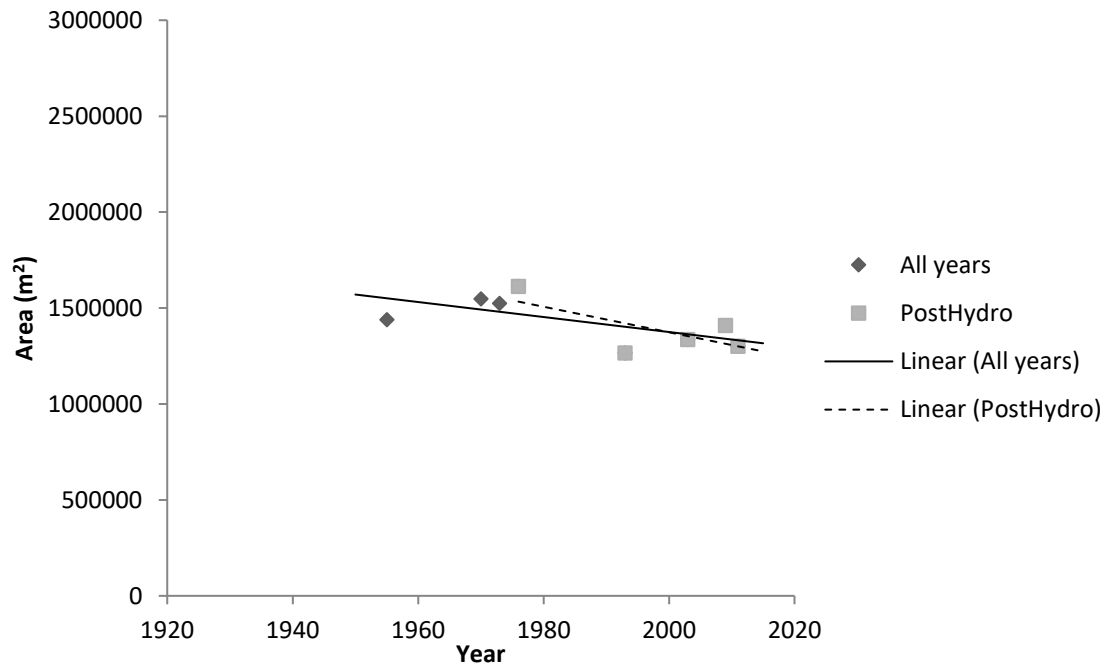
Overall, no significant trend in open water area over time existed for Grand Marais ( $y = -2168.8x + 7 \times 10^6$ ) ( $r^2 = 0.13$ ,  $p = 0.42$ ) and no significant trend existed ( $r^2 = 0.39$ ,  $p = 0.26$ ) when only post-regulation years were tested ( $y = -8354.2x + 2 \times 10^7$ ) (Figure. 26).

**Figure 26.** Trends of Grand Marais open water areas from 1948 to 2011. Trend lines were calculated using all years of area data (solid line) and post regulation years of area data (dashed line).



Overall, there was a decreasing significant trend in open water area over time ( $r^2 = 0.42$ ,  $p = 0.08$ ) at Hillside Beach ( $y = -3907.8x + 9 \times 10^6$ ). When post regulation years are examined we see that no significant trend in open water area over time existed ( $r^2 = 0.48$ ,  $p = 0.20$ ) (Figure. 27).

**Figure 27.** Trends of Hillside Beach open water areas from 1955 to 2011. Trend lines were calculated using all years of area data (solid line) and post regulation years of area data (dashed line).



### 3.3 Red River Discharge versus Open Water Areas

#### 3.3.1 Netley Cut Discharge

Contrary to assumptions by Grosshans et al. (2004) and Watchorn (2015) that the Netley Cut formed in 1913 and has remained open for more than a century, my archival research and aerial image analyses demonstrate that the Netley Cut did not erode gradually since 1913 but, instead, was closed between the 1929 and 1968 aerial photographs, except in 1950 when major flooding overtopped the shoreline between the Red River and Netley Lake. The successful closure of the Netley Cut was the

result of a sheet pile dam constructed on October 27<sup>th</sup>, 1925 after it was realized that the Cut did nothing to alleviate flooding upstream and was eroding rapidly. (Public Works Canada 1925).

“In connection with the closing of Netley Cut for which money was appropriated this season, I beg to report that the wall consisting of 6” T & G. Sheet piles was completed on October 27<sup>th</sup> and is reported as watertight and most satisfactory...It was planned to pump an earth fill on both sides of the wall and between the new and old walls. Unfortunately freeze-up seemed earlier than usual and this work could not be carried out. The men acquainted with the place and conditions are of the opinion that the work as it stands is unlikely to suffer any damage and the fill will be pumped in early in the spring. On the day after driving was completed, there was a 2½ foot head against the wall, due to a strong north wind. No leakage could be noticed.”

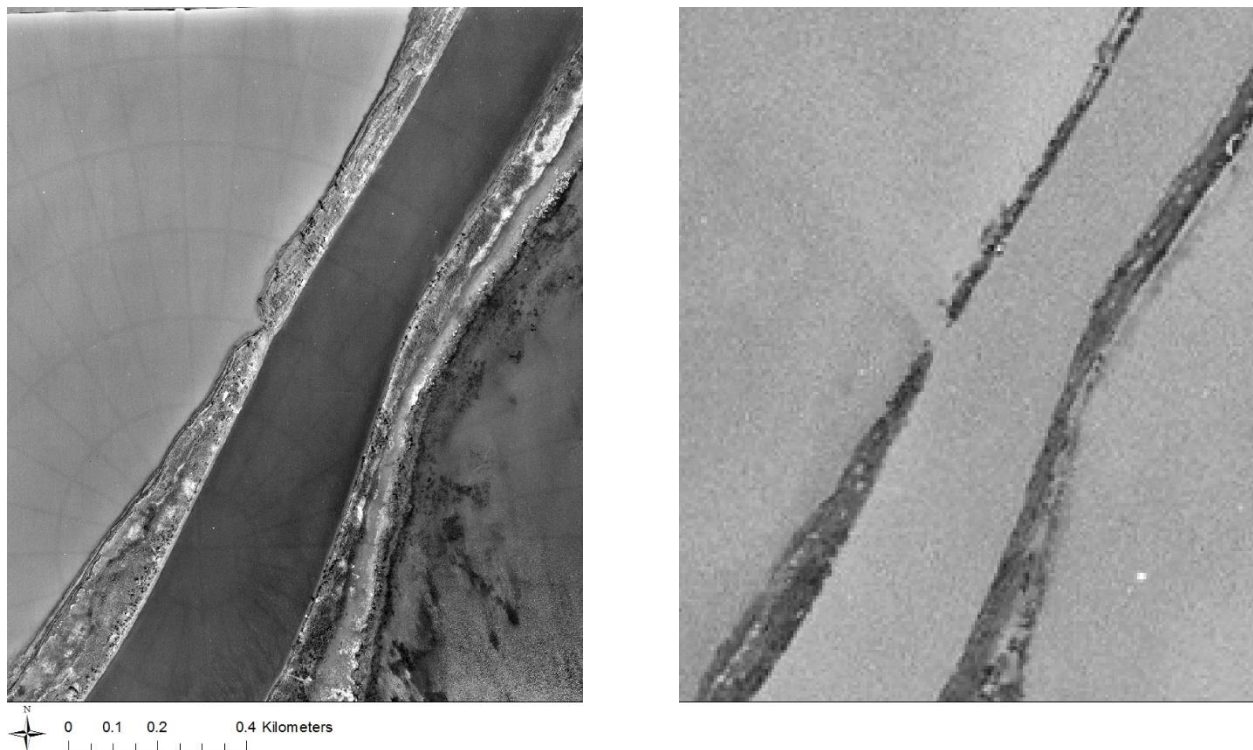
After remaining closed for 43 years, the Netley Cut reopened following higher than average May-October mean seasonal Lake Winnipeg levels in the five years prior to 1970 (mean = 218.06 m asl) and intense flooding in 1970 (218.28 m asl), causing the Red River to be reconnected to Netley Lake (Figure 28). The period in which the Netley Cut reopened had above-average Lake Winnipeg level and Red River discharges (Figure 29). No archival records could be found to examine the condition of the sheet pile dam immediately prior to its reopening by 1970. It is possible that the dam had fallen into disrepair after the 1950 flood and was destroyed by the combination of high Lake Winnipeg levels and Red River discharge in 1970. In all of the images acquired after 1970 the Netley Cut was never closed and it eroded substantially wider. Between 1968 and 2015, the Netley Cut width increased linearly ( $R^2 = 0.98$ ,  $p < 0.05$ ) at an average rate of 13.5 metres/year, reaching a total width of 457.66 metres by 2015, or about 117% percent of the Red River channel width at that time. Between 2011 and 2015 it appears the Netley Cut width decreased, however due to 2011 Red River flooding it is more likely that the shoreline on either side of the Cut was submerged under river water, resulting in the higher 2011 width measurement compared that of 2015 (Figure 29).

$$\text{Eq.6 } y=9.9856x-19614$$

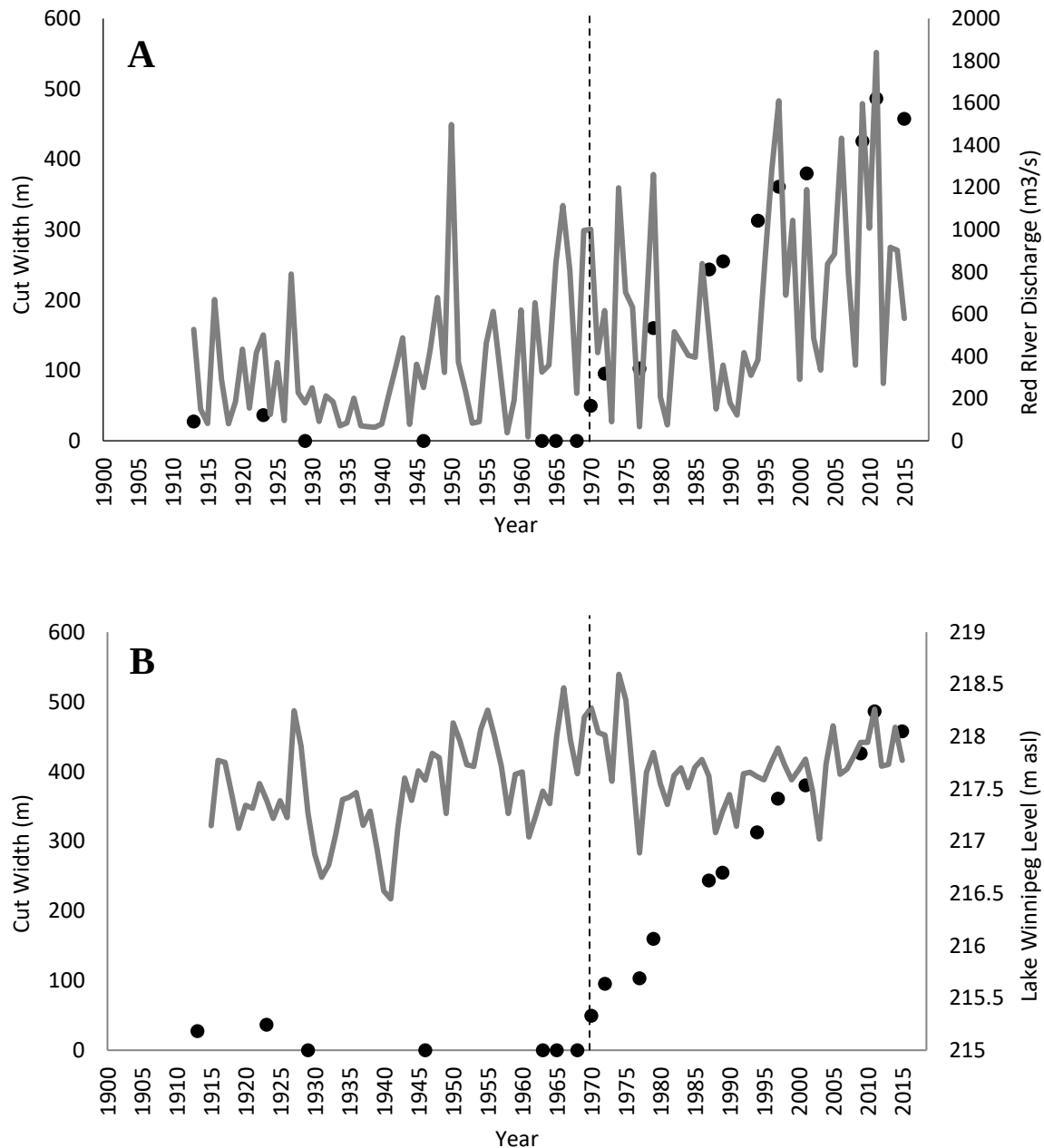
Where  $x$ = year

$y$ = Cut Width (m)

**Figure 28.** The Netley Cut reopened sometime between 11 May 1968 (left) and 25 July 1970 (right) and has grown continually wider in the 45-year period to 2015.



**Figure 29.** A) Netley Cut width (black circles) in metres and April-June mean Red River discharge estimates (line) in cubic metres per second. B) Netley Cut width (black circles) in metres and May-October mean Lake Winnipeg levels (line) in metres above sea level over time. The vertical black line marks the year 1970, in which the Cut was observed to be open again.



A time series of aerial and satellite images (Figures 30-47) show how the Netley Cut and the Netley Lake area have changed between 1929 and 2015.

**Figure 30.** Aerial photograph of the Netley Cut, 13 October 1929. The photo could not be georeferenced so no scale bars shown.

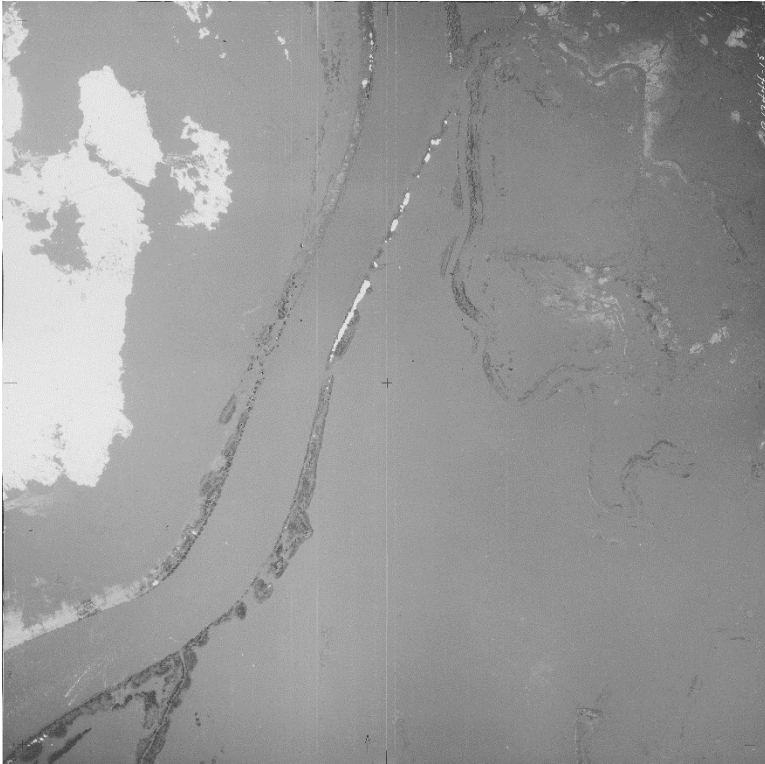


**Figure 31.** Aerial photograph of the Netley Cut, 22 August 1946. Could not be georeferenced so no scale bar is shown.

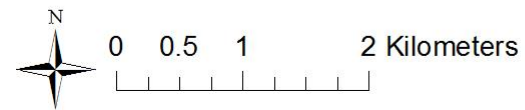
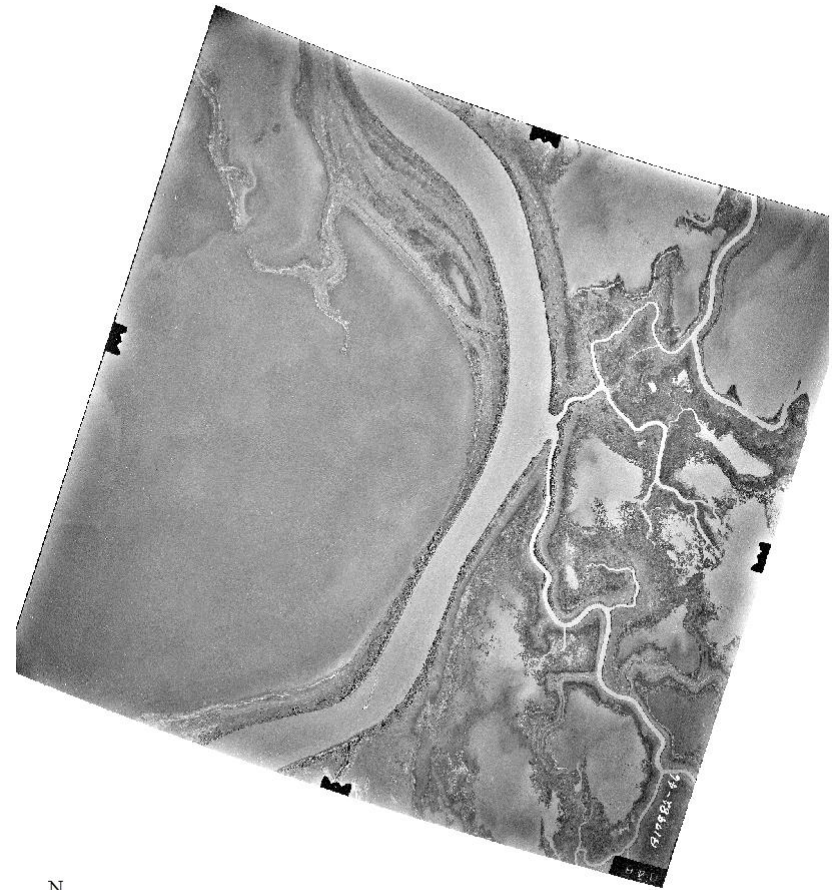


**Figure 32.** Aerial photograph of the Netley Cut, May 8, 1950.

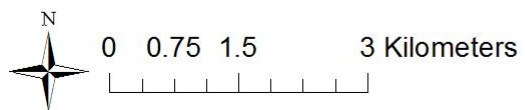
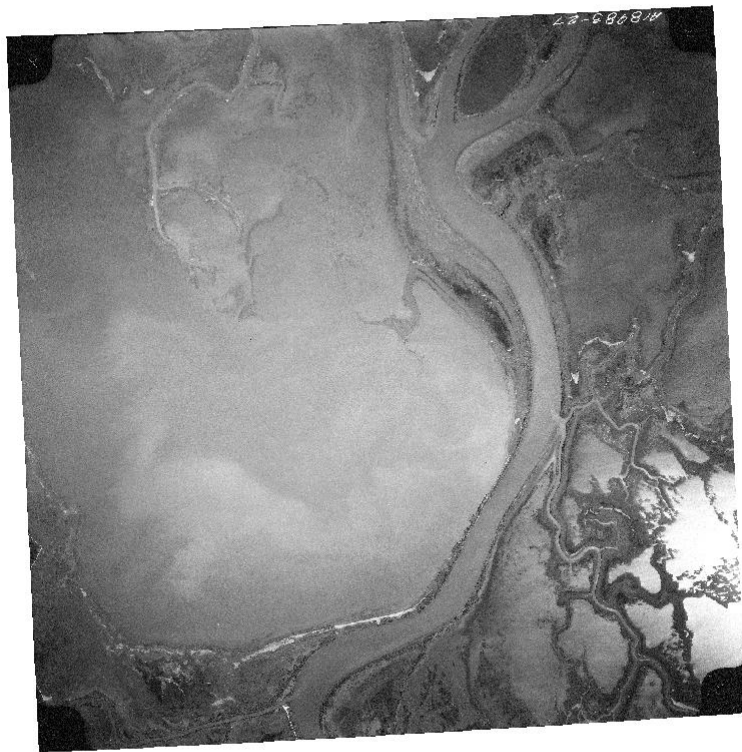
Could not be georeferenced so no scale bar is shown.



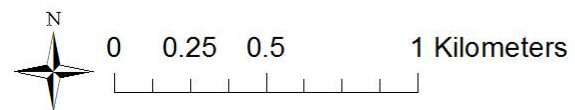
**Figure 33.** Aerial photograph of the Netley Cut, June 14, 1963.



**Figure 34.** Aerial photograph of the Netley Cut and south end of Netley Lake, August 15, 1965.



**Figure 35.** Aerial photograph of the Netley Cut, May 11, 1968.



**Figure 36.** Aerial photograph of the Netley Cut and Netley Lake, July 25, 1970.



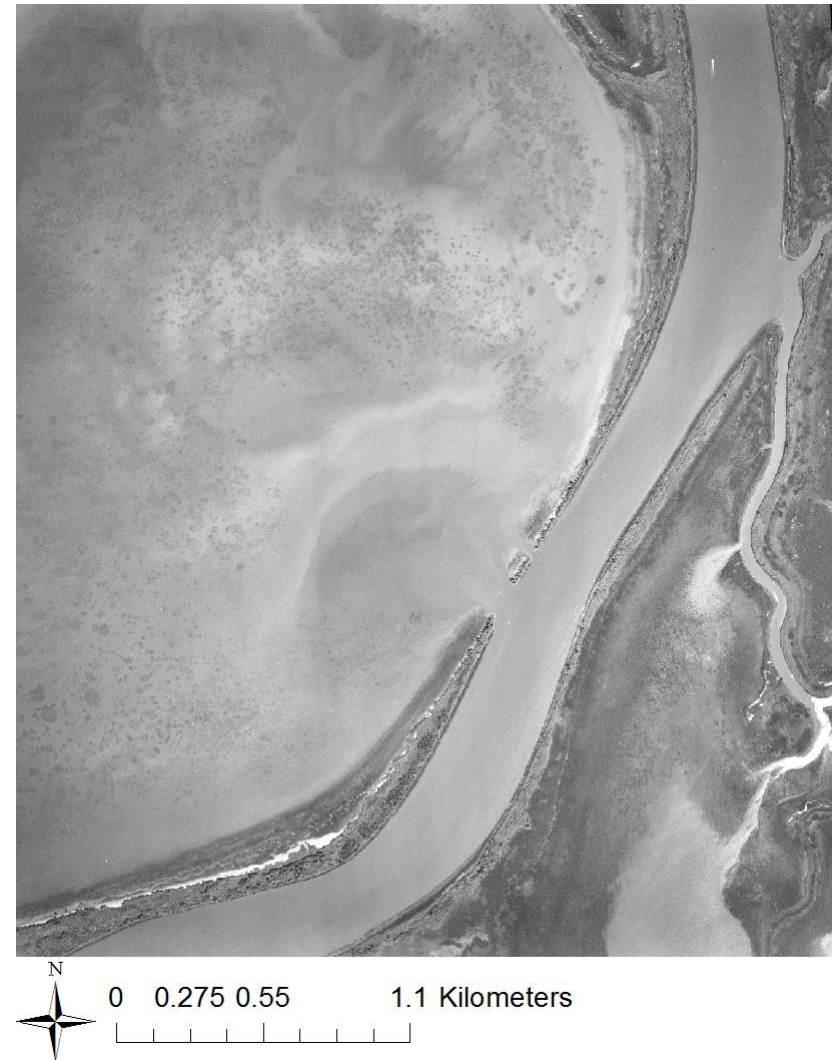
**Figure 37.** Aerial photograph of the Netley Cut and Netley Lake, May 21, 1972.



**Figure 38.** Aerial photograph of the Netley Cut and Netley Lake, July 12, 1977.



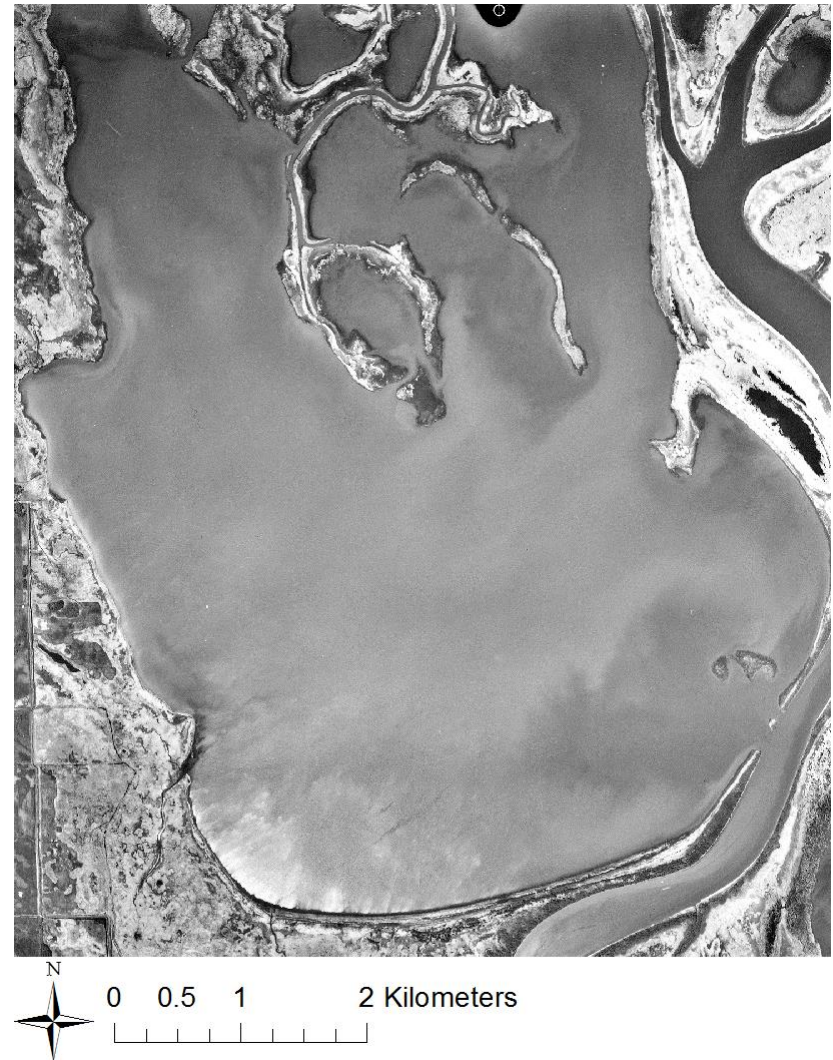
**Figure 39.** Aerial photograph of the Netley Cut and southeast section of Netley Lake, July 28, 1979.



**Figure 40.** Aerial photograph of the Netley Cut and south section of Netley Lake, April 28, 1987.



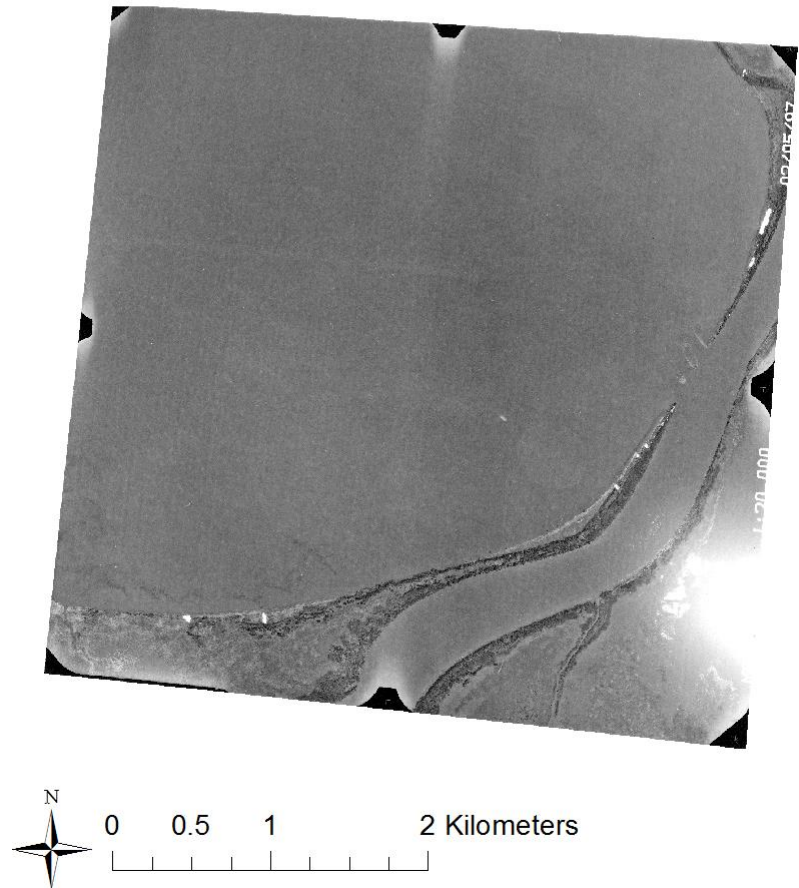
**Figure 41.** Aerial photograph of the Netley Cut and south section of Netley Lake, June 15, 1989.



**Figure 42.** Aerial photograph of the Netley Cut and Netley Lake, May 26, 1994.



**Figure 43.** Aerial photograph of the Netley Cut and southeast section of Netley Lake, May 2, 1997.



**Figure 44.** Orthophotograph mosaic of the Netley Cut and Netley Lake, Aug 3, 2001.



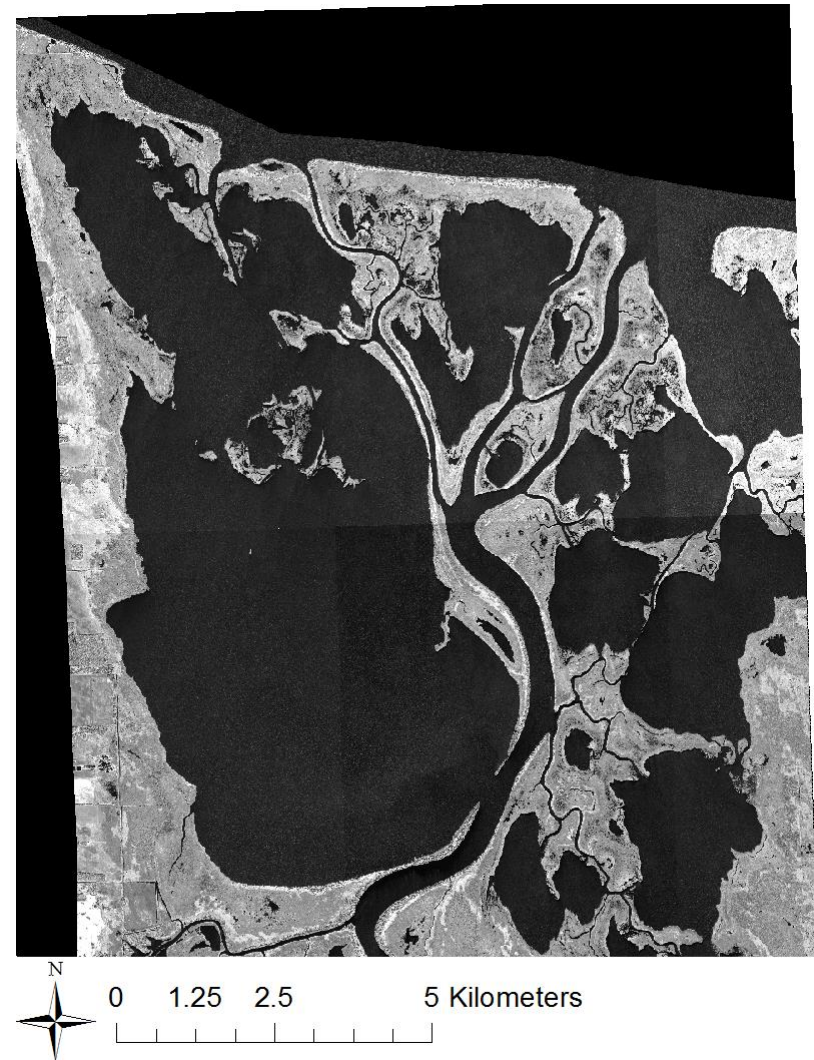
**Figure 45.** Satellite image of the Netley Cut and Netley Lake, Aug 20, 2009.



**Figure 46.** Satellite image of the Netley Cut and Netley Lake, July 14, 2011.



**Figure 47.** Satellite image of the Netley Cut and Netley Lake, Aug 15, 2015.



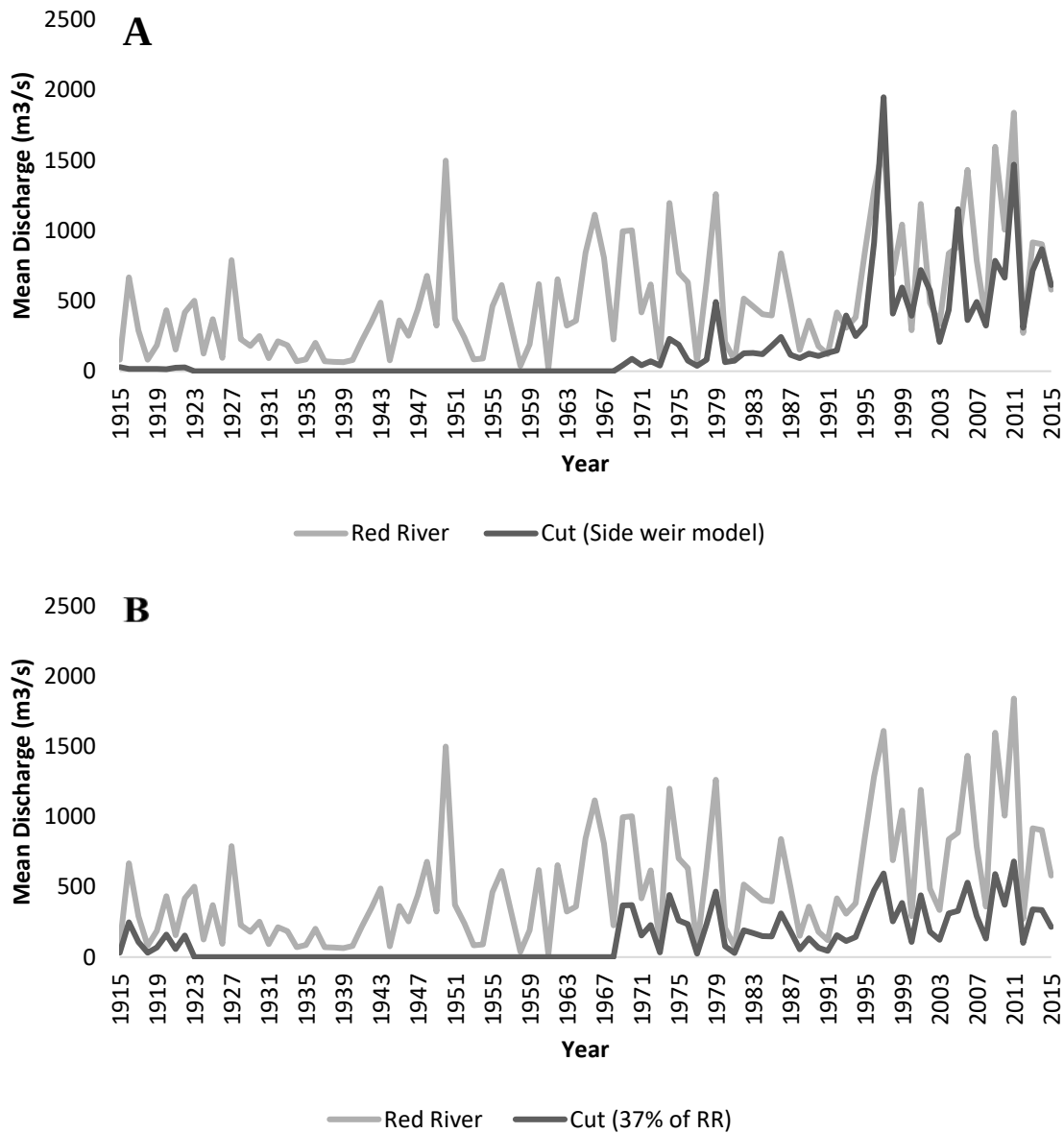
Accurate estimates of Red River water discharge through the Netley Cut over time were not fully attainable through the modified broad-crested side weir model outlined in section 2.4. The resulting average April-June discharge values exceeded the discharge of the Red River in eight years between 1991 and 2015 (Figure 48A). It is obviously not possible for a greater volume of Red River water to be flowing through the Netley Cut than there is flowing in the river itself. Using the modified broad-crested side weir model, average calculated Netley Cut discharge into Netley Lake was  $180 \text{ m}^3/\text{s}$  between 1915 and 2015.

An alternate and more simplistic way of estimating the amount of Red River water discharging through the Netley Cut was simply to multiply Red River discharge values by a fixed percentage of total river flow. Clark (unpublished data, 2014) estimated, based on eight Netley Cut discharge measurements ( $185.81\text{-}540.58 \text{ m}^3/\text{s}$ ) in the spring and summer of 2009 and summer and fall of 2014, that the average percent of Red River water discharging through the Cut was 37%. Using the 37% calculation method, average Netley Cut discharge into Netley Lake was  $126 \text{ m}^3/\text{s}$  between 1915 and 2015.

Between 1915 and 1968, prior to the aerial photograph confirming the Netley Cut reopening, the average Netley Cut discharge was three  $\text{m}^3/\text{s}$  based off the broad-crested side weir model and  $16 \text{ m}^3/\text{s}$  using the fixed percentage method. Between 1970 and 2015, after the Cut reopened, the average Netley Cut discharge was  $390 \text{ m}^3/\text{s}$  based off the broad-crested side weir model and  $250 \text{ m}^3/\text{s}$  using the fixed percentage method. The accuracy of the broad-crested side weir model was examined by comparing the calculated discharge estimates to the actual measurements taken in spring 2009 and 2014 (Clark. 2014 unpublished data). The results of this

comparison show that when using the broad-crested side weir calculation, discharge values were overestimated with a mean difference of +699 m<sup>3</sup>/s from actual 2009 and 2014 discharge measurements. This is because Netley Cut discharge measurements used for the broad-crested side weir model were obtained from a total of eight measurements in 2009 and 2014 combined. These two years did not have Red River discharges especially high or low with a minimum measurement of 509 m<sup>3</sup>/s and maximum of 1266 m<sup>3</sup>/s.

**Figure 48.** A) April – June discharges over time of the Red River (light gray line) and Netley Cut (dark gray line) in cubic metres per second, estimated using the modified broad-crested side weir calculation (Eq. 3). B) April-June discharges over time of the Red River and Netley Cut, estimated at 37% of Red River flow.



### 3.3.2 Regression Analyses

Stepwise multiple regression analyses showed there were no statistically significant relationships between Red River discharges and changes in open water areas in Hardman ( $r^2 = 0.084$ ,  $p = 0.449$ ) and Folster lakes ( $r^2 = 0.005$ ,  $p = 0.833$ ). However, it was clear from 1950 and 1970 Netley-Libau Marsh aerial photos (Figures 32 and 43) that expansions of open water area in Netley-Libau Marsh occurred during times of extreme Red River flooding. In Section 3.2.1, I noted that open water area in the Netley-Libau marshes was largest when both mean April-June Red River flows and mean May-October Lake Winnipeg levels were high.

### 3.4 Lake Winnipeg Levels versus Open Water Areas

Regression modelling indicated there were significant relationships ( $p < 0.1$ ) between open water area and Lake Winnipeg level in all six study marshes (Table 1). When area data for the pre- and post-regulation periods (1915-2015) were combined, all the optimal stepwise regression models between open water area and Lake Winnipeg levels included both year of image capture and one lag-year of mean seasonal Lake Winnipeg levels (Table 1).

A strong and significant positive relationship ( $r^2 = 0.64$ ,  $p = 0.01$ ,  $n = 12$ ) existed between Balsam Bay open water area and two growing seasons of mean Lake Winnipeg levels over the entire time period of study (1915-2015). Even more of the variation in open water area was explained by the previous growing season (LVLA; Table 1) Lake Winnipeg levels ( $r^2 = 0.72$ ,  $p = 0.03$ ,  $n = 6$ ; Table 1) when only post-regulation years (1976-2015) data were tested. Stepwise regression analyses of pre-regulation years resulted in a statistically insignificant relationship ( $r^2 = 0.74$ ,  $p = 0.13$ ,  $n = 6$ ; Table 1); although the linear regression analysis of pre-regulation data

showed a moderate, statistically significant relationship between lag year mean seasonal Lake Winnipeg levels (LVLA) and open water area at Balsam Bay ( $r^2 = 0.54$ ,  $p = 0.09$ ,  $n = 6$ ).

Willow Point had the strongest relationships between open water area and Lake Winnipeg levels over the entire time period of study with 95% of variation in open water area explained by two growing seasons (LVLA and LVLB; Table 1) of mean lake levels ( $r^2 = 0.95$ ,  $p = < 0.05$ ,  $n = 10$ ; Table 1). Stepwise regression analyses of pre-regulation years resulted in an insignificant relationship ( $r^2 = 0.99$ ,  $p = 0.14$ ,  $n = 5$ ; Table 1), although there was a strong significant linear relationship using year of photo capture levels ( $r^2 = 0.69$ ,  $p = 0.08$ ,  $n = 5$ ). Stepwise regression analyses of post-regulation years resulted in a very strong significant relationship between Willow Point open water area and Lake Winnipeg water levels ( $r^2 = 0.89$ ,  $p = 0.02$ ,  $n = 5$ ; Table 1).

Stepwise regression analyses of Folster Lake over the entire time period of study showed that 56% of that variation ( $r^2 = 0.56$ ,  $p = 0.02$ ,  $n = 13$ ; Table 1) in open water area was explained by two growing seasons of mean Lake Winnipeg water levels. In pre-regulation years both lag year (LVLA) and photo capture year (LVLB) lake levels resulted in a perfect fit with open water areas ( $r^2 = 1.0$ ,  $p = 0.05$ ,  $n = 4$ ; Table 1). The Lake Winnipeg level-marsh open water area relationship weakened yet remained significant ( $r^2 = 0.39$ ,  $p = 0.07$ ,  $n = 9$ ; Table 1) when only post-regulation years were tested. Mean lake levels of the previous year growing season (LVLA) explained 39% of the variation in Folster Lake open water area (Table 1).

In Hardman Lake, 65% of the variation in open water area was explained by two growing seasons of mean Lake Winnipeg levels ( $r^2 = 0.65$ ,  $p = 0.02$ ,  $n = 10$ ; Table 1) when all years of

data were included in the analyses. The relationship weakened yet remained significant ( $r^2 = 0.56$ ,  $p = 0.09$ ,  $n = 6$ ; Table 1) when only post-regulation years were included in the stepwise regression analysis. Mean lake levels of the growing season in photo capture year (LVLB; Table 1) explained most of the variation in open water area. The optimal pre-regulation relationship was not statistically significant ( $R^2 = 0.75$ ,  $p = 0.14$ ,  $n = 4$ ; Table 1) when only pre-regulation lag year (LVLA) data was included in stepwise regression analyses for Hardman Lake.

Grand Marais open water area had a strong statistically significant relationship ( $r^2 = 0.87$ ,  $p = 0.08$ ,  $n = 7$ ; Table 1) to Lake Winnipeg levels when all years of data were used. Two growing seasons of mean Lake Winnipeg levels explained 87% of the variation in open water area when the entire study time period was analyzed. This relationship weakened slightly when only post-regulation years were included in the stepwise regression analysis ( $r^2 = 0.70$ ,  $p = 0.08$ ,  $n = 5$ ; Table 1). The pre-regulation relationship could not be tested for Grand Marais due to the lack of open water area data prior to 1976 ( $n = 2$ ).

Hillside Beach open water area was strongly and significantly related ( $r^2 = 0.85$ ,  $p = 0.01$ ,  $n = 8$ ; Table 1) to Lake Winnipeg levels when all years of data were included in the stepwise regression analysis. Two growing seasons of mean Lake Winnipeg levels accounted for 85% of the variation in Hillside Beach open water area. The relationship was statistically insignificant when only post-regulation years were included in the Hillside Beach stepwise regression analysis ( $r^2 = 0.86$ ,  $p = 0.14$ ,  $n = 5$ ; Table 1). The pre-regulation relationship could not be tested for Hillside Beach due to the lack of open water area data prior to 1976 ( $n = 3$ ).

**Table 1.** Summarized  $r^2$ , p-value, and n of stepwise multiple regression analyses of open water areas (m<sup>2</sup>) and mean May-Oct Lake Winnipeg wind smoothed levels (metres above sea level). Stepwise multiple regression equations of the optimal models are also included. Overall = entire period of study (1915 – 2015); pre-reg = pre-regulation period of lake levels (1915-1976); post-reg = post-regulation period of lake levels (1976-2015). LVLA = lag year mean May-Oct Lake Winnipeg levels (m asl); LVLB = photo capture year mean May-Oct Lake Winnipeg levels (m asl).

|              |             | Optimal Model |        |    |                                                                                |
|--------------|-------------|---------------|--------|----|--------------------------------------------------------------------------------|
| Site         | Time Period | $r^2$         | p      | n  | Regression Equation                                                            |
| Balsam       | Overall     | 0.64          | 0.01   | 12 | Area= -5.38e <sup>8</sup> +1.30e <sup>6</sup> (LVLA)+1.19e <sup>6</sup> (LVLB) |
|              | Pre-reg     | 0.74          | 0.13   | 6  | Area= -6.36e <sup>8</sup> +1.35e <sup>6</sup> (LVLA)+1.59e <sup>6</sup> (LVLB) |
|              | Post-reg    | 0.72          | 0.03   | 6  | Area= -4.27e <sup>8</sup> +1.97e <sup>6</sup> (LVLA)                           |
| Folster      | Overall     | 0.56          | 0.02   | 13 | Area= -1.45e <sup>9</sup> +3.56e <sup>6</sup> (LVLA)+3.15e <sup>6</sup> (LVLB) |
|              | Pre-reg     | 1.0           | 0.05   | 4  | Area= -2.20e <sup>9</sup> +6.02e <sup>6</sup> (LVLA)+4.15 <sup>6</sup> (LVLB)  |
|              | Post-reg    | 0.39          | 0.07   | 9  | Area= -7.21e <sup>8</sup> +3.35e <sup>6</sup> (LVLA)                           |
| Grand Marais | Overall     | 0.87          | 0.08   | 7  | Area= 3.64e <sup>10</sup> +7.71e <sup>5</sup> (LVLA*LVLB)                      |
|              | Pre-reg     | x             | x      | 2  |                                                                                |
|              | Post-reg    | 0.70          | 0.08   | 5  | Area= -1.04e <sup>8</sup> +4.89e <sup>5</sup> (LVLA)                           |
| Hardman      | Overall     | 0.65          | 0.02   | 10 | Area= -9.89e <sup>8</sup> +1.87e <sup>6</sup> (LVLA)+2.70e <sup>6</sup> (LVLB) |
|              | Pre-reg     | 0.75          | 0.14   | 4  | Area= -9.04e <sup>8</sup> +4.18e <sup>6</sup> (LVLA)                           |
|              | Post-reg    | 0.56          | 0.09   | 6  | Area= -5.76e <sup>8</sup> +2.67e <sup>6</sup> (LVLB)                           |
| Hillside     | Overall     | 0.85          | 0.01   | 8  | Area= -7.89e <sup>7</sup> +5.10e <sup>5</sup> (LVLA)-1.42e <sup>5</sup> (LVLB) |
|              | Pre-reg     | x             | x      | 3  |                                                                                |
|              | Post-reg    | 0.86          | 0.14   | 5  | Area= -6.68e <sup>7</sup> +4.81e <sup>5</sup> (LVLA)-1.68e <sup>5</sup> (LVLB) |
| Willow       | Overall     | 0.95          | < 0.05 | 10 | Area= -3.73e <sup>10</sup> +7.88e <sup>5</sup> (LVLA*LVLB)                     |
|              | Pre-reg     | 0.99          | 0.14   | 5  | Area= 2.51e <sup>10</sup> +5.32e <sup>5</sup> (LVLA*LVLB)                      |
|              | Post-reg    | 0.89          | 0.02   | 5  | Area= -4.88e <sup>7</sup> +2.43e <sup>5</sup> (LVLB)                           |

### 3.5 Autocorrelation and Hurst Re-scaled Range Analysis of Lake Winnipeg levels

Results of the temporal autocorrelation and Hurst re-scaled range analyses showed there had been a decrease in the occurrence of water level trends from the pre- to post-regulation time periods. Over the course of the entire time series, there have been switches in the autocorrelation trends from positive (above zero) to negative (below zero) and vice versa. Positive autocorrelation values indicate a positive relationship with the dataset and itself. For example, in Figure 49 there is a positive autocorrelation value that is greater than 0.6 at a lag of one. In this dataset this means that water level values one year apart are over 0.6 correlated, meaning that water level values are moderately similar to one another up to one year apart. Negative autocorrelation values indicate a negative relationship with the dataset and itself. For example, in Figure 49 there is a significant negative autocorrelation value that is lower than -0.2 at a lag of thirty-five. In this dataset this means that water level values thirty-five years apart are under -0.2 correlated, meaning that water level values thirty-five years apart are dissimilar to one another. As previously stated in section 2.9, aquatic systems with no long-term trends in water levels may form a very chaotic habitat where many emergent vegetation species may not be able to thrive. Low water level trends lasting three to four years long might allow for a greater emergent vegetation recruitment and a more robust and perhaps diverse emergent vegetation community to become established.

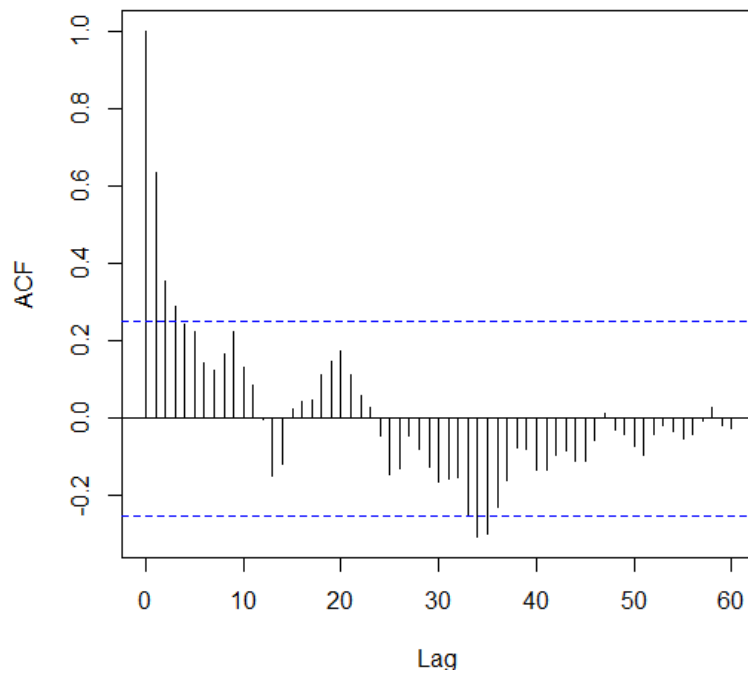
From the pre-regulation correlogram (Figure 49) the strongest positive relationship between water levels are when they are separated by a period of only one year. Water level autocorrelation values were significant ( $p < 0.05$ ) up to three to four years apart, indicating that 3-4 year long trends in Lake Winnipeg water levels existed prior to regulation. At the 25-30 year lag mark there is a significant switch from positive to negative autocorrelations, meaning that at

25-30 years there was a switching of water level trends from high water levels to low water levels or vice versa.

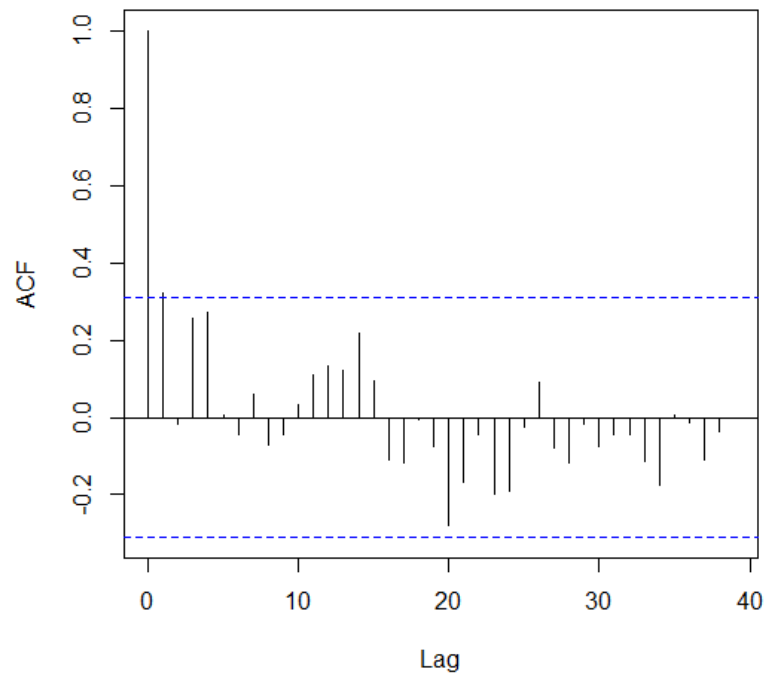
Regulated Lake Winnipeg levels are more predictable in the sense that they will most likely fall within the operating range, but there is still 1.2 metres of fluctuation between the minimum and maximum operating range values. In post-regulation years, positive and negative autocorrelations switched more frequently and insignificantly, with shortened water level trends persisting only up to one year, meaning that post-regulation Lake Winnipeg had shorter and less predictable trends in its water levels than in pre-regulation years (Figure 50). Positive autocorrelation for a lag period of one year was also much stronger in pre-regulation years with a value of  $r = 0.62$  ( $p = < 0.05$ ) while post-regulation autocorrelation was only  $r = 0.26$  ( $p = < 0.05$ ) meaning that short term water level trends are also weaker in post regulation years (Figures 49 and 50).

Pre-regulation mean open water season (May-October) wind-smoothed water levels had a Hurst exponent of  $H = 0.70$  while post regulation years had a lower value of  $H = 0.62$ . The Hurst exponent of the entire time period (1915-2015) was  $H = 0.68$ . A higher Hurst exponent in pre-regulation years further confirms the autocorrelation results that persistence in long-term Lake Winnipeg water level trends was higher in pre-regulation years.

**Figure 49.** Autocorrelation profile (correlogram) for pre-regulation (1915-1975) mean May-October Lake Winnipeg water levels. The x axis is the number of years (lag) in the time series and the y axis is correlation. Dotted lines denote the 95% confidence interval.



**Figure 50.** Autocorrelation profile (correlogram) for post-regulation (1976-2015) mean May-October Lake Winnipeg water levels. The x axis is the number of years (lag) in the time series and the y axis is correlation. Dotted lines denote the 95% confidence interval.



## 4 DISCUSSION/CONCLUSIONS

This section discusses the thesis objectives and summarizes the significance of results presented in Chapter 3.

### 4.1 Objective 1

**Quantify, describe, and compare variations in the open water area, and thus emergent vegetation cover, of two large coastal marshes within the Netley-Libau Marsh complex and four other large coastal wetlands around the south basin of Lake Winnipeg to assess whether emergent vegetation extent changes within Netley-Libau Marsh are also reflected in other Lake Winnipeg coastal marshes. A similar expansion of open water areas in marshes outside of the Netley-Libau Marsh complex would indicate that marsh habitat degradation is linked to Lake Winnipeg hydrology. A dissimilar expansion of open water areas in marshes outside of the Netley-Libau Marsh complex would indicate that marsh habitat degradation is linked to Red River hydrology.**

The open water area measurements make clear that the hydrology of the six coastal marshes in this study is influenced strongly by the hydrology of Lake Winnipeg. The smallest sizes in open water area tended to occur during periods of low Lake Winnipeg levels and the largest measurements of open water area were typically obtained during periods of high Lake Winnipeg levels. Noted also in Watchorn's (2015) 1990-2013 change through time analyses of Netley-Libau Marsh, the expansion of open water area during 1929-2015 has not been a steady progression through time in my selected study marshes, but instead these changes typically occurred in response to extreme high and low Lake Winnipeg water levels. This is in agreement with Watchorn's (2015) 1990-2013 findings that the significant relationship between Lake Winnipeg levels and marsh open water area was influenced the most by especially high or low

water levels. In all six study marshes, 1915-2015 average May-October mean Lake Winnipeg water levels explained the majority (56-95%) of the open water area variation. Chow-Fraser (2005) observed a similar hydrological relationship between Lake Ontario water levels and percent cover of emergent vegetation in Cootes Paradise Marsh, where mean May-September water levels explained close to 90% of the variation in emergent vegetation cover. Due to the almost perfect ( $r = 0.99$ ) negative correlation between Netley-Libau Marsh open water area and emergent vegetation area found by Watchorn (2015), I can assume with reasonable confidence that, as Lake Winnipeg water levels increase within its managed range, water levels increase in the coastal marshes, causing emergent vegetation to diminish in abundance and spatial extent due to drowning. The most optimal stepwise regression between marsh open water area and overall Lake Winnipeg water levels were when image capture year and the previous year growing seasons of mean water levels were included, meaning that from a marsh management standpoint, water level drawdowns for at least two growing seasons would account for a greater vegetation growth response. This is similar to the results obtained by Nilsson and Keddy (1988) when trying to predict changes in diversity and percent cover of shoreline vegetation in a hydroelectric reservoir, as length of flooding time in the preceding year accounted for most of the variation in abundance of shoreline vegetation.

Between 1934 and 2015, Folster and Hardman lakes showed the largest variations in open water areas out of all six study sites. None of the other study marshes have undergone changes in open water areal extent to the same magnitude as those within Netley-Libau Marsh and the Balsam Bay marsh, which are the three most southerly study marshes. However, out of the six study marshes, May-October mean seasonal Lake Winnipeg levels accounted for the least amount of this variation in open water area at the Folster Lake, Hardman Lake, and Balsam Bay

study sites (Folster = 56%, Hardman = 65%, and Balsam = 64%). Both Hardman and Folster lakes are located within Netley-Libau Marsh and are the only ones that could potentially be affected by Red River connectivity. However, stepwise regression results indicated no causal relationship between Folster and Hardman open water areas versus Red River discharge. The most variation in open water areas explained by Lake Winnipeg levels occurred at the most northerly marshes (Hillside Beach = 85%, Grand Marais = 87%, and Willow Point = 95%) that had the lowest overall variation in open water areas. Variation in open water area also did not change drastically in these marshes before and after regulation began, resulting in a stronger relationship with Lake Winnipeg levels overall. Presently, it is unclear why the most northerly coastal marshes exhibit such a low amount of variation over the entire study time period as compared to the southerly Netley-Libau and Balsam Bay marshes, although some potential factors are discussed through the following speculations.

A factor that may be at play in the response of emergent vegetation to water levels is the differing orientations of surface water connections and locations of the six study marshes to Lake Winnipeg. The Netley-Libau and Balsam Bay marshes are connected to Lake Winnipeg by channels oriented facing in the direction of prevailing northwest winds. The lake-marsh surface water connection at Willow Point is oriented southeast which would help shelter it from the prevailing winds coming from the northwest and associated wave action. At Hillside Beach, the most northerly site, the lake-marsh connection is in a bay oriented in a more westerly direction that would shelter it from the prevailing northwest winds and subsequent erosion caused by wind setup of Lake Winnipeg and the scouring effect of waves. Grand Marais is also one of the more northerly sites, with a lake-marsh surface water connection oriented in a northern direction. These three marshes showed the least amount of variation suggesting marsh latitude and lake

connection orientation may be variables in the amount of erosion and emergent plant cover growth, perhaps relating to relative susceptibility of marsh shorelines to wind-driven shoreline erosion.

Wind tides (seiches) are a common occurrence on Lake Winnipeg and can occur within a matter of hours if there is a strong, sustained, typically north or northwest wind. These seiches often cause Lake Winnipeg water to be pushed towards the south end of the lake by the prevailing winds coming from the north/northwest direction, resulting in water level fluctuations exceeding one metre (Einarsson and Lowe 1968). Areal extent of emergent vegetation in wetlands on the south shore of Lake Winnipeg might decrease due to the higher water levels at the south end of the south basin caused by seiches and the associated erosion by wave action. The possible effect of seiches on the areal extent of open water area is largely dismissed in Watchorn's (2015) 1990-2013 analysis of Netley-Libau Marsh because there existed a stronger relationship between seasonal lake levels and open water area as opposed to daily lake levels and open water area. The significance of the scouring effect of wave action during these wind setups should not be understated, however, as my fieldwork photographs of shoreline erosion would suggest that as mudflats and shorelines are washed out this would cause a loss of suitable habitat for establishment of emergent plants. We see this wind-driven shoreline erosion on the south shores within the Netley-Libau Marsh complex, causing abrupt changes in depth along the shoreline and having led to the undermining of large tree root systems. (Figure 51).

**Figure 51.** Wind driven erosion along the southern edge of Folster Lake open water area has caused scouring of the shoreline and many large trees to fall over. Pictures taken during field work conducted on October 17, 2015.



All of the coastal marshes in this study have had their surrounding catchment areas settled by people for a similar length of time, harkening back to the late 19<sup>th</sup> and early 20<sup>th</sup> centuries so, in theory, the timing of human development would not explain the differences in emergent vegetation area variation between these sites. However, differences in the amount and proximity of human development at each site are evident when aerial photographs of these areas are examined. Roads, dykes, and other anthropogenic developments have formed boundaries constraining the study marshes located outside of Netley-Libau Marsh complex (Figures 6-12). This marsh vegetation containment by anthropogenic development is further exacerbated by the

steeper elevation gradients inland from the Willow Point, Grand Marais, and Hillside Beach marshes (Natural Resources Canada 2017). When water levels are high, these developments are barriers which prevent flooding of soils farther inland, essentially preventing hydrophilic marsh vegetation communities from advancing landwards during periods of high Lake Winnipeg levels. This phenomenon is suggested by aerial images of the Balsam Bay marsh in 1929 and 2003 (Figure 20), which were both years of lower than average (1913-2015) water levels. This marsh progressed landwards steadily up to the end of the 20<sup>th</sup> century where it was halted by an old railway right-of-way on the east side of the marsh. Changes in elevation within the catchment areas of Lake Winnipeg coastal marshes are typically less than one metre (Natural Resources Canada 2017) so altering the topography of the area even slightly via human development could radically alter the natural hydrology of these marshes. Fewer human developments in and around the Netley-Libau Marsh complex compared to the other four study marshes would allow for shoreline emergent vegetation extent to respond to fluctuations in lake water level elevations, colonizing landward areas when water levels are high and extending lakeward when water levels are low. In the other four marshes, water movement and emergent vegetation encroachment would be more constrained, causing any expansion of open water area or emergent vegetation area to be small. Anthropogenic pressure as measured by human population size accounted for an additional 4.2% of the variation in Cootes Paradise Marsh emergent vegetation areal extent when the effects of high water levels and urbanization were isolated from one another (Wei & Chow-Fraser 2005). A similar analysis could be conducted in all the marshes selected for my study to quantify any possible effects of human development on emergent vegetation areal extent (Chapter 6).

My finding that Lake Winnipeg levels accounted for less open water area variation at Folster Lake (56%) than Hardman Lake (65%) may be due to the differing bathymetries of these two marshes. Bathymetric data collected in September 2010 across the entire Netley-Libau Marsh (Aquatics Environmental Services Inc. 2011) revealed that the bottom of Folster Lake is at a lower elevation (at or below 216.79 m asl) from that of nearby Hardman Lake (between 216.80 and 217.09 m asl). Thus, Folster Lake sediments and emergent vegetation seedbank would be about 0.30 metres deeper than those of Hardman Lake. This would result in fewer exposed mudflats and shallow water edge area to be colonized by emergent vegetation in Folster Lake when water levels are low, meaning that the emergent vegetation growth response to lower lake levels would be to a lesser degree than that of Hardman Lake. Water surface elevations would have to be sustained below a threshold elevation of a minimum of 217.00 m asl during the emergent vegetation growing season to allow for mudflats and shallow water areas to be colonized. Since the 1950s, mean May-October Lake Winnipeg water levels have reached levels below 217.00 m asl only once, in 1977, when Hardman Lake reached its second-lowest open water area. In 2003, Lake Winnipeg levels were at 217.02 m asl which was also the year Folster Lake was at its second-lowest and Hardman at its third-lowest open water area. The years 1977 and 2003 were important in demonstrating that lowered water levels will trigger a marked germination and growth response by emergent marsh vegetation. Not only did low water levels in 2002 and drought levels in 2003 trigger immediate vegetation growth, Watchorn (2015) found that some of those emergent vegetation stands were able to persist up to ten years after 2003 despite water levels being higher than average during that decade. The non-linear relationship between water levels and percent cover of emergent vegetation observed in Cootes Paradise Marsh by Chow-Fraser (2005) suggested that a threshold water depth also existed in that marsh.

Water level elevations above 74.40 m asl resulted in far smaller emergent vegetation cover than when water levels were lower than 74.40 m asl (Chow-Fraser 2005). Within Netley-Libau marshes, the threshold water level elevation would be approximately 217.00 m asl as this is the level at which regrowth and persistence of emergent vegetation was triggered in 1977 and 2003. Possible management implications of this finding are discussed in Chapter 6.

## 4.2 Objective 2

**Estimate the total volume of water flowing over time into the Netley-Libau Marsh from the Red River via the Netley Cut in order to test for any relationship between changes in Netley-Libau open water areal extent and Red River connectivity.**

Due to the lack of actual flow, level, and depth measurements other than those made in 2009 and 2014, obtaining accurate estimates of Netley Cut discharge over the past 50 years is challenging. As 2009 and 2014 were not particularly high or low flow years for the Red River, calculated Netley Cut discharges are overestimated in very low flow years and underestimated in very high flow years. I suggest a combination of the modified broad-crested side weir model and average flow percentage method to estimate Netley Cut discharge until consistent flow monitoring takes place (Chapter 6). The modified broad-crested side weir model takes into account the changing dimensions of the Netley Cut channel through time. Using this model, Netley Cut discharges can be estimated using Red River discharge and water surface elevation values that fall within the minimum ( $509 \text{ m}^3/\text{s}$ ) and maximum ( $1266 \text{ m}^3/\text{s}$ ) measured values from 2009 and 2014 (Clark unpublished data). Once Red River discharges and levels fall below  $509 \text{ m}^3/\text{s}$  or exceed  $1266 \text{ m}^3/\text{s}$ , it is necessary to multiply these discharge measurements by 0.37 (37%) to obtain estimates of Netley Cut discharges. By combining these two Netley Cut discharge calculation methods, the changing dimensions of the Cut are considered while also limiting overestimated discharge values when Red River flow exceeds the actual measurement range used to construct the broad-crested side weir model. However, neither of these two methods can account for the effect that wind setup has on the flow of the Red River. Strong, sustained wind setup from Lake Winnipeg can push water to the south end of Lake Winnipeg causing a backup of water discharging from the Red River. This causes a temporary slowing or

even a reversal of flow through the Netley Cut, meaning that water would be discharging through the Netley Cut from the marsh to the Red River (Clark. 2014 unpublished data). Consequently, the development of future discharge models should take into account wind speed and direction in conjunction with Red River and Netley Cut discharge measurements (Chapter 6).

Archived aerial photographs show that the loss of emergent vegetation in Netley Lake began prior to the Netley Cut reopening in the late 1960s and the start Lake Winnipeg level regulation in 1976, implying that macrophyte decline may have multiple, interacting causes. During the period between 1929 and 1970, the Netley Cut remained closed, yet erosion of islands and shorelines and a loss of emergent vegetation was marked (Figures 30-35). This erosion and vegetation loss occurred even though there was no direct connection between south Netley Lake and the Red River during this time, with the exception of flooding in 1950. It is interesting to note that, despite major flooding in 1950 which overtopped virtually all shorelines in the Netley-Libau Marsh, the Netley Cut was able to reclose after this year, yet another less-devastating flood in 1970 caused the Netley Cut to reopen and remain open. There are two possible reasons for the Netley Cut remaining open after 1970 rather than reclosing as it did after the 1950 flood. First, shorelines may have been weakened during the 1950 flood and were therefore more likely to be affected by a future erosive event. Second, there has been a greater duration of high water levels since 1970 that contribute to greater erosion potential. The longer lake levels are sustained high, the more erosion caused to shorelines. In the five years prior to 1970, average Lake Winnipeg levels were 0.43 metres higher than in the five years before 1950. Then, in the five years after 1970, average levels were 0.17 metres higher than they were in the five years after 1950.

For the most part, Red River discharges tended not to cause an expansion of open water areas in Hardman and Folster lakes, except in the years with extreme flooding. Given that the amount of open water area variation in study marshes located within Netley-Libau Marsh was not reflected in all other marshes located outside of the marsh complex, it is clear that Lake Winnipeg levels are not impacting all of the six study marshes to the same degree.

Unsurprisingly, the marshes located outside of Netley-Libau Marsh complex had no relationship with Red River discharge via the Netley Cut. Curiously, neither of the two marshes within the Netley-Libau complex had a statistically detectable relationship between open water area variation and estimated Netley Cut discharges, nor with average spring Red River flows. Most notably Hardman Lake, which is directly connected to the Red River, showed no statistical relationship. This finding agrees with Watchorn's (2015) analyses for the period 1990-2013, in which she did not find significant correlations between Red River discharges/spring freshet and changes to open water area. This suggests that Red River connectivity is not a factor affecting emergent vegetation growth in the Hardman or Folster lakes of Netley-Libau Marsh, except possibly during times of extremely low or high river flows. Both Hardman and Folster lakes experienced smallest open water areas in 1934 when mean seasonal Red River flow was well below average (-86%). A large peak in Hardman and Folster open water area expansion took place in 1970 when mean seasonal Lake Winnipeg levels (+100%) and Red River flow (+202%) were higher than average. The 1970 aerial photo of the Netley Cut (Figure 36) shows that this was also the year the Cut was first observed to be open since its closure in the 1920s. This suggests that emergent vegetation within the Netley-Libau Marsh complex responds to extremely low and extremely high Red River flows in conjunction with Lake Winnipeg levels. However, these observations do not explain why the degree of variation in open water size in the Balsam

Bay marsh with no Red River influence were comparable to variation seen in Netley-Libau marshes. What I may be detecting is the strong relationship between mean seasonal Red River flows and Lake Winnipeg levels ( $r = 0.62$ ,  $p\text{-value} < 0.05$ ). If Red River flow is higher than average then Lake Winnipeg levels are likely higher than average and vice versa.

Although it was outside the scope of my study, qualitative observations of shoreline erosion and loss of emergent vegetation cover from aerial and satellite images suggests that the connection of the Red River to Netley-Libau Marsh via the Netley Cut has had detrimental effects on the area of the marsh called Netley Lake, namely in the form of the erosion of mud banks and islands in this area. Given that Hardman and Folster emergent vegetation seemed to respond to extreme changes in Red River flows, it would make sense that vegetation and shorelines within Netley Lake would also have a similar response. Watchorn et al (2015) found that extreme highs and lows in peak spring Red River flows heavily influenced non-vegetated/disturbed area (i.e., non-vegetated mudflats), causing a downward trend in these areas with increasing river flows. Qualitative analyses of Netley Lake aerial/satellite images in conjunction with historical Red River flow and Lake Winnipeg levels also imply some relationship to Lake Winnipeg levels and Red River discharge. In 1977 and 2003 where there were large expanses of exposed mud banks and islands in Netley Lake, the mean May-October Lake Winnipeg levels were 216.89 and 217.02 m asl respectively. Mean April-June Red River flows were unusually low in 1977 but not in 2003. This means that the influence of Lake Winnipeg water levels may overpower the influence of Red River flows except in the most extreme Red River flood years.

The trend of increasing Red River flows that has characterized the latter part of the 20<sup>th</sup> and early 21<sup>st</sup> centuries, observed by McCullough (2015) and supported by increasing mean April-

June Red River flow data from my study, is expected to continue due to increasing precipitation and landscape drainage in the watershed. Through a study conducted by Bayley & Guimond (2009) on riverine marshes in Jasper National Park, AB, Canada, river connection was shown to increase plant biomass during years of relatively normal flows by providing an influx of nutrients and sediments. However, in years of extreme flooding, disturbance has been found to reduce plant biomass (Bayley & Guimond 2009). The frequency of disastrous floods will likely increase with projected rising precipitation and runoff trends within the Red River Basin (McCullough 2015) which, in turn, will negatively impact emergent vegetation growth within the Netley-Libau Marsh if no changes are made to current watershed management practices (Chapter 6).

### **4.3 Objective 3**

**Examine historical Lake Winnipeg water levels as a possible factor affecting erosion and emergent vegetation cover in the Netley-Libau Marsh and four other coastal marshes around the south basin of Lake Winnipeg. Compare statistical relationships and trends in open water area and thus emergent vegetation cover gains and losses in the six study marshes in the years before Lake Winnipeg level stabilization (regulation) began (1915-1975) to the years after regulation stabilization came into effect (1976-2015) in order to assess whether marsh ecosystem degradation has been greater since regulation began.**

Weaker post-regulation Lake Winnipeg level versus open water area relationships, reduced open water area variations, and the breakdown in water level trends indicates that hydrological changes to the Lake Winnipeg system has played a role in the changes seen in the marsh emergent vegetation extent over time. Vegetation extent in five out of the six marshes was less variable over time in the post-1975 years, relative to pre-1976 years, indicating that Lake Winnipeg water level fluctuations needed for vegetation reestablishment in its coastal marshes

have decreased. However, it is important to note that the decrease in open water variation from pre-regulation to post-regulation time periods found in the Folster, Hardman, and Balsam study sites in comparison to the other three marshes is largely due to these marshes having aerial photos dating back much earlier and from the very low water period of the 1920s to the 1930s.

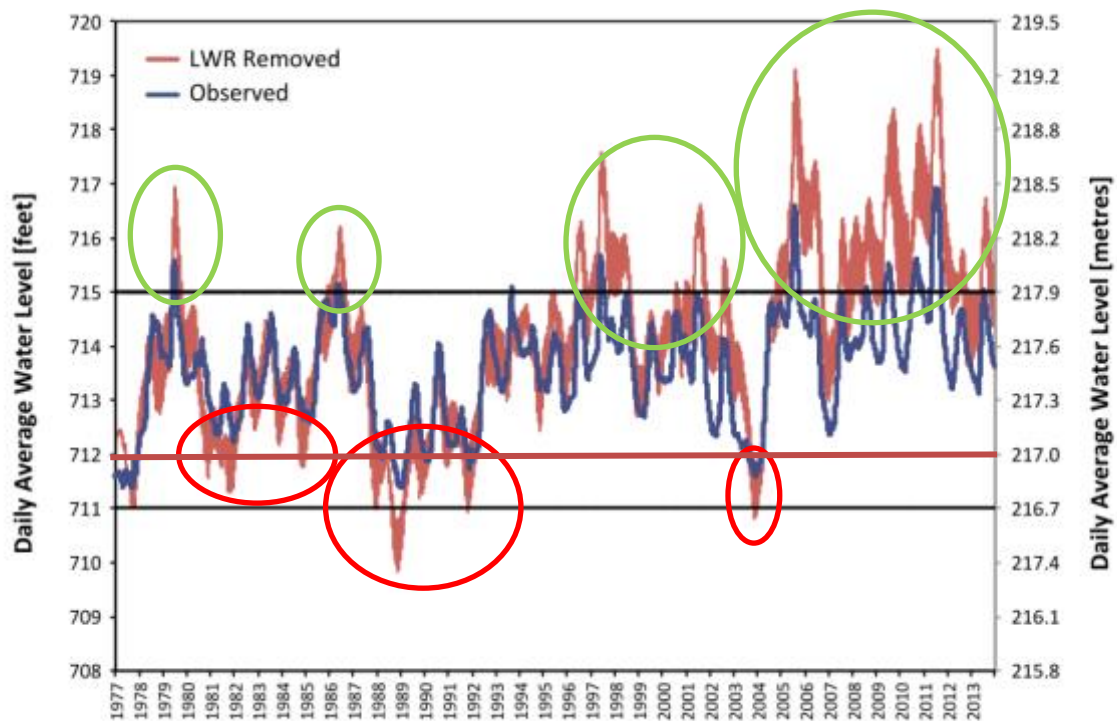
Comparisons of the pre- and post-regulation Lake Winnipeg level relationship to that of open water areal extent in all six study marshes were conflicting. The strong relationships between Lake Winnipeg levels and open water area at Willow Point, Grand Marais, and Hillside Beach over the entire 1915-2015 time period, coupled with their low variations in open water areas, indicate that gradual degradation of these coastal marshes began before Lake Winnipeg stabilization came into effect in 1976. The three marshes that have open water area measurements dating back to the 1920s and 1930s (Balsam Bay, Folster Lake, and Hardman Lake) had open water area change rates more dramatic in non-level regulated years (1915-1975) relative to regulated level years (1976-2015). Low water conditions can instigate emergent vegetative growth and recruitment from the seed bank in one to two growing seasons as seen in Netley-Libau Marsh in 2003 (Grosshans et al. 2004) but drowning of flood resistant emergent vegetation roots can be a longer process, requiring sustained periods of high water levels to cause a full die off of the emergent vegetation in a particular area. In a controlled field experiment at Delta Marsh, MB it took five years for emergent vegetation to die-off to a point where open water area expanded to cover 40-44% of the study cells in flooding treatments 0.30-0.60 metres above the control treatments of natural water levels (van der Valk et al. 1994). Rapid emergent vegetation growth at Netley-Libau Marsh in dry 2003, followed by the continuity of some emergent vegetation stands up until 2013 (Watchorn 2015), demonstrates that the growth response of vegetation to low water levels is more rapid compared to vegetation drowning in

response to high water. Stands of vegetation from 2003 persisted in the ten years after, despite the fact that average water levels were 0.62-1.24 metres asl higher than the 2003 average (217.02 metres asl). The 1920s-1940s represents a period, long before regulation, of low water levels as well as long term trends in water levels in which emergent vegetation recruitment and growth would have been rapid. The wetter decades of the 1950s, 1960s, and early 1970s, just prior to regulation, would limit the germination of emergent vegetation seeds and eventually drown out mature vegetation and so result in a slower rate of change. During the first half of the study period (1915-1965) there were 32 below average ( $< 217.59$  m asl) Lake Winnipeg mean seasonal levels as opposed to 13 below average seasons between 1966 and 2015. Since the commencement of regulation in 1976 coincided with a wetter time period, it is most likely that increasing mean May-October Lake Winnipeg levels is undermining the comparison of post-regulation years open water areal coverage with that of pre-regulation years. This may partly explain why half of the study marshes (Hardman, Folster, and Balsam) had higher rates of change in the years prior to regulation, as usable aerial photographs of Willow Point, Grand Marais, and Hillside Beach were not available prior to the 1940s.

It is evident that it is not just Netley-Libau Marsh that has experienced ecological degradation among Lake Winnipeg coastal marshes. All of the coastal marshes selected for this study seem to be in a shallow lake state with fewer gains in emergent vegetation areal extent as low water periods become less frequent. Continued trends of high tributary flows into Lake Winnipeg (McCullough (2015), further supported by increasing April-June Red River flows of this study, show that there has been an increase in precipitation and drainage in the Lake Winnipeg watershed since the latter years of the 20<sup>th</sup> century. Extreme flood events can drown out emergent vegetation and erode colonizable shoreline areas in the Netley-Libau Marsh as well

as other coastal marshes connected to Lake Winnipeg (Section 4.2). If increasing tributary inputs causes the frequency and amplitude of these disastrous flood pulses to also increase, it will become difficult to keep Lake Winnipeg levels below the upper regulation operating limit of 217.9 metres above sea level. This, in turn, would further drive the loss of vegetation as permanently flooded areas become too anoxic to support the growth of vegetation in coastal marshes. A graph of estimated Lake Winnipeg levels with the effects of regulation removed (Figure 52) demonstrates that low water periods will become less frequent, especially with Lake Winnipeg regulation limiting how low natural water levels could be, as was the case in the 1980s, early 1990s, as well as in 2003. However, because of the higher water levels observed in the early 21<sup>st</sup> century, Lake Winnipeg regulation has also limited the severity of flooding events by increasing outlet discharges (Figure 52).

**Figure 52.** Lake Winnipeg observed water levels under regulation and estimated water levels if Lake Winnipeg was left unregulated between 1977 and 2014 (CEC 2015, Figure 7.2). Red circles indicate specific time periods when Lake Winnipeg regulation kept water levels higher than they otherwise would have been. Green circles indicate specific time periods when Lake Winnipeg regulation kept water levels lower than they otherwise would have been. (Observed = observed water levels; LWR Removed = simulated unregulated water levels). Regulation removed water levels were estimated by comparing calculated Lake Winnipeg inflows to natural outflow prior to water level regulation, creating a water balance model that would determine water level rise or fall. This model was then applied to post-regulation year's inflows and outflows (CEC 2015).



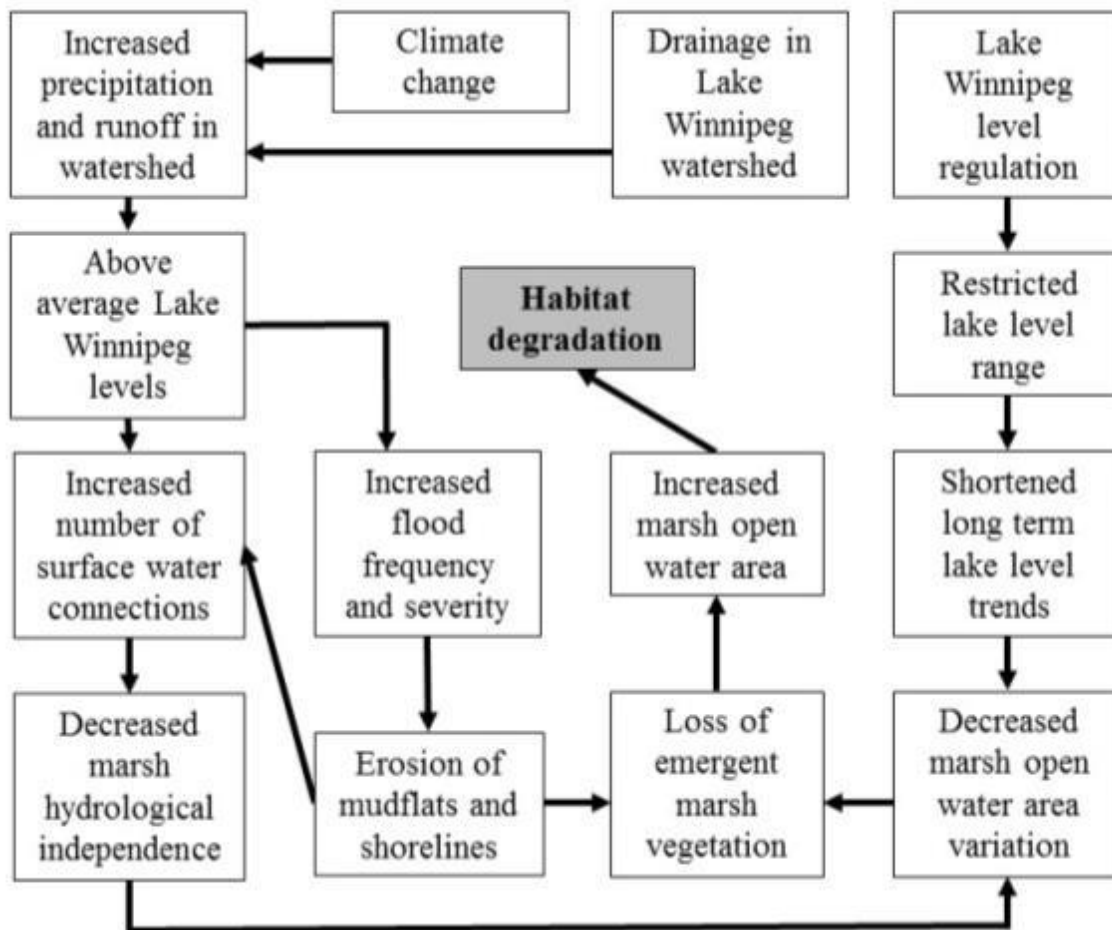
## 5 Summary

Mean May-October Lake Winnipeg levels explained the most variation in open water area in the three study sites located farthest north: Hillside Beach (85%), Grand Marais (87%), and Willow Point (95%). Mean May-October Lake Winnipeg levels explained the least amount of open water variation in the three study sites located farthest south: Netley-Libau marshes Folster (56%) and Hardman lakes (65%) and the Balsam Bay marsh (64%). During the 1915-2015 study period, Hardman and Folster lakes within Netley-Libau Marsh as well as the Balsam Bay marsh showed fourteen times greater variation in open water areal extent than Hillside Beach, Grand Marias, and Willow Point. Much of this variation took place between below average and above average water level periods. Open water areal extent fluctuations decreased (thus so did emergent vegetation area) after Lake Winnipeg level stabilization in all study marshes, with the exception of Hillside Beach. Red River flow and calculated Netley Cut discharge estimates did not significantly account for any of the open water area variation in Hardman and Folster lakes. This means that other unconsidered variables such as wind set up, marsh orientation/positioning, and anthropogenic development may explain some of the open water variation and the differences in variation between study sites.

A conceptual model summarizes the climactic and hydrological factors leading to habitat degradation in Lake Winnipeg coastal marshes, including those marshes located within the Netley-Libau Marsh complex (Figure 53). Habitat degradation in the form of open water area expansion began prior to the Netley Cut reopening and Lake Winnipeg regulation at all study sites, most likely owing to disastrous flooding events of 1950 and 1970. These 1950 and 1970 flooding events were driven by the especially wet conditions and increased runoff in the Lake Winnipeg watershed during the late-twentieth century due to climate change and widespread

landscape drainage. Increases in precipitation and runoff in the Lake Winnipeg watershed will further drive above average Lake Winnipeg levels, causing increasingly frequent and severe flooding in coastal areas of Lake Winnipeg. Flooding exacerbates the erosion of colonizable mudflats and shorelines within coastal marshes, directly leading to the loss of emergent marsh vegetation which in turn increases open expanses of water devoid of vegetation and habitat complexity. Above-average Lake Winnipeg levels and erosion of shorelines from flooding increases the number of surface water connections between coastal marshes and Lake Winnipeg. This reduces marsh hydrological independence from the lake which further contributes to reduced open water areal extent variations and ultimately losses in emergent vegetation, expansion of open water areas, and marsh habitat degradation. Although Lake Winnipeg level regulation may not be the primary driver of habitat degradation in coastal marshes, it is exacerbating it by restricting the range of Lake Winnipeg water levels and so to the range of variation of open water area in coastal marshes. This limits the duration and number of low water periods after flooding events when emergent vegetation could make gains in extent through establishment of seedlings and further vegetative growth, further contributing to loss of habitat complexity and ultimately habitat degradation of Lake Winnipeg coastal freshwater marshes. The aforementioned factors must be considered as working in concert in order to make informed and effective decisions in potential coastal marsh restoration and management efforts.

**Figure 53.** A conceptual model of the climatic and hydrological forces driving the increased open water area and degradation of vegetation and wildlife habitat in Lake Winnipeg's freshwater coastal marshes.



## **6 Recommendations**

### **6.1 Recommendations for Future Research**

1. Investigate flood and storm impacts on the Netley-Libau Marsh ecosystem compared to other coastal marshes in various locations connected to Lake Winnipeg using historical records of strength, duration, and direction of prevailing winds during storms/strong winds and flooding events. Further investigation into wave-induced erosion of shorelines in coastal marshes should be undertaken to better quantify the response of major flood pulses on island erosion and shoreline vegetation loss.
2. Install flow-tracking devices at the Netley Cut and the three outlets of the Red River to Lake Winnipeg to provide a more complete record of the amount and direction of water discharging through the Netley Cut and Red River mouths. Such data can then be used to model future Netley Cut discharges in conjunction with meteorological data (wind speed and direction precipitation, etc.). If any future dredging of the Red River mouth is planned in the hopes to alleviate flooding upstream, it would be valuable to compare discharges before and after such work commences to measure how much Red River flow backup is actually alleviated by such dredging and whether discharge through the Netley Cut is affected by dredging downstream as well.
3. Examine seedbank composition in marsh sediment samples obtained in various near shore/shallow water areas of each coastal marsh of this study to track historical changes in vegetation community assemblages. Examining coastal marsh land cover changes over time is extremely useful in measuring the amount of habitat available to flora and fauna as is the case in this thesis; but this thesis work cannot account for some changes in the emergent community that have also occurred.

4. Compare land cover changes over time in coastal marshes connected to the north and south basins of Lake Winnipeg to determine if the degradation seen in south basin coastal marshes is occurring in the north basin of Lake Winnipeg as well. As my findings in this thesis show that change in open water area is greatest in the most southerly marshes (Folster, Hardman, and Balsam), I would expect coastal marshes in the north basin to have undergone less overall expansion in open water area than marshes in the south basin.
5. Quantify the percent of open water area variation, and thus emergent vegetation variation, which is explained by human development in all six of my selected study marshes by using stepwise regression analyses of open water areal extent measurements, Lake Winnipeg water levels, and human population data or areal extent of human-made developments and their proximity to the study marshes.
6. Identify shorelines that separate distinct bays and ponds of the Netley-Libau Marsh complex that may be presently or at future risk of erosion.

## **6.2 Recommendations for Management**

1. To promote emergent vegetation growth in Lake Winnipeg coastal marshes, there must be periodic water level drawdowns to below 217.00 metres above sea level, which is within Manitoba Hydro's operating range for Lake Winnipeg levels. Although regulation is not the main driver of marsh degradation, it could be part of the solution to restoration of not only Netley-Libau Marsh but the other degraded marshes connected to it. Similar circumstances have led to changes in water regulation in the Great Lakes to address concerns over aquatic ecosystem health. The International Joint Commission adopted a new regulation plan for the St. Lawrence River and Lake Ontario in 2016 to address the flooding and shoreline erosion concerns of the public as well as improve coastal wetland

habitat. With hydrological changes brought on from climate change and increasing human developments in the Lake Winnipeg watershed, there is a need to adapt our water management practices that allow for at least two growing seasons of water levels below 217.00 m asl to allow gains in emergent vegetation extent.

2. Deposit sediment into Netley-Libau Marsh bays such as Hardman Lake and Folster Lake to raise the marsh bottom and artificially construct mudflats that would be colonized by emergent vegetation either via the existing seedbank or manual seeding. Efforts at constructing artificial mudflats should be concentrated in areas of bays that have bottoms sediments at or above 217.00 m asl. The bottom sediment elevation of 217.00 m asl has been selected as this is also the water surface elevation that has triggered emergent vegetation growth in low water years in the past such as in 1977 and 2003. Qualitative examination of the historical aerial images used in this study could help identify what areas of these bays would likely provide sheltered habitat for the growth and hopefully ongoing persistence of emergent vegetation.
3. Stabilize and reinforce shorelines and islands in Lake Winnipeg coastal marshes to prevent continued erosion and prevent increased connectivity to other water bodies. One such area that this could be applied to first would be the shoreline on either side of the eroding Netley Cut. Although it is likely not possible to entirely rebuild the shoreline that once separated Netley Lake from the Red River, efforts should be undertaken to ensure this connection does not erode even wider in the future.

## 7 REFERENCES

- Albert, D.A. and Minc, L.D. 2004. Plants as regional indicators of Great Lakes coastal wetland health. *Aquatic Ecosystem Health & Management* 7(2): 233-247 pp.
- Albert, D.A., Wilcox, D.A., and Thompson, T.A. 2005. Hydrogeomorphic classification for Great Lakes coastal wetlands. *J. Great Lakes Res.* 31 (Supplement 1):129–146
- Aquatics Environmental Services Inc. 2011. Bathymetry of lakes in the Netley-Libau Marsh. St. Andrews, Manitoba. Raw data collected in 2010.
- Bailey, K.M., Bedford, B.L. 2003. Transient geomorphic control of water table and hydraulic head reversals in a coastal freshwater peatland. *Wetlands* 23(4): 969-978 pp.
- Baird W.F. & Associates Coastal Engineers Ltd. 2000. Review of Lake Winnipeg water level reporting procedures. Prepared for the Lake Winnipeg Shoreline Erosion Advisory Group. 1-85 pp. Retrieved December 4, 2015 from [https://www.gov.mb.ca/waterstewardship/licensing/pdf/review\\_lake\\_wpg\\_reporting\\_procedures.pdf](https://www.gov.mb.ca/waterstewardship/licensing/pdf/review_lake_wpg_reporting_procedures.pdf)
- Baldwin, A.H., Egnatovich, M.S., and Clarke, E. 2001. Hydrologic change and vegetation of tidal freshwater marshes: field, greenhouse, and seed-bank experiments. *Wetlands* 21(4): 519-531 pp.
- Batzer D., Boix D. 2016. An introduction to freshwater wetlands and their invertebrates. In: Batzer D., Boix D. (eds) *Invertebrates in Freshwater Wetlands*. Springer, Cham.
- Batzer, D.P. and Sharitz, R.R. 2006. *Ecology of freshwater and estuarine wetlands*. Berkley and Los Angeles, CA: University of California Press, Ltd.
- Bayley, A.E. and Guimond, J.K. 2009. Aboveground biomass and nutrient limitation in relation to river connectivity in montane floodplain marshes. *Wetlands* 29(4): 1243-1254 pp.

- Boers, A.M. and Zedler, J.B. 2008. Stabilized water levels and *Typha* invasiveness. *Wetlands* 28(3): 676–685 pp.
- Chapin, D.M. and Paige, D.K. 2013. Response of delta vegetation to water level changes in a regulated mountain lake, Washington State, USA. *Wetlands* 33(3): 431-444 pp.
- Clark, S.P. 2014. Physical and hydrological characteristics of Netley-Libau Marsh. Netley-Libau Marsh Workshop PowerPoint presentation. Obtained through personal communication.
- Link to workshop proceedings:  
<http://www.lakewinnipegfoundation.org/sites/default/files/Netley-Libau%20Marsh%20Workshop%202014%20Final%20Report.%20web.version.pdf>
- Canada Map Sales. 1934. Plan of special survey: townships 15 and 16. Acquired from Manitoba Sustainable Development. Land Information Division.
- Clean Environment Commission. 2015. Lake Winnipeg regulation report. Lake Winnipeg Regulation Hearing. 187pp.
- Deegan, B.M., White, S.D., and Ganf, G.G. 2007. The influence of water level fluctuations on the growth of four emergent macrophyte species. *Aquatic Botany* 86(4): 309-315 pp.
- DigitalGlobe. 2015. WorldView 3 scene 15AUG17174552-M2AS-054197380020\_01\_P001 and Multispectral\_15AUG17174539-M2AS-054197380020\_01\_P002. University of Manitoba, Elizabeth Dafoe Library. Unpublished data. August 17, 2015
- DigitalGlobe. 2009. Quickbird 2 scene 052192603010\_01\_P001 and 052192603010\_01\_P002. DigitalGlobe. Longmont, Colorado. August 20, 2009.
- Einarsson, E. and Lowe, A. B. 1968. Seiches and set up on Lake Winnipeg. *Limnology and Oceanography* 13(2): 257-271 pp.

Environment Canada, Manitoba Water Stewardship. 2011. State of Lake Winnipeg: 1999-2007.

Retrieved July 1, 2015 from

[http://www.gov.mb.ca/waterstewardship/water\\_quality/state\\_lk\\_winnipeg\\_report/pdf/state\\_of\\_lake\\_winnipeg\\_rpt\\_technical\\_low\\_resolution.pdf](http://www.gov.mb.ca/waterstewardship/water_quality/state_lk_winnipeg_report/pdf/state_of_lake_winnipeg_rpt_technical_low_resolution.pdf)

Farell, J.M., Murry, B.A., Leopold, D.J., Halpern, A., Rippke, M.B., Godwin, K.S., Hafner, S.D. 2010. *Hydrobiologia* 647(1): 127-144 pp.

Gottgens, J. F., Swartz, B. P., Kroll, R. W., and Eboch, M. 1998. Long-term GIS-based records of habitat changes in a Lake Erie coastal marsh. *Wetlands Ecology and Management* 6: 5–17 pp.

Halsey, L., Vitt, D., Zoltai, S. 1997. Climatic and physiographic controls on wetland type and distribution in Manitoba, Canada. *Wetlands* 17: 243–262 pp.

Grosshans, R.E. 2001. Long-term vegetation dynamics following water level stabilization in a prairie marsh. Thesis submitted to the University of Manitoba, Winnipeg, MB, Canada. Retrieved August 29, 2016 from <http://hdl.handle.net/1993/2610>.

Grosshans, R. E., Venema, H. D., and Osborne, B. 2012. Advancing Netley-Libau Marsh restoration efforts: cattail biomass and nutrient survey of Netley-Libau Marsh. International Institute for Sustainable Development report. 37pp.

Grosshans, R. E., Wrubleski, D. A. and Goldsborough, L. G. 2004. Changes in the emergent plant community of Netley-Libau Marsh between 1979 and 2001. Delta Marsh Field Station (University of Manitoba) Occasional Publication No. 4, Winnipeg, MB, Canada. 52 pp.

Hudon, C. 1997. Impact of water level fluctuations on St. Lawrence River aquatic vegetation. *Can. J. Fish. Aquat. Sci.* 54: 2853-2865 pp.

- Hudon, C. 2004. Shift in wetland plant composition and biomass following low-level episodes in the St. Lawrence River: looking into the future. *Can. J. Fish. Aquat. Sci.* 63: 603-617 pp.
- Hudon, C., Gagnon, P., Amyot, J.P., Letourneau, G., Jean, M., Plante, C., Rioux, D., Deschenes. Historical changes in herbaceous wetland distribution induced by hydrological conditions in Lake Saint-Pierre (St. Lawrence River, Quebec, Canada). *Hydrobiologia*. 539: 205-224 pp.
- Keddy, P.A. and Fraser, L. H. 2000. Four general principles for the management and conservation of wetlands in large lakes: The role of water levels, nutrients, competitive hierarchies and centrifugal organization. *Lakes & Reservoirs: Research and Management* 2000 (5): 177–185
- Keddy, P.A. and Reznicek, A. A. 1986. Great lakes vegetation dynamics: the role of fluctuating water levels and buried seeds. *J. Great Lakes Res.* 12(1):25-36. 36pp.
- Kenkal, N.C. 1995. Environmental persistence and the structure/composition of northern prairie marshes. *Delta Marsh, University Field Station Annual Report*, 30: 93-98pp.
- Keough, J., Thompson, T., Guntenspergen, G., and Wilcox, D. 1999. Hydrogeomorphic factors and ecosystem responses in coastal wetlands of the Great Lakes. *Wetlands*. 19(4): 821-834pp.
- Kowalski, K.P. and Wilcox, D. A. 1999. Use of historical and geospatial data to guide the restoration of a Lake Erie coastal marsh. *Wetlands*. 19(4): 858-868 pp.
- Krieger, K.A. 2003. Effectiveness of a coastal wetland in reducing pollution of a Laurentian great lake: hydrology, sediment, and nutrients. *Wetlands*. 23(4): 778-791 pp.

- Leahy, M.G., Jollineau, M.L., Howarth, P.J., Gillespie, A.R. 2005. The use of Landsat data for investigating the long-term trends in wetland change at Long Point, Ontario. Can. J. Remote Sensing. 31(3): 240-254 pp.
- Lindgren, C.J. and the Netley Libau Marsh Foundation Inc. 2001. Netley-Libau Marsh Important Bird Area Community Conservation Plan. Prepared for the Canadian Nature Federation, Bird Studies Canada, Bird Life International and the Manitoba Naturalists Society. Winnipeg, Manitoba. 50 pp.
- Lyon, J.G., Aff. M. ASCE, and Drobney, R.D. 1984. Lake level effects as measured from aerial photos. J. Surv. Eng. 110(2): 103-111 pp.
- Manitoba Hydro. 2014. A document in support of Manitoba Hydro's request for a final license under the Manitoba Water Power Act. Retrieved April 28, 2018 from [https://www.hydro.mb.ca/regulatory\\_affairs/pdf/lake\\_wpg\\_regulation/lwr\\_complete\\_report.pdf](https://www.hydro.mb.ca/regulatory_affairs/pdf/lake_wpg_regulation/lwr_complete_report.pdf)
- Manitoba Land Initiative. 2010. Digital orthophotos [img\_070142\_rgb\_1.0m\_blk\_160\_sid\_mosaic.sid and img\_070142\_rgb\_1.0m\_blk\_170\_sid\_mosaic.sid]. Retrieved May 8, 2015 from [http://mli2.gov.mb.ca/ortho/index\\_ortho\\_refresh\\_all.html](http://mli2.gov.mb.ca/ortho/index_ortho_refresh_all.html)
- McCullough, G.K. 2015. Climate in the Lake Winnipeg watershed and the level of Lake Winnipeg. Prepared for the Manitoba Clean Environment Commission. Retrieved November 3, 2015 from <http://www.cecmanitoba.ca/resource/hearings/33/Climate%20in%20the%20Lake%20Winnipeg%20Watershed,%20McCullough%202015.pdf>

- Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being: wetlands and water synthesis. World Resources Institute, Washington, DC.
- Mitsch, W. J., Gosselink, J. G. 2007. Wetlands - 4<sup>th</sup> ed. Hoboken, NJ: John Wiley & Sons, Inc.
- Mitsch, W. J., Gosselink, J. G., Anderson, C. J., Zhang, L. 2009. Wetland Ecosystems. Hoboken, NJ: John Wiley & Sons, Inc.
- Mitsch, W.J. and Wang, N. 2000. Large-scale coastal wetland restoration on the Laurentian Great Lakes: Determining the potential for water quality improvement. *Ecological Engineering*. 15(3-4): 267-282 pp.
- Murkin, H.R., Murkin, E.J, and Ball, J.P. 1997. Avian habitat selection and prairie wetland dynamics: a 10-year experiment. *Ecological Applications*. 7(4): 1144-1159 pp.
- NASA Landsat Program. 2016. Landsat TM scene LT50310252011202PAC01. USGS, Sioux Falls. 2011/07/14. Retrieved January 23, 2017 from <https://earthexplorer.usgs.gov/>.
- NASA Landsat Program. 2016. Landsat TM scene LT50310252011234PAC01. USGS, Sioux Falls. 2011/08/22. Retrieved January 23, 2017 from <https://earthexplorer.usgs.gov/>
- National Wetlands Working Group (NWWG). 1988. Canada Committee on Ecological Land Classification. Wetlands of Canada. Ecological Land Classification Series, No. 24, Environment Canada, Ottawa, ON.
- Natural Resources Canada. 2017. Canadian digital elevation model [GeoTif cdem\_062I]. Retrieved January 15, 2018 from [http://ftp.geogratis.gc.ca/pub/nrcan\\_rncan/elevation/cdem\\_mnec/062/ on](http://ftp.geogratis.gc.ca/pub/nrcan_rncan/elevation/cdem_mnec/062/ on)
- Nielsen, E. 1998. Lake Winnipeg coastal submergence over the last three centuries. *Journal of Paleolimnology*. 19: 335–342 pp.

- Nilsson, C., and Keddy, P.A. 1988. Predictability of change in shoreline vegetation in a hydroelectric reservoir, northern Sweden. *Can. J. Fish. Aquat. Sci.* 45: 1896-1904 pp.
- Public Works Canada Canada. 1907. Petition to A. R. Du Fresne, Resident Engineer, Public Works Canada, Winnipeg, dated 31 July 1907, from group at Selkirk. Public Works Canada file at Library and Archives Winnipeg. Accession W84-85/493 Box 26 “Netley, Man”
- Public Works Canada. 1915. Federal Annual Departmental Reports. Elizabeth Dafoe Library, University of Manitoba.
- Public Works Canada. 1925. Memo from F. G. Goodspeed (District Engineer, Department of Public Works) to K. M. Cameron (Chief Engineer, Department of Public Works) November 5<sup>th</sup>, 1925. Public Works Canada file at Library and Archives Winnipeg. Accession W84-85/493 Box 26 “Netley, Man”
- Public Works Canada. 1923. Blueprints of sheet pile wall constructed to close the Netley Cut in 1923 – 1924. Public Works Canada file at Library and Archives Winnipeg. Accession W84-85/493 Box 26 “Netley, Man”
- Shay, J.M., de Guess, P.M.J., and Kapinga, M.R.M. 1999. Changes in shoreline vegetation over a 50-year period in the Delta Marsh, Manitoba in response to water levels. *Wetlands*. 19(2): 413-425 pp.
- Tiner, R.W. 2017. Wetland indicators: a guide to wetland formation, identification, delineation, classification, and mapping. Boca Raton, FL: Taylor & Francis Group.
- Trebitz, A.S., Morrice, J.A., and Cotter, A.M. 2002. Relative role of lake and tributary in hydrology of Lake Superior coastal wetlands. *J. Great Lakes Res.* 28(2):212–227 pp.

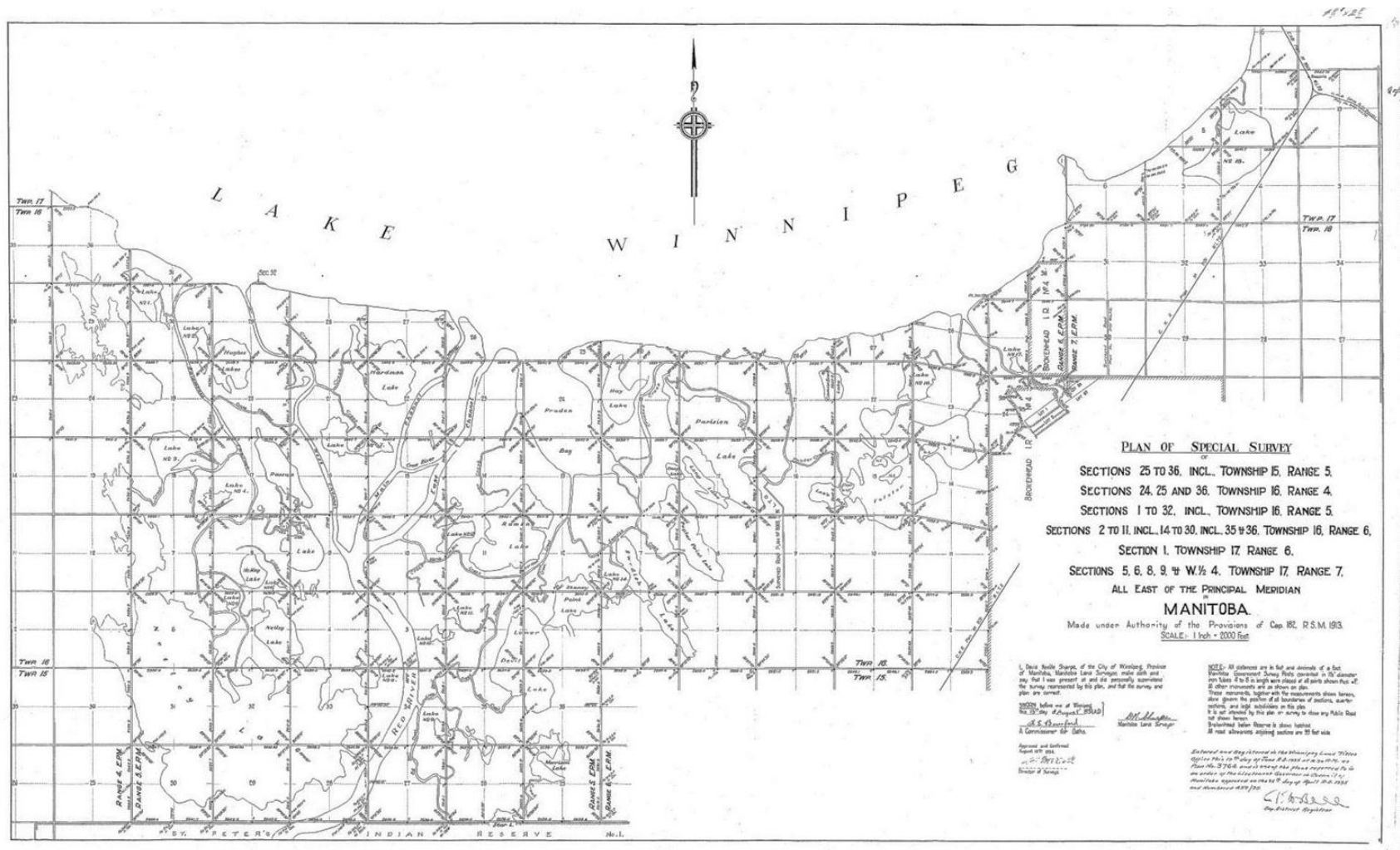
- Trebitz, A.S., Morrice, J.A., Taylor, D.L. Anderson, R.L., West, C.W., and Kelly, J.R. 2005. Hydromorphic determinants of aquatic habitat variability in Lake Superior coastal wetlands. *Wetlands*: 25(3): 505-519 pp.
- van der Valk, A.G. and Davis, C.B. 1978. The role of seed banks in the vegetation dynamics of prairie glacial marshes. *Ecology*, 59: 322-335pp.
- van der Valk, A.G., Squires, L., and Welling, C.H. 1994. Assessing the impacts of an increase in water level on wetland vegetation. *Ecological Applications*, 4(3): 525-534pp.
- Verbiwski, B.N. 1986. Netley-Libau Marshes Resource Development and Management Proposal. Manitoba Dept. Natural Resources, Wildlife Branch.
- Wassenaar, L.I. and Rao, Y.R. 2012. Lake Winnipeg: the forgotten lake. *J. of Great Lakes Res.* 38: 1-5 pp.
- Water Survey of Canada. Data extracted from the Environment and Climate Change Canada Historical Hydrometric Data web site. Retrieved August 2015 from [https://wateroffice.ec.gc.ca/mainmenu/historical\\_data\\_index\\_e.html](https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html)
- Watchorn, E. 2014. An analysis of digital wetland vegetation map coverages produced based on aerial photography and satellite imagery Netley-Libau Marsh 2001. Unpublished Report prepared for Environment and Climate Change Canada.
- Watchorn, E. 2015. Water and vegetation cover in Netley-Libau Marsh 1990-2013. Phase II Report: A time series analysis based on Landsat imagery. Unpublished report prepared for Environment and Climate Change Canada
- Watchorn, E., Goldsborough, L. G., Wrubleski, D. A., Mooney, B. G. 2012. A hydrogeomorphic inventory of coastal wetlands of the Manitoba Great Lakes: Lakes Winnipeg, Manitoba, and Winnipegosis. *J. of Great Lakes Res.* 38(3): 115-122pp.

- Weller, M. W. 1999. Wetland birds: habitat resources and conservation implications. Cambridge: Cambridge University Press.
- Wilcox, D.A., Apfelbaum, S.I., Hiebert, R.D. 1985. Cattail invasion of sedge meadows following hydrologic disturbance in the Cowles Bog wetland complex, Indiana Dunes National Lakeshore. *Wetlands*. 4: 115-128 pp.
- Wilcox, D.A, Kowalski, K.P., Hoare, H.L., Carlson, M.L., Morgan, H.N. 2008. Cattail invasion of sedge/grass meadows in Lake Ontario: photointerpretation analysis of sixteen wetlands over five decades. *J. Great Lakes Res.* 34: 301–323 pp.
- Wilcox, D.A. and Meeker, J.E. 1991. Disturbance effects on aquatic vegetation in regulated and unregulated lakes in northern Minnesota. *Can. J. Bot.* 69: 1542-1551 pp.
- Wilcox, D. and Nichols, S. 2008. The effects of water-level fluctuations on vegetation in a Lake Huron wetland. *Wetlands*. 28(2): 487-501 pp.
- Williams, D.C. and Lyon, J.G. 1997. Historical aerial photographs and a geographic information system (GIS) to determine effects of long-term water level fluctuations on wetlands along the St. Marys River, Michigan, USA. *Aquatic Botany* 58 (1997) 363-378 pp.

The image contains three technical drawings related to the Red River Cut project:

- PLAN OF LOCATION:** A map showing the Red River flowing through Winnipeg, Manitoba. Key features include Lake Winnipeg, Lake Assiniboine, Lake St. Charles, and the Red River. The cut is located near the intersection of the Red River and the Assiniboine River. The map includes a scale of 1/2 inch = 1 mile and a north arrow.
- DETAIL PLAN OF LOCATION:** A detailed plan view of the cut area. It shows the "OLD DREDGE ASSINIBOINE #201" and the "SHEET PILE DAM" constructed in 1916-17. The plan includes soundings, a scale of 40 feet = 1 inch, and a north arrow.
- PROFILE OF CUT:** A cross-sectional view of the cut. It shows the "HEAVY HATCHED LINE, BOTTOM OF CUT" and the "DOTTED LINE, JULY 1922". The profile includes a scale of 20 feet = 1 inch vertically and 40 feet = 1 inch horizontally.

Appendix B Manitoba Land Survey map of the Netley-Libau Marsh and the Balsam Bay marsh area completed in 1934 (Canada Map Sales 1934).



Appendix C: Open water area measurements (metres<sup>2</sup>) of six freshwater coastal marshes connected to the south basin of Lake Winnipeg (1929-2015).

| Study Site          | Date of image capture | Area of open water (m <sup>2</sup> ) |
|---------------------|-----------------------|--------------------------------------|
| <b>Balsam Bay</b>   | Sept 13 1929          | 2689990                              |
|                     | 1934 (no month date)  | 1689340                              |
|                     | Aug 25 1955           | 4136512                              |
|                     | Oct 20 1957           | 3964043                              |
|                     | Aug15 1965            | 3990309                              |
|                     | Aug 23 1970           | 5059464                              |
|                     | Aug 6 1976            | 4558669                              |
|                     | Sept 7 1986           | 3325102                              |
|                     | Sept 11 1993          | 2832868                              |
|                     | Aug 16 2003           | 2593939                              |
|                     | Oct 5 2010            | 3188477                              |
|                     | Aug 22 2011           | 2816108                              |
| <b>Folster Lake</b> | 1934 (no month date)  | 4528180                              |
|                     | Aug 15 1965           | 10026501                             |
|                     | July 25 1968          | 11883640                             |
|                     | July 24 1970          | 16158940                             |
|                     | Aug 6 1976            | 12311907                             |
|                     | Aug 1 1979            | 7279661                              |
|                     | Aug 9 1989            | 7072399                              |
|                     | Sept 11 1993          | 7411340                              |
|                     | Aug 3 2001            | 11085487                             |
|                     | Aug 16 2003           | 6891916                              |
|                     | Aug 20 2009           | 7892511                              |
|                     | Aug 22 2011           | 7167296                              |
| <b>Grand Marais</b> | Aug15 2015            | 8944403                              |
|                     | Sept 11 1948          | 2532507                              |
|                     | Aug 8 1970            | 2951101                              |
|                     | Aug 6 1976            | 2876296                              |
|                     | Sept 18 1993          | 2491774                              |
|                     | Aug 16 2003           | 2436270                              |
|                     | Oct 4 2010            | 2707627                              |
| <b>Hardman Lake</b> | Aug 22 2011           | 2444415                              |
|                     | 1934 (no month date)  | 2038666                              |

| Study Site            | Date of image capture | Area of open water (m <sup>2</sup> ) |
|-----------------------|-----------------------|--------------------------------------|
| <b>Hardman Lake</b>   | Aug 15 1965           | 7055974                              |
|                       | July 25 1968          | 6970730                              |
|                       | July 25 1970          | 8353587                              |
|                       | July 12 1977          | 2735738                              |
|                       | Aug 3 2001            | 7909847                              |
|                       | Aug 16 2003           | 4776137                              |
|                       | Aug 20, 2009          | 5351379                              |
|                       | Aug 22 2011           | 5377126                              |
|                       | Aug 15 2015           | 5998968                              |
| <b>Hillside Beach</b> | Aug 25 1955           | 1437743                              |
|                       | Aug 8 1970            | 1547006                              |
|                       | Aug 11 1973           | 1523159                              |
|                       | Aug 6 1976            | 1612113                              |
|                       | Sept 11 1993          | 1265210                              |
|                       | Aug 16 2003           | 1334574                              |
|                       | Sept 7 2009           | 1409122                              |
|                       | July 14 2011          | 1300481                              |
| <b>Willow Point</b>   | Sept 1 1950           | 3980112                              |
|                       | Aug 4 1952            | 4060474                              |
|                       | Aug 3 1961            | 3810577                              |
|                       | Aug 8 1970            | 4613813                              |
|                       | Aug 8 1973            | 4081458                              |
|                       | July 12 1977          | 3893515                              |
|                       | Sept 18 1993          | 3979547                              |
|                       | Aug 16 2003           | 3868837                              |
|                       | Sept 7 2009           | 4162859                              |
|                       | Aug 22 2011           | 4081888                              |

Appendix D: List of all acquired aerial and satellite images (1923-2015) with date of image acquisition as well as roll number, photo ID, and image scale if applicable.

| <b>Location</b>   | <b>Date</b>       | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b> | <b>Comments</b>             |
|-------------------|-------------------|------------------------|----------------------------|--------------|-----------------------------|
| <b>Balsam Bay</b> | Sept. 13,<br>1929 | A1964                  | 83                         | 1:15000      | Mosaicked together          |
|                   | Sept. 13,<br>1929 | A1964                  | 85                         | 1:15000      |                             |
|                   | Sept. 13,<br>1929 | A1964                  | 94                         | 1:15000      |                             |
|                   | 1934              |                        |                            |              | Manitoba Land<br>Survey map |
|                   | May 1,<br>1946    | A9686                  | 45                         | 1:20000      | Mosaicked<br>together.      |
|                   | May 1,<br>1946    | A9686                  | 46                         | 1:20000      |                             |
|                   | Aug. 25,<br>1955  | A14862                 | 44                         | 1:20000      | Mosaicked together          |
|                   | Aug. 25,<br>1955  | A14862                 | 45                         | 1:20000      |                             |
|                   | Oct.20,<br>1957   | A15918                 | 17                         | 1:40000      |                             |

| <b>Location</b>   | <b>Date</b>        | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>    |
|-------------------|--------------------|------------------------|----------------------------|------------------|--------------------|
| <b>Balsam Bay</b> | Aug. 15,<br>1965   | A18983                 | 55                         | 1:35000          |                    |
|                   | Aug. 23,<br>1970   | A21932                 | 20                         | not<br>available | Mosaicked together |
|                   | Aug. 23,<br>1970   | A21932                 | 21                         | not<br>available |                    |
|                   | May 21,<br>1972    | A22665                 | 121                        | 1:80000          |                    |
|                   | Aug. 6,<br>1976    | A24541                 | 9                          | 1:50000          |                    |
|                   | Sept. 7,<br>1986   | A27017                 | 58                         | not<br>available |                    |
|                   | April. 28,<br>1987 | MB87001                | 70                         | not<br>available |                    |
|                   | June 15,<br>1989   | A27454                 | 7                          | 1:50000          |                    |
|                   | Sept. 11,<br>1993  | MH9357042<br>6         | 161                        | not<br>available | Mosaicked together |
|                   | Sept. 11,<br>1993  | MH9357042<br>6         | 162                        | not<br>available |                    |

| <b>Location</b>         | <b>Date</b>        | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>                                                                                                      |
|-------------------------|--------------------|------------------------|----------------------------|------------------|----------------------------------------------------------------------------------------------------------------------|
| <b>Balsam Bay</b>       | May 26,<br>1994    | A28069                 | 26                         | 1:60000          |                                                                                                                      |
|                         | June 16,<br>1997   | MB97034                | 92                         | not<br>available |                                                                                                                      |
|                         | August 16,<br>2003 |                        |                            | not<br>available | Goldsborough 2003<br>unpublished data.                                                                               |
|                         | October 5,<br>2010 |                        |                            |                  | OrthoRefresh<br>imagery                                                                                              |
|                         | August 22,<br>2011 |                        |                            |                  | Landsat satellite<br>imagery                                                                                         |
| <b>Folster<br/>Lake</b> | Sept. 13,<br>1929  | A1963                  | 27                         | 1:15000          | Could not<br>georeference and<br>mosaic together<br>accurately due to<br>lack of GCPs Use<br>as supplemental<br>data |
|                         | Sept. 13,<br>1929  | A1963                  | 28                         | 1:15000          |                                                                                                                      |
|                         | Sept. 13,<br>1929  | A1963                  | 30                         | 1:15000          |                                                                                                                      |
|                         | Sept. 13,<br>1929  | A1963                  | 50                         | 1:15000          |                                                                                                                      |
|                         | Sept. 13,<br>1929  | A1963                  | 52                         | 1:15000          |                                                                                                                      |

| Location                | Date              | Roll<br>Number | Photo ID<br>Number | Scale   | Comments                                                                       |
|-------------------------|-------------------|----------------|--------------------|---------|--------------------------------------------------------------------------------|
| <b>Folster<br/>Lake</b> | Sept. 13,<br>1929 | A1963          | 53                 | 1:15000 |                                                                                |
|                         | Sept. 13,<br>1929 | A1963          | 32                 | 1:15000 |                                                                                |
|                         | 1934              |                |                    |         | Manitoba Land<br>Survey map                                                    |
|                         | May 1,<br>1946    | A9693          | 10                 | 1:20000 | Entire study site<br>covered by these<br>images but taken on<br>different days |
|                         | May 1,<br>1946    | A9693          | 11                 | 1:20000 |                                                                                |
|                         | May 1,<br>1946    | A9693          | 12                 | 1:20000 |                                                                                |
|                         | May 7,<br>1946    | A9693          | 95                 | 1:20000 |                                                                                |
|                         | May 7,<br>1946    | A9693          | 96                 | 1:20000 |                                                                                |
|                         | May 7,<br>1946    | A9693          | 97                 | 1:20000 |                                                                                |
|                         | June 14,<br>1963  | A17982         | 54                 | 1:25000 | Mosaicked<br>together.                                                         |

| <b>Location</b>         | <b>Date</b>      | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>        |
|-------------------------|------------------|------------------------|----------------------------|------------------|------------------------|
| <b>Folster<br/>Lake</b> | June 14,<br>1963 | A17982                 | 74                         | 1:25000          |                        |
|                         | Aug. 15,<br>1965 | A18983                 | 44                         | 1:35000          |                        |
|                         | May 11,<br>1968  | A20399                 | 108                        | 1:12000          | Mosaicked<br>together. |
|                         | May 11,<br>1968  | A20399                 | 109                        | 1:12000          |                        |
|                         | May 11,<br>1968  | A20399                 | 110                        | 1:12000          |                        |
|                         | May 11,<br>1968  | A20399                 | 50                         | 1:12000          |                        |
|                         | May 11,<br>1968  | A20399                 | 52                         | 1:12000          |                        |
|                         | May 11,<br>1968  | A20399                 | 54                         | 1:12000          |                        |
|                         | July 25,<br>1968 | A20663                 | 155                        | not<br>available |                        |
|                         | July 24,<br>1970 | A21742                 | 42                         | 1:80000          |                        |

| <b>Location</b>         | <b>Date</b>      | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>  | <b>Comments</b>                                                     |
|-------------------------|------------------|------------------------|----------------------------|---------------|---------------------------------------------------------------------|
| <b>Folster<br/>Lake</b> | Aug. 6,<br>1976  | A24541                 | 37                         | 1:50000       |                                                                     |
|                         | July 12,<br>1977 | A24700                 | 137                        | 1:50000       | Image does not capture entire study site. Use as supplemental data. |
|                         | Aug. 1,<br>1979  | A25227                 | 2                          | not available | Mosaicked together                                                  |
|                         | Aug. 1,<br>1979  | A25227                 | 4                          | not available |                                                                     |
|                         | Aug. 1,<br>1979  | A25227                 | 235                        | not available |                                                                     |
|                         | Aug. 1,<br>1979  | A25227                 | 237                        | not available |                                                                     |
|                         | May 7,<br>1987   | MB87003                | 152                        | not available |                                                                     |
|                         | June 15,<br>1989 | A27454                 | 5                          | 1:50000       |                                                                     |
|                         | Aug. 9,<br>1989  | MB89022                | 113                        | not available |                                                                     |

| <b>Location</b>         | <b>Date</b>        | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>                                                    |
|-------------------------|--------------------|------------------------|----------------------------|------------------|--------------------------------------------------------------------|
| <b>Folster<br/>Lake</b> | Sept. 11,<br>1993  | MH9357042<br>6         | 156                        | not<br>available | Mosaicked<br>together.                                             |
|                         | Sept. 11,<br>1993  | MH9357042<br>6         | 155                        | not<br>available |                                                                    |
|                         | May 26,<br>1994    | A28069                 | 28                         | 1:60000          |                                                                    |
|                         | August 3,<br>2001  |                        |                            | 1:10000          | Grosshans et al.<br>2004.                                          |
|                         | August 16,<br>2003 |                        |                            | not<br>available | Goldsborough 2003<br>unpublished data.                             |
|                         | August 20,<br>2009 |                        |                            |                  | Quickbird satellite<br>imagery                                     |
|                         | August 22,<br>2011 |                        |                            |                  | Landsat satellite<br>imagery                                       |
|                         | August 15,<br>2015 |                        |                            | not<br>available | University of<br>Manitoba.<br><br>WorldView-2<br>satellite imagery |
| <b>Grand<br/>Marais</b> | May 12,<br>1948    | A11333                 | 248                        | 1:35000          | Mosaicked together                                                 |

| <b>Location</b>         | <b>Date</b>       | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b> | <b>Comments</b>                                   |
|-------------------------|-------------------|------------------------|----------------------------|--------------|---------------------------------------------------|
| <b>Grand<br/>Marais</b> | May 12,<br>1948   | A11333                 | 250                        | 1:35000      |                                                   |
|                         | Sept. 11,<br>1948 | A11704                 | 256                        | 1:35000      | Part of study site is<br>not included in<br>image |
|                         | May 11,<br>1958   | A15955                 | 14                         | 1:40000      |                                                   |
|                         | May 21,<br>1968   | A20442                 | 29                         | 1:12000      | Mosaicked together                                |
|                         | May 21,<br>1968   | A20442                 | 30                         | 1:12000      |                                                   |
|                         | May 21,<br>1968   | A20442                 | 31                         | 1:12000      |                                                   |
|                         | May 21,<br>1968   | A20442                 | 33                         | 1:12000      |                                                   |
|                         | August 8,<br>1970 | A21815                 | 58                         | 1:80000      |                                                   |
|                         | May 21,<br>1972   | A22665                 | 68                         | 1:80000      |                                                   |
|                         | August 6,<br>1976 | A24541                 | 7                          | 1:50000      |                                                   |

| <b>Location</b>         | <b>Date</b>        | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>                        |
|-------------------------|--------------------|------------------------|----------------------------|------------------|----------------------------------------|
| <b>Grand<br/>Marais</b> | June 11,<br>1983   | A26263                 | 38                         | not<br>available | Mosaicked together                     |
|                         | June 11,<br>1983   | A26263                 | 39                         | not<br>available |                                        |
|                         | June 11,<br>1983   | A26263                 | 40                         | not<br>available |                                        |
|                         | May 12,<br>1990    | A27577                 | 25                         | 1:60000          |                                        |
|                         | Sept. 18,<br>1993  | MH9357042<br>7         | 107                        | not<br>available | Mosaicked together                     |
|                         | Sept. 18,<br>1993  | MH9357042<br>7         | 108                        | not<br>available |                                        |
|                         | June 16,<br>1997   | MB97034                | 95                         | not<br>available |                                        |
|                         | August 16,<br>2003 |                        |                            | not<br>available | Goldsborough 2003<br>unpublished data. |
|                         | October 4,<br>2010 |                        |                            |                  | OrthoRefresh<br>imagery                |
|                         | August 22,<br>2001 |                        |                            |                  | Landsat satellite<br>imagery           |

| <b>Location</b>         | <b>Date</b>       | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b> | <b>Comments</b>                                                                                      |
|-------------------------|-------------------|------------------------|----------------------------|--------------|------------------------------------------------------------------------------------------------------|
| <b>Hardman<br/>Lake</b> | Sept. 13,<br>1929 | A1963                  | 14                         | 1:15000      | Mosaicked together. Did not use because it only partially captures Hardman. Use as supplemental data |
|                         | Sept. 13,<br>1929 | A1963                  | 15                         | 1:15000      |                                                                                                      |
|                         | Sept. 13,<br>1929 | A1963                  | 17                         | 1:15000      |                                                                                                      |
|                         | Sept. 13,<br>1929 | A1963                  | 64                         | 1:15000      |                                                                                                      |
|                         | Sept. 13,<br>1929 | A1963                  | 66                         | 1:15000      |                                                                                                      |
|                         | April 8,<br>1950  | A12444                 | 26                         | 1:20000      | Did not use because they are partial and have ice or cloud cover                                     |
|                         | April 8,<br>1950  | A12444                 | 27                         | 1:20000      |                                                                                                      |
|                         | June 14,<br>1963  | A17982                 | 59                         | 1:25000      | Mosaicked together                                                                                   |
|                         | June 14,<br>1963  | A17982                 | 60                         | 1:25000      |                                                                                                      |
|                         | June 14,<br>1963  | A17982                 | 69                         | 1:25000      |                                                                                                      |

| <b>Location</b>         | <b>Date</b>      | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>        |
|-------------------------|------------------|------------------------|----------------------------|------------------|------------------------|
| <b>Hardman<br/>Lake</b> | Aug. 15,<br>1965 | A18983                 | 40                         | 1:35000          |                        |
|                         | May 11,<br>1968  | A20399                 | 11                         | 1:12000          | Mosaicked<br>together. |
|                         | May 11,<br>1968  | A20399                 | 12                         | 1:12000          |                        |
|                         | May 11,<br>1968  | A20399                 | 14                         | 1:12000          |                        |
|                         | May 11,<br>1968  | A20399                 | 64                         | 1:12000          |                        |
|                         | May 11,<br>1968  | A20399                 | 66                         | 1:12000          |                        |
|                         | May 11,<br>1968  | A20399                 | 97                         | 1:12000          |                        |
|                         | July 25,<br>1968 | A20663                 | 151                        | not<br>available |                        |
|                         | July 25,<br>1970 | A21742                 | 44                         | 1:80000          |                        |
|                         | May 21,<br>1972  | A22665                 | 135                        | 1:80000          | Mosaicked together     |

| <b>Location</b>         | <b>Date</b>       | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>                                                                |
|-------------------------|-------------------|------------------------|----------------------------|------------------|--------------------------------------------------------------------------------|
| <b>Hardman<br/>Lake</b> | May 21,<br>1972   | A22665                 | 126                        | 1:80000          |                                                                                |
|                         | July 12,<br>1977  | A24700                 | 134                        | 1:50000          |                                                                                |
|                         | July 28,<br>1979  | A25188                 | 90                         | not<br>available | Mosaicked<br>together. Study site<br>partially captured<br>and image is blurry |
|                         | July 28,<br>1979  | A25188                 | 92                         | not<br>available |                                                                                |
|                         | Apr. 28,<br>1987  | MB87001                | 107                        | not<br>available | Mosaicked<br>together.                                                         |
|                         | Apr. 28,<br>1987  | MB87001                | 154                        | not<br>available |                                                                                |
|                         | June 14,<br>1989  | A27451                 | 200                        | 1:50000          |                                                                                |
|                         | June 15,<br>1989  | A27454                 | 2                          | 1:50000          |                                                                                |
|                         | Sept. 11,<br>1993 | MH9357042<br>6         | 144                        | not<br>available | Only partially<br>captures study site                                          |
|                         | May 26,<br>1994   | A28069                 | 30                         | 1:60000          |                                                                                |

| <b>Location</b>           | <b>Date</b>          | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>                                                  |
|---------------------------|----------------------|------------------------|----------------------------|------------------|------------------------------------------------------------------|
| <b>Hardman<br/>Lake</b>   | August 3,<br>2001    |                        |                            | 1:10000          | Grosshans et al.<br><br>2004. Whole marsh<br>image               |
|                           | August 16,<br>2003   |                        |                            | not<br>available | Goldsborough 2003<br>unpublished data.                           |
|                           | September<br>7, 2009 |                        |                            |                  | Quickbird satellite<br>imagery                                   |
|                           | July 14,<br>2011     |                        |                            |                  | Landsat satellite<br>imagery                                     |
|                           | August 15,<br>2015   |                        |                            | not<br>available | University of<br>Manitoba.<br><br>WorldView-2<br>satellite image |
| <b>Hillside<br/>Beach</b> | Aug. 25,<br>1955     | A14862                 | 8                          | 1:20000          | Mosaicked together                                               |
|                           | Aug. 25,<br>1955     | A14862                 | 72                         | 1:20000          |                                                                  |
|                           | May 11,<br>1958      | A15955                 | 32                         | 1:40000          |                                                                  |
|                           | May 27,<br>1967      | A19952                 | 149                        | not<br>available | Mosaicked<br>together. Study site                                |

| <b>Location</b>           | <b>Date</b>        | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>                                     |
|---------------------------|--------------------|------------------------|----------------------------|------------------|-----------------------------------------------------|
| <b>Hillside<br/>Beach</b> | May 27,<br>1967    | A19952                 | 150                        | not<br>available | is partially<br>captured.                           |
|                           | Aug. 8,<br>1970    | A21815                 | 27                         | 1:80000          |                                                     |
|                           | May 21,<br>1972    | A22665                 | 51                         | 1:80000          |                                                     |
|                           | Aug. 6,<br>1973    | A24541                 | 4                          | not<br>available | Low contrast<br>between land and<br>water in image. |
|                           | Aug. 11,<br>1973   | A23570                 | 31                         | 1:25000          |                                                     |
|                           | June 11,<br>1983   | A26263                 | 72                         | not<br>available |                                                     |
|                           | May 12,<br>1990    | A27577                 | 99                         | 1:60000          |                                                     |
|                           | Sept. 11,<br>1993  | MH9357042<br>6         | 166                        | not<br>available |                                                     |
| <b>Hillside<br/>Beach</b> | August 16,<br>2003 |                        |                            | not<br>available | Grosshans et al.<br>2004.                           |

| <b>Location</b>         | <b>Date</b>      | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b> | <b>Comments</b>                                               |
|-------------------------|------------------|------------------------|----------------------------|--------------|---------------------------------------------------------------|
| <b>Willow<br/>Point</b> | May 24,<br>1949  | A11916                 | 162                        | 1:20000      | Mosaicked<br>together. Did not<br>use due to lack of<br>GCPs  |
|                         | May 24,<br>1949  | A11916                 | 54                         | 1:20000      |                                                               |
|                         | Sept. 1,<br>1950 | A12970                 | 232                        | 1:20000      | Mosaicked<br>together. Did not<br>use due to lack of<br>GCPs. |
|                         | Sept. 1,<br>1950 | A12970                 | 236                        | 1:20000      |                                                               |
|                         | Aug. 4,<br>1952  | A13508                 | 265                        | 1:20000      | Mosaicked together                                            |
|                         | Aug. 4,<br>1952  | A13508                 | 269                        | 1:20000      |                                                               |
|                         | June 14,<br>1955 | A14680                 | 6                          | 1:20000      | Mosaicked<br>together. Did not<br>use due to lack of<br>GCPs  |
|                         | June 14,<br>1955 | A14680                 | 30                         | 1:20000      |                                                               |
| <b>Willow<br/>Point</b> | June 14,<br>1955 | A14680                 | 32                         | 1:20000      |                                                               |
|                         | Aug. 3,<br>1961  | A17333                 | 80                         | 1:20000      | Mosaicked together                                            |

| Location                | Date             | Roll<br>Number | Photo ID<br>Number | Scale            | Comments           |
|-------------------------|------------------|----------------|--------------------|------------------|--------------------|
| <b>Willow<br/>Point</b> | Aug. 3,<br>1961  | A17333         | 83                 | 1:20000          |                    |
|                         | Aug. 3,<br>1961  | A17333         | 79                 | 1:20000          |                    |
|                         | Aug. 8,<br>1970  | A21815         | 31                 | 1:80000          |                    |
|                         | May 21,<br>1972  | A22665         | 63                 | 1:80000          |                    |
|                         | Aug. 8,<br>1973  | A23502         | 140                | 1:40000          |                    |
|                         | July 12,<br>1977 | A24700         | 88                 | 1:50000          |                    |
|                         | June 2,<br>1981  | A25737         | 197                | not<br>available | Mosaicked together |
|                         | June 2,<br>1981  | A25737         | 198                | not<br>available |                    |
|                         | May 18,<br>1986  | MB86010        | 136                | not<br>available | Mosaicked together |
|                         | May 18,<br>1986  | MB86010        | 137                | not<br>available |                    |

| <b>Location</b>   | <b>Date</b>          | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>                         |
|-------------------|----------------------|------------------------|----------------------------|------------------|-----------------------------------------|
|                   | May 12,<br>1990      | A27577                 | 56                         | 1:60000          |                                         |
|                   | Sept. 18,<br>1993    | MH9357042<br>7         | 31                         | not<br>available |                                         |
|                   | August 16,<br>2003   |                        |                            | not<br>available | Goldsborough 2003<br>unpublished data.  |
|                   | September<br>7, 2009 |                        |                            |                  | OrthoRefresh<br>imagery                 |
|                   | August 22,<br>2011   |                        |                            |                  | Landsat satellite<br>imagery            |
| <b>Netley Cut</b> | 1923                 | FA23                   | 9                          |                  | Oblique. No month<br>date               |
| <b>Netley Cut</b> | Oct. 13,<br>1929     | A1962                  | 83                         | 1:15000          |                                         |
|                   | Aug. 22,<br>1946     | A10491                 | 32                         | 1:20000          |                                         |
|                   | May 8,<br>1950       | A12444                 | 15                         | 1:20000          | Major flooding in<br>the image made for |

| Location   | Date             | Roll<br>Number | Photo ID<br>Number | Scale   | Comments                                      |
|------------|------------------|----------------|--------------------|---------|-----------------------------------------------|
| Netley Cut |                  |                |                    |         | too few GCPs. Use<br>as supplemental<br>data. |
|            | June 14,<br>1963 | A17982         | 46                 | 1:25000 |                                               |
|            | Aug. 15,<br>1965 | A18983         | 27                 | 1:35000 |                                               |
|            | May 11,<br>1968  | A20400         | 16                 | 1:12000 |                                               |
|            | July 25,<br>1970 | A21742         | 44                 | 1:80000 |                                               |
|            | May 21,<br>1972  | A22665         | 135                | 1:80000 |                                               |
|            | July 12,<br>1977 | A24700         | 133                | 1:50000 |                                               |
|            | July 28,<br>1979 | A25188         | 96                 |         |                                               |
|            | Apr. 28,<br>1987 | MB87001        | 157                |         |                                               |
|            | June 15,<br>1989 | A27453         | 267                | 1:50000 |                                               |

| <b>Location</b> | <b>Date</b>        | <b>Roll<br/>Number</b> | <b>Photo ID<br/>Number</b> | <b>Scale</b>     | <b>Comments</b>                                                  |
|-----------------|--------------------|------------------------|----------------------------|------------------|------------------------------------------------------------------|
|                 | May 26,<br>1994    | A28069                 | 65                         | 1:60000          |                                                                  |
|                 | May 2,<br>1997     | MB97003                | 53                         | not<br>available |                                                                  |
|                 | August 3,<br>2001  |                        |                            | 1:10000          | Grosshans et al.<br>2004.                                        |
|                 | August 20,<br>2009 |                        |                            |                  | Quickbird satellite<br>imagery                                   |
|                 | July 14,<br>2011   |                        |                            |                  | Landsat satellite<br>imagery                                     |
|                 | August 15,<br>2015 |                        |                            | not<br>available | University of<br>Manitoba.<br><br>WorldView-2<br>satellite image |