Hydrology of the Delta Marsh Watershed: Water Balance Characterization and Analysis of Land Use Changes

by

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Abstract

A hydrological model was used to examine the water balance of the Delta Marsh Watershed (DMW) currently and as impacted by land use changes. Understanding DMW hydrology can help to improve conditions in the Delta Marsh. MIKE SHE model results showed that the water balance is typical of prairie conditions with limited wintertime activity, significant spring melt runoff, and high summertime evapotranspiration and infiltration. Results showed that the DMW contributes approximately 40 million m^3 of water to the Delta Marsh in an average year, or 710 m^3/ha/yr. Portage Creek is the single greatest inflow from the watershed (31% of total) and the West Marsh area also receives large runoff volumes (combined 37% of total). Analysis of land use changes showed that urban expansion in the DMW would increase annual marsh inflows by over 50% under one urbanization scenario due to associated decreases in infiltration and transpiration. An agricultural shift towards row crop predominance would have minimal impact on the DMW water balance. Conversion of cropland to natural vegetation would decrease annual runoff by 12% to the marsh due to increased surface ponding, infiltration, and transpiration.

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Chapter 1

Introduction

Coastal wetlands form an important link between the hydrosphere and biosphere. By definition, coastal wetlands are low-lying areas adjacent to major water bodies (i.e. a lake, bay, or ocean) that hold water. These regions have ecological significance since they provide habitat for plants and animals away from the more hostile environment of the lake or ocean itself (Watchorn et al., 2012). Coastal wetlands can act as a flood buffer, protecting the upland regions from high water levels on the adjoining water body. Conversely, they can also protect the water body from runoff flowing into it from the surrounding watershed. Indeed, this may be the most important role of a coastal wetland: since it is the initial point of inflow for overland runoff, the wetland helps to guard the adjoining water body from the negative impacts of both high water quantity and poor water quality. Sometimes referred to as its “kidneys”, an adjoining coastal wetland can have an extremely important role in maintaining the health of a lake.

Considering the quality or quantity of water that reaches a coastal wetland (or any outlet point) begins with analyzing the contributing watershed. A watershed, or drainage basin, is usually defined as an area of land within which all surface water drains to the same point. Coastal wetland watersheds can differ slightly from a river basin since their outlets are usually a lineal *outlet face* – a collection of outlet points along the landside wetland banks – rather than a single point. Coastal wetlands may receive runoff from the upland watershed through either local overland flow (from areas just upland of the wetland boundary that drain directly into the wetland) or channelized flow (resulting from the combination of overland flow areas from further upland). The physiography of the watershed and the hydrological processes occurring therein define these flow pathways as well as the basin *water budget* or *water balance*. The water balance is essentially a tracking of the hydrological cycle as it pertains to a given region or watershed. Since the hydrological cycle is a closed system, one can perform analyses to account for the many pathways that water may follow and the changes of state that occur along the way. Making a number of simplifications, the surface water budget of a watershed can be defined by Equation 1.1 (Bedient et al., 2013), where R = runoff, P = precipitation, ET = evapotranspiration, and I = infiltration.

$$R = P - ET - I \tag{1.1}$$

Therefore, the quantity of rainfall or snowmelt that is not lost to the atmosphere through evapotranspiration or to the subsurface through infiltration becomes runoff that travels overland into creeks, streams, or rivers. These pathways convey water downhill towards a larger water body such as a marsh, lake, or ocean.

Equation 1.1 shows that runoff volumes are affected by evapotranspirative and infiltrative processes which are, in turn, impacted by the physical nature of the surface on which precipitation falls and over which runoff flows. The physical composition of the ground surface is referred to as *land cover*. Land cover can impact the proportion of rainfall or snowmelt that infiltrates into the ground. For example, infiltration through agricultural soils would be greater than through a gravel roadway, so the runoff volume would be larger from the roadway versus the field. Evaporation is affected by land cover since different surface features have varying capacities to store and subsequently evaporate water. Transpiration rates also vary with land cover; for example, the amount of root uptake would differ between a field of wheat and a coniferous forest. Finally, the actual runoff rate from a particular area is also strongly influenced by land cover type since surface roughness, and therefore overland conveyance, varies by surface type.

Though often used synonymously with land cover, *land use* refers specifically to the purpose that a certain area of land serves, which implies some degree of human influence.

For example, the land *cover* of an area may be shrub/grass land while the land *use* of this same area could be pastureland for cattle grazing. Land use changes are frequently associated with population increases (Cuo et al., 2011); growing cities often result in urbanization of native or agricultural land. A common land use change in the prairies is the conversion from natural grasslands to cultivated agricultural lands (Wang et al., 2014). This anthropogenic change is often accompanied by draining of natural wetlands, usually low-lying "sloughs" or "pothole lakes" on a farmer's land, to use this space for more profitable agricultural purposes. Many studies have shown that reassignment of land use can have dramatic effects on runoff or streamflow characteristics, as well as the overall water balance of a region (Conly and van der Kamp, 2001; van der Kamp et al., 2003; Im et al., 2008; Cuo et al., 2011).

The connection between a coastal wetland and its upland watershed cannot be overstated. Anthropogenic or natural changes occurring in the watershed can greatly impact the coastal wetland that forms the watershed outlet. Given the importance of these regions as wildlife habitat and the benefits they offer humans, anthropogenic influence on the contributing watershed must be carefully considered and appropriately managed.

1.1 Project Motivation

The Delta Marsh, bordering the southern coast of Lake Manitoba and covering approximately 185 km^2, is one of the largest freshwater coastal wetlands in all of North America (Watchorn et al., 2012). The marsh is a diverse ecosystem hosting various bird and fish species, and is also a popular area for waterfowl hunters. However, several indicators have shown the health of the marsh to be declining (Watchorn et al., 2012; Ducks Unlimited Canada, 2013). These indicators include the diminishing quantity of emerging vegetation as well as the decline in biodiversity and abundance of the local wildlife (Watchorn et al., 2012; Ducks Unlimited Canada, 2013). Reasons for this deterioration have not yet been clearly defined, though several factors are expected to have contributed. The introduction of a large carp population to the marsh, the regulation of Lake Manitoba water levels, increases in nutrient deposition, overabundance of hybrid cattail, frequent flooding and high discharges through the Portage Diversion, and other processes or events may have led to the aforementioned indicators of declining marsh condition (Watchorn et al., 2012; Ducks Unlimited Canada, 2013). Despite its ecological importance, there are currently limited data regarding the hydraulic and hydrologic processes occurring within the Delta Marsh and its watershed. As such, there is minimal information available for stakeholders working to restore the ecological health of the marsh. This thesis presents the first comprehensive research study of the water balance and dominant hydrologic processes occurring within the **Delta Marsh Watershed (DMW)**. With this understanding available, researchers and other stakeholders will be able to make informed decisions regarding marsh rehabilitation strategies.

1.2 Objectives

The first objective of this project is to better understand the water balance of the Delta Marsh Watershed under current hydrometeorologic and land use conditions. This objective includes:

- Field monitoring of DMW hydrology (measuring streamflow within watershed channels, recording meteorological conditions, etc.) and accessing other available digital data
- Identifying the extents of the DMW by completing a watershed delineation
- Establishing a complete hydrological model (including both surface and subsurface processes) of the DMW to represent current conditions
- Quantifying water balance terms such as precipitation, evapotranspiration, infiltration, groundwater recharge, and overland flow
- Defining how the contribution of each water balance term changes within a given period of time (seasonally or annually)

- Determining the factors that influence each water balance term and what causes them to change temporally
- Estimating total hydrological contribution from the DMW to the Delta Marsh (volume and timing) from overland flow
- Determining the pathways by which water reaches the Delta Marsh and which sub-basins of the DMW are the most hydrologically active

Dissecting the watershed in this way helps to characterize its precipitation-runoff response, as well as the pathways and rates by which water reaches the marsh under normal hydrometeorologic and land use conditions, henceforth referred to as “baseline” conditions.

The second objective of the project is to examine the *relative* hydrological response to land use changes within the DMW. Analyzing the results on a relative basis (i.e. focusing on increases or decreases as compared to the baseline conditions) allows for an understanding of the hydrological impact of introducing such changes. The goal of this component of the project is *not* to evaluate alternatives or provide predictions of streamflow volumes under future scenarios, but to identify the degree to which a land use change may alter the baseline hydrological conditions. As such, this objective includes:

- Modifying the baseline hydrological model to reflect selected land use change scenarios

- Estimating increases or decreases in the DMW's hydrological contribution to the marsh versus that of baseline conditions
- Examining the reasons behind any changes in marsh contribution by comparing water balance terms of the land use change scenarios to those of the baseline

This second component of the project aims to characterize changes to the baseline water balance under altered land use conditions such as urbanization or modified agricultural practices. Examining land use scenarios in this way will allow stakeholders to better understand the risks that may be associated with prospective changes as well as the hydrological rationale behind these risks. Therefore, the results of this study will be instrumental in planning for the future of the Delta Marsh.

Chapter 2

Literature Review

Understanding DMW hydrology begins by dissecting the diverse region of Canada within which it is located. While specific details on the study area are provided in Chapter 3, this chapter describes the dominant hydrological processes of the Canadian Prairies as an introduction to the factors that may govern within the DMW. Details on hydrological models, how models are classified, and how they represent watershed processes are also provided in this chapter. Water balance characterizations are defined in this chapter and a description of past research highlights the importance of undertaking such a study for the DMW. Studies on land use changes and their effects on hydrology are described in this chapter; analyses specific to the prairie region illustrate the impacts that land use changes may have on the DMW. Finally, past studies on the Delta Marsh are introduced to illustrate the longstanding foundation and motivation for the current study.

2.1 Canadian Prairie Hydrology

The Canadian Prairies stretch from the Rocky Mountains in western Alberta to the Canadian Shield in eastern Manitoba. Bound to the north by the Boreal Plains, the prairies form the northernmost portion of the Great Plains of North America. Most of the prairies are drained by the Saskatchewan and Assiniboine Rivers and their respective tributaries, generally flowing east towards Lake Winnipeg. The prairie ecozone, shown in yellow in Figure 2.1, is characterized by relatively flat topography and is dominated by grass and croplands. The following sections provide further detail on dominant meteorological and hydrological processes and the role they play in the overall prairie water balance.

2.1.1 Climate

The Köppen-Geiger climate classification system defines Canadian Prairie climate as ranging from dry, semi-arid to somewhat dry, humid continental (Kottek et al., 2006). As such, climate in the prairies is typified by long, cold winters and relatively low annual precipitation (Fang et al., 2007). The climate of the Canadian Prairies, like that of any region, is generally a function of its geographic location. Situated near the middle of the

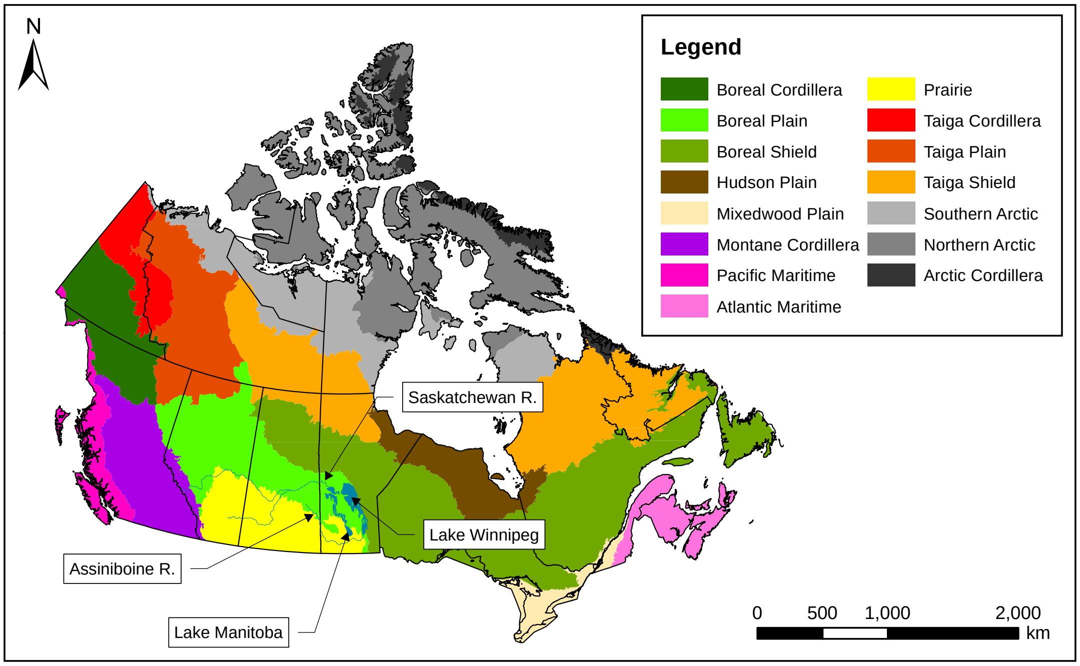


FIGURE 2.1: Ecozones of Canada

North American continent, the Canadian Prairies experience climatic influence from all sides therefore experience a wide range of weather conditions.

The general circulation of the atmosphere results in westerly winds dominating in the prairie provinces; these winds drive moisture and pressure systems inland from the west coast of Canada (Hare, 1997). The physiographic features of Canada also play a role in prairie meteorology. The Rocky Mountains, situated at the western edge of the prairies, form a physical barrier to the westerly winds. These mountains drive warm air masses upwards, a process called orographic uplift. This mechanism cools the moist air, resulting in condensation and then precipitation over the windward side of the mountains.

Having been forced upwards by the Rocky Mountains, the westerlies do not typically fall back to lower levels in the atmosphere. This leaves an atmospheric “gap” that can be filled by cold, arctic airstreams moving southwards and ushering in cold prairie temperatures (Hare, 1997). In the same way, warm air masses from the tropics can travel northward towards the prairies. These warm fronts may converge with an existing cold air mass, resulting in frontal uplift where the less dense warm air rises above the more dense cold air (Lutgens and Tarbuck, 2001). Prairie rainfall events are most frequently caused by this uplift mechanism and are relatively low in intensity but large in spatial coverage (Lutgens and Tarbuck, 2001; Fang et al., 2007). Smaller, more intense summer rainstorms are caused by convective uplift where unequal heating of the ground surface can cause warmer, less dense air to rise above cooler air and condense (Lutgens and Tarbuck, 2001). The resulting storms can be very unstable and capable of producing high rainfall intensities, especially when combined with other uplift mechanisms (Lutgens and Tarbuck, 2001; Dingman, 2002). Raddatz and Hanesiak (2008) analyzed nearly 1000 significant rainfall events in the prairies and concluded that most (79%) were either completely or partially convective in nature. The large spatial extent and geographic features of the Canadian Prairies result in precipitation formation by any combination of orographic, frontal, and convective uplift mechanisms.

Zooming into the yellow prairie region in Figure 2.1, Figure 2.2 illustrates average climatic conditions (from 1981 to 2010) for a selection of four prairie cities; data were retrieved from Environment Canada's climate normals (`http://climate.weather.gc.ca/climate_normals/`). This image depicts typical prairie weather where frozen temperatures persist from late October through March or April, followed by a warmer summer with temperatures typically peaking in July. Precipitation generally follows the same trend as temperature with less falling in the winter as snow than as rain in the summer. In the prairies, approximately one third of total annual precipitation falls as snow during the winter months (Gray et al., 1988). The following subsection describes evapotranspiration and how the precipitation that falls on the prairie landscape is eventually returned to the atmosphere.

2.1.2 Evapotranspiration

The term *evapotranspiration* (ET) is a compound word used to describe both evaporation and transpiration. Evaporation is the process by which water changes state from liquid to gas while transpiration is simply evaporation from plant leaves (Chow, 1964; Dingman, 2002). Sublimation is the process by which water changes state from solid (snow) directly to a gas without passing through the liquid stage. Approximately 60% of total terrestrial precipitation, a volume of 65,500 km^3 per year, is returned to the atmosphere via evapotranspiration (Oki and Kanae, 2006; Jung et al., 2010). Therefore,

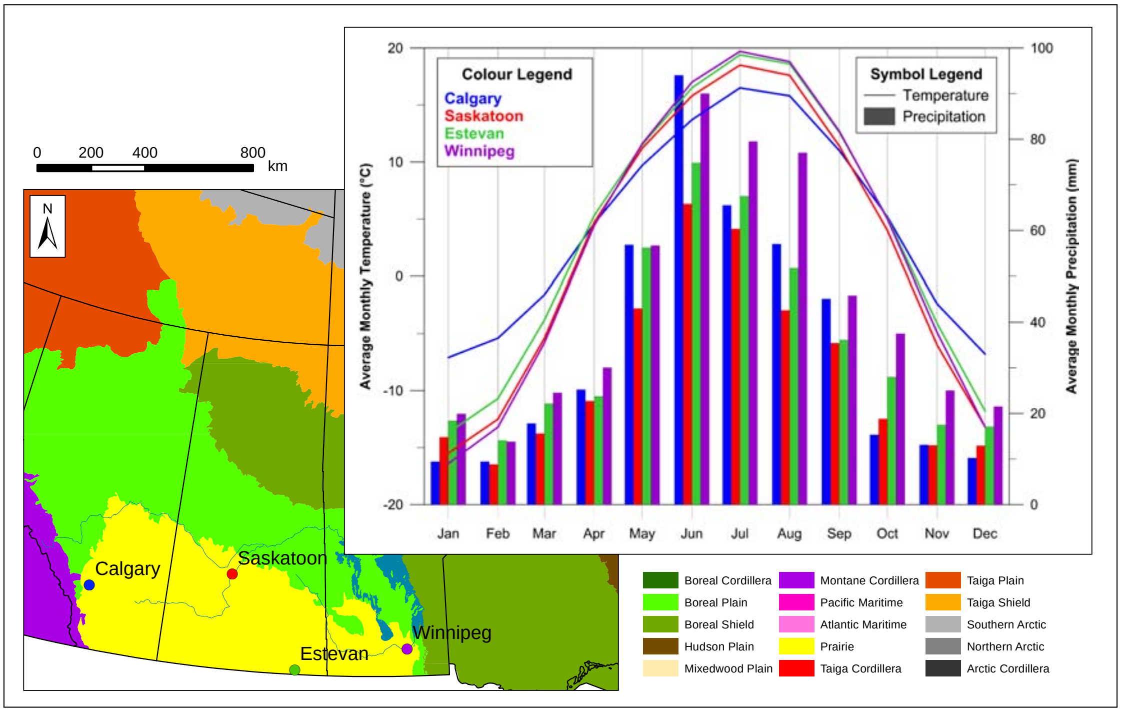


FIGURE 2.2: Climate normals of selected prairie cities (1981 - 2010)

understanding ET processes and controlling factors is an important step in describing a region's water balance.

Factors that influence evaporation are predominantly climatic while transpiration is also controlled by some vegetative and soil parameters (Chow, 1964). Evaporation occurs at a rate proportional to the difference in vapor pressures of the evaporating surface and the air above it (Dingman, 2002). The temperature gradient between the surface and surrounding air is also a factor since vapor pressure is a function of temperature. Additionally, evaporation from a free water body is controlled by the wind; the wind carries away air saturated with evaporated water, making way for less saturated air that can accept additional water vapor.

Jasechko et al. (2013) determined that 80 to 90% of total terrestrial ET flux can be attributed to transpiration specifically. This major component of the global water balance is a combination of plant growth processes occurring around the world. Atmospheric carbon dioxide fuels plant growth but can only be absorbed when dissolved in water (Farquhar and Sharkey, 1982). Therefore, plants draw in soil water through their roots, transport it through the stem and branches, and into stomatal cavities in the leaves (Dingman, 2002). These cavities hold water into which atmospheric carbon dioxide dissolves, but some of the water is lost to the atmosphere in the process. This evaporation of water from stomatal cavities is known as transpiration. Transpiration is impacted by the same factors as evaporation as well as physiological conditions of the plant and properties of the soil in which it is rooted (Farquhar and Sharkey, 1982; Tuzet et al., 2003).

Ranging from physical models such as an evaporation pan to complex equations, Lu et al. (2005) estimates that there are approximately 50 methods that can be used to estimate ET. Many comparison studies have been carried out to determine which method is best suited for a particular region or application (Wilson et al., 2001; Chen et al., 2005; Lu et al., 2005; Rosenberry et al., 2007). Gasca-Tucker et al. (2007) compared methods more broadly, weighing the advantages and disadvantages of each general category or approach to evaporation estimation. The estimation method used for a particular study or region depends on a variety of factors; weighing these factors and determining which are most important often determines the approach that is selected.

On the semi-arid prairies, annual potential ET can equal or exceed precipitation (van der Kamp et al., 2003; van der Kamp and Hayashi, 2008). Combining this characteristic with the high infiltration capacity of prairie soils (see Subsection 2.1.3) leads to minimal surface runoff in the summer (van der Kamp et al., 2003). Armstrong et al. (2015) simulated evaporation over much of the prairies for a 46 year period and found that this component of the water balance is subject to significant spatial and temporal variability. Average annual ET over the prairies ranged from 350 to 400 mm in this time period; average daily ET rates at Winnipeg, for example, are between 2.5 and 3 mm/day (Armstrong et al., 2015). Armstrong et al. (2008) measured ET in central Saskatchewan during the summer of 2006 and found that daily ET rates peaked at the end of June and decreased steadily in the following months. The authors made the observation that, although ET rates decreased after the end of June, there was no similar trend in air temperature, surface temperature, wind speed, or relative humidity (Armstrong et al., 2008). These climatic factors are often considered the main drivers of ET, but did not appear to play a dominant role in this instance. The only measured variable that followed a similar trend to ET was soil moisture (Armstrong et al., 2008), indicating that decreasing water availability in the soil is largely responsible for decreased ET rates. Phillips (1976) used hydrostatic lysimeters to directly measure ET by Phragmites plants in the Delta Marsh and analyzed relationships between ET and shallow groundwater fluctuations. Results of this study showed that ET peaked in July or August, with average daily values around 3.7 mm/day through the late summer/early fall. The study also showed that transpiration can exceed 75% of total ET at the analyzed sites. These results emphasize the importance of the transpiration component of ET in vegetated regions such as the prairies. The combination of ET and infiltration, described in the next subsection, make up the main extractions of surface water in the prairies.

2.1.3 Infiltration

Infiltration is simply defined by Chow (1964) as the flow of water through the soil surface and into the ground. This process is driven by the forces of gravity and capillarity (Parlange, 1971; Tarboton, 2003). Gravity drives water downwards and into the soil matrix while capillary forces pull it downwards due to the difference in water pressure between the surface and subsurface. Infiltration is controlled by landscape features such as topography, soil texture and composition, characteristics of the available surface water (e.g. rainfall rate, snowmelt volume, depth of ponding), as well as type and density of vegetation coverage (Chow, 1964; Bharati et al., 2002; Dingman, 2002). Scientists have developed many models that aim to represent the physical processes governing infiltration; these models vary in complexity and range from empirical to physically-based.

Mishra et al. (2003) provides a concise description of 14 prominent infiltration models and evaluates each of them on sets of laboratory and field data. One of the most popular conceptualizations of the infiltration process is that of Horton (1933). This method states that infiltration begins at a relatively high rate and gradually decreases to a near constant rate as precipitation continues to fall (Beven, 2004; Bedient et al., 2013). Under a steady supply of surface water, the rate of infiltration approaches the saturated hydraulic conductivity of the soil in question (Dingman, 2002).

Unfrozen infiltration capacity of the glacially-deposited prairie soils is relatively high (van der Kamp and Hayashi, 2008). Pomeroy et al. (2005) report summer infiltration rates on the order of 3 to 25 mm/hr in cultivated and grassland regions within Saskatchewan. The unfrozen infiltration capacity is predominantly influenced by soil properties and vegetation coverage (Granger et al., 1984).

On the prairies, cold temperatures result in frozen soils for much of the winter. Gray et al. (1986) postulated that infiltration can be either completely inhibited, partially inhibited, or completely unaffected by the presence of frozen soils. Winter infiltration depends on the amount of snow available and how fast it melts, the characteristics of the soil at both freezeup and thaw, and the extent of freezing in the soil (Granger et al., 1984; Zhao and Gray, 1999; Gray et al., 2001). Infiltration into frozen soils is limited by the formation of an impervious ice layer at the ground surface while passage of water through the soil itself is reduced by the presence of ice within void spaces (Gray et al., 2001; Hayashi, 2013). van der Kamp et al. (2003) measured infiltration rates in southern Saskatchewan and found that frozen infiltration rates were on the order of 0 to 3.2 mm/hr while unfrozen rates ranged from 10 to 100 mm/hr.

2.1.4 Groundwater

Water stored underground comprises the largest source of fresh, liquid water on the planet (Dingman, 2002) and is therefore a very important component of the hydrological cycle. Water enters the ground via the infiltrative processes described in Subsection 2.1.3 and proceeds to flow through the porous subsurface media in three dimensions, generally at a restricted rate. The subsurface can be partitioned into two zones: the vadose, or unsaturated zone and the phreatic, or saturated zone. These two zones are separated by the phreatic surface, or water table, where the unsaturated zone lies above and the saturated zone below. Void spaces in the unsaturated zone are filled with both air and water while voids in the saturated zone are completely filled with water (Schwartz and Zhang, 2003). Water entering the saturated zone from either the unsaturated zone or surface water is referred to as recharge while water exiting the saturated zone is called discharge (Dingman, 2002).

Groundwater flow is a function of the physical composition of the region in question as well as both fluid and subsurface material properties. Darcy's Law generally governs groundwater flow (Schwartz and Zhang, 2003). The two key components of this law are the hydraulic gradient, which represents the gravitational and pressure forces driving the flow, and the hydraulic conductivity, which represents the ease at which water passes through the porous medium. Hydraulic conductivities vary widely for different subsurface materials. For example, a stiff clay may have a hydraulic conductivity on the order of 10^{-10} m/day while a coarse sand or gravel may be on the order of 10^{3} m/day (Dingman, 2002). Hydraulic conductivities may also differ directionally: the horizontal to vertical, or anisotropy ratio of hydraulic conductivities can be on the order of 100 or greater (Barwell and Lee, 1981), meaning that rates of vertical groundwater flow can be much higher than the horizontal. Water would therefore flow more readily in the vertical direction as groundwater flows preferentially through low hydraulic conductivity materials or directions.

The Canadian prairie subsurface is defined by thick, clay-rich glacial tills that limit the role of deep groundwater in the prairie water budget (van der Kamp et al., 2003; van der Kamp and Hayashi, 2008; Cummings et al., 2012). Hydraulic conductivity in this material decreases with depth so prairie groundwater hydrology is dominated by shallow groundwater and unsaturated flow (van der Kamp and Hayashi, 2008). Cummings et al. (2012) reports hydraulic conductivities on the order of 10^{-5} to 10^{-3} m/day for weathered till closer to the surface and smaller values of 10^{-7} to 10^{-5} m/day for the deeper, unweathered till. Studies have reported that percolation velocities through the unweathered till are very low: Shaw and Hendry (1998) estimated downward velocities through this medium to be between 50 and 80 cm per 10,000 years.

Groundwater recharge does occur in the prairies, but typically only around the perimeter of small depressions (often referred to as “sloughs”, or “prairie potholes”) where surface water level and the groundwater table are continuous (van der Kamp and Hayashi, 1998). However, the majority of the recharging water flows horizontally through the more permeable weathered till and is lost through evapotranspiration as it is absorbed by the vegetation surrounding the sloughs. As a result, vertical groundwater recharge rates are typically very low, approximately 1 to 45 mm per year (Hendry, 1988; Hayashi et al., 1998; van der Kamp and Hayashi, 1998). Since the prairie groundwater table typically mirrors surface topography, it follows that groundwater discharge does occur into local depressions or sloughs in which the surface water elevation is lower than that of the water table (Hayashi et al., 1998; Cummings et al., 2012). Therefore, groundwater can flow both into and out of prairie wetlands, depending on the time of year and other conditions of the local water balance (Hayashi et al., 1998).

2.1.5 Overland flow

On a global scale, the oceans evaporate more water than they receive as precipitation while the land receives more precipitation than is lost by evapotranspiration (Oki and Kanae, 2006). The continuity of the global hydrological cycle dictates that an equilibrium must be reached. Conveying excess precipitation towards rivers, lakes, and eventually the oceans, overland flow is the hydrological process that closes the earth's water balance.

This component of the hydrological cycle is often referred to interchangeably as overland flow or runoff. Several different overland flow mechanisms have been postulated (Betson, 1964; Whipkey, 1965; Hewlett and Hibbert, 1967; Kirkby and Chorley, 1967) but perhaps the most widely recognized are infiltration excess, or Hortonian overland flow (Horton, 1933) and saturation excess overland flow (Dunne and Black, 1970). Infiltration excess overland flow occurs when rainfall intensity or rate of snowmelt exceeds the infiltration capacity (equal to the saturated hydraulic conductivity) of the soil in question. If the rate of rainfall or snowmelt is less than the soil's infiltration capacity, then all of the surface water passes into the ground at the rate that it becomes available. However, if the rainfall intensity or snowmelt rate exceeds the infiltration capacity of the soil, surface water will begin to collect or *pond* on the land, becoming available to flow over the surface (Tarboton, 2003). Saturation excess overland flow, on the other hand, occurs when the water table rises high enough to flow upward through the ground surface and onto the land (Dingman, 2002). The overland flow mechanism that governs in a certain region depends on the climatic and physiographic characteristics of the area. As a general rule, infiltration excess overland flow dominates in areas that experience intense rainstorms or rapid snowmelt with relatively impervious soils while saturation excess overland flow occurs mostly in humid regions with permeable soils and active groundwater (Hewlett and Hibbert, 1967; Dunne and Leopold, 1978; Tarboton, 2003).

Once generated, overland flow travels at a rate that increases with increasing slope and decreasing surface roughness (Dingman, 2002). The hydraulics of overland flow are usually described by either the Darcy-Weisbach, Chézy, or Manning equations (Smith et al., 2007). Each of these equations incorporate a parameter to represent the roughness, or resistance to flow, of the surface over which water is flowing. However, it has been shown that flow resistance is a function of the rate of flow itself (Emmett, 1970; Gilley et al., 1991), so most representations of overland flow incorporate some relationship between surface roughness and Reynolds number (Gilley et al., 1991; Smith et al., 2007). Surface roughness is a function of land cover, and by extension, so to is overland flow. The type of coverage and surface features in a particular region determine the roughness and therefore the ability for surface water to flow. Engman (1986) developed estimates of the Manning's n roughness value for a variety of land cover types and agricultural conditions. Flowing over the various land cover types under the force of gravity, surface runoff will eventually reach a creek, river, or man-made channel that continues to carry water down slope. Channelized flow is somewhat more efficient than overland flow as it takes place within the well-defined bounds of the channel, collecting momentum as it flows downstream (Sturm, 2001). However, bed roughness still serves to resist flow within the channel; roughness characteristics of natural and man-made channels have been extensively studied (Barnes, 1967; Coon, 1997; Sturm, 2001; Yen, 2002).

As mentioned previously, it is estimated that 80% or more of annual prairie runoff results from snowmelt (Granger et al., 1984). The mechanism that dominates spring runoff on the prairies is infiltration excess overland flow since liquid water is released relatively quickly from the snowpack onto impervious frozen or partially frozen soils (Fang et al., 2007). Runoff during unfrozen conditions is also predominantly caused by infiltration excess due to the low hydraulic conductivity of the prairie soils, relatively deep and in-active groundwater, and the high intensity convective storms that provide much of the summer precipitation. Indeed, Shook and Pomeroy (2012) state that saturation excess overland flow is rare in the prairies, occurring only under extended frontal precipitation events. The consensus remains that the high evapotranspiration and infiltration capacities on the prairies normally results in minimal summertime runoff (van der Kamp et al., 2003; Fang et al., 2007). The minimal runoff capacity of the prairies combines with its low topographical relief to result in a poorly-defined drainage network and ubiquitous non-contributing areas (Shook and Pomeroy, 2011). Much of the prairies are covered by small wetlands (the aforementioned prairie potholes or sloughs) that are deemed to be non-contributing under normal conditions, meaning that they are drained internally and do not contribute flow downstream except under very wet conditions (Spence and Woo, 2003; van der Kamp and Hayashi, 2008; Pomeroy et al., 2010).

2.2 Hydrological Modelling

Researchers and watershed managers are often interested in understanding and quantifying the hydrological processes occurring within a watershed, including those described in the previous sections. Engineering applications such as flood forecasting, dam design, and urban drainage design require quantification of a watershed's processes with the goal of defining storm hydrographs and corresponding water levels. Alternatively, ecological applications such as nutrient flux monitoring and aquatic wildlife management also require an understanding of basin hydrology. Climate and land use changes play a dominant role in many modern hydrological applications; the effects of changing meteorological and physiographic conditions on hydrological processes must also be understood (Peel and Bloschl, 2011). Operational hydrologists typically develop models that can be used to characterize a particular watershed and quantify each of the processes occurring therein. The overarching goal of a hydrological model is to digitally represent a watershed by describing its physical processes mathematically. By their nature, hydrological models are merely representations of many complex, interconnected, and often unpredictable natural phenomena. Therefore, representing these processes requires either large amounts of data and computational power or simplifications and assumptions, and often a fair amount of creativity (Savenije, 2009).

2.2.1 Model classifications

Hydrological models are often grouped into different categories so that they may be compared and so users are aware of their abilities and limitations prior to making a selection. Model classification identifies the method by which a hydrologic system is represented in terms of the mathematical equations used, how the spatial extents of the study area are represented, what the model parameters represent, and what overarching assumptions are made. A common distinction for a hydrological model is whether it is physically based (uses equations derived from first principles to describe hydrological processes) or conceptual (uses deduced relationships to represent physical processes). A hydrological model may also be lumped (large region represented by a single parameter set) or distributed (discretized in space to represent hydrological variability), as well as event-based (representing the hydrological response to a single event only) or continuous (representation of multiple events spanning a specific time period) (Dingman, 2002). A host of model classification terms and categories can be found in the literature, as can comparisons between the different model structures and arguments on which type may be most useful in a given situation (Beven, 1989; Refsgaard and Knudsen, 1996;

Beven and Young, 2013). As per the objectives stated in Section 1.2, this project aims to define DMW hydrology under both current and potential future conditions. Therefore, the hydrological model selected for this purpose must suit the characteristics of the DMW. Understanding model classifications helps to direct the model selection process; Section 4.1 provides details on this process for the current project.

2.3 Water Balance Characterization

As introduced in Chapter 1, the different pathways water takes through the hydrological cycle can be identified and quantified. This analysis can be referred to as a *water balance characterization*, and can be performed on scales ranging from global (L'vovitch, 1973; Oki and Kanae, 2006; McCabe and Wolock, 2013) to local (Woo and Roswell, 1993; Rovansek et al., 1996; Quinton et al., 2004). A key component of the first objective described in Section 1.2 is the quantification of water balance terms for the DMW using a comprehensive hydrological model and an analysis of what factors influence each of them.

Quinton et al. (2004) performed a water balance study of the wetland-dominated Liard River valley in northern Canada. This study aimed to quantify the precipitation, evaporation, and runoff water balance components with specific interest in the relative contributions of each primary type of wetland present in the study area. This study used a relatively simple water balance methodology, subtracting measured runoff from measured precipitation to estimate evapotranspiration loss. Although a hydrogeological chloride mass balance was also used to verify this estimate of ET, this study did not incorporate a full hydrological model in its water balance dissection. A similar methodology was taken by Hayashi et al. (2004) but this study also used isotopic and chemical tracers as verification of the ET estimate. Neither of these studies incorporated a complete hydrological model as is performed in the current study on the DMW.

A unique characteristic of the DMW is that its outlet is one of the largest freshwater coastal wetlands in North America. If a hydrological model is to be useful for characterizing such a region's water balance, it must effectively incorporate the hydrological features unique to a coastal environment. Much coastal wetland research has focused on the Laurentian Great Lakes. Quinn and Guerra (1986) performed a water balance study on Lake Erie and found that localized runoff into the lake has a significant impact on lake levels even though the majority of Lake Erie's inflow is delivered by the Detroit River. Although this study quantified the major water balance components for Lake Erie, it did not incorporate a full hydrological model. Quinn and Guerra's study also focused on the water balance of Lake Erie itself rather than any coastal wetlands that surround it, but showed that tributary inflows are key components of the lake water balance. Trebitz et al. (2002) also demonstrated that tributary inflow plays a major role in the water balance in the Lake Superior region, but this study focused on coastal wetlands bordering the lake itself. Indeed, this study found that the connection between tributaries and coastal wetlands often has greater influence on conditions in the wetlands than does the connection between the coastal wetland and Lake Superior. This demonstrates a need for proper analysis of runoff and tributary inflow into coastal wetlands.

Vano et al. (2006) created a complete land surface model to simulate flow and storage of water in northern Wisconsin using a suite of meteorological parameters. While this study did not explicitly focus on a coastal wetland watershed, the development of a complete surface model was found to be useful in characterizing the local water balance. The study states that water balance quantification with a complete physical surface model (i.e. one that includes the full range of hydrological processes) can be verified even without extensive field data. This indicates that capturing the full hydrological cycle within a water balance study is important, especially when measured data are limited. This study also emphasized spring and snowmelt hydrological processes, which are expected to play a dominant role in the DMW water balance.

A significant amount of research has been done on Canadian Prairie and prairie wetland hydrology, with some of these studies including water balance characterizations. Woo and Roswell (1993) performed hydrological analyses on a small wetland catchment in Saskatchewan and quantified both surface and subsurface water balance terms, largely through field measurement. Relevant to the current study is that Woo and Roswell (1993) analyzed the upland areas and the wetland separately. This study found that overland flow is only a significant water balance component during the spring melt; summer time runoff is minimal since most rainfall is lost to either ET or infiltration. This study focused on a catchment much smaller than the DMW, and it did not incorporate a hydrological model to perform the water balance characterization. van der Kamp and Hayashi (2008) studied prairie wetlands and described their water balance, concluding that each individual wetland in an area exhibits a different hydrologic behavior but all are interconnected. The study also found that wetland water balance is sensitive to land use changes; an objective of the current study is to understand how land use changes affect the water balance of the DMW. Su et al. (2000) used a modified SLURP model to simulate hydrologic processes in a small prairie wetland catchment and was able to do so with reasonable accuracy. However, the study area was very small (3 ha) and focused on the area surrounding a single prairie pothole, rather than an extensive coastal wetland watershed such as the DMW.

Various water balance studies exist in the literature, but there are very few with methodologies that would meet the objectives of the current project. Firstly, it is clear from the literature that there has never been a water balance study on the DMW. It has also been shown that few studies on coastal wetland watersheds have been performed at all and that the unique setting of the Delta Marsh and its watershed warrants a specialized water balance study. Additionally, few studies incorporate a comprehensive hydrological model for the purposes of water balance characterization. Of the few studies that have used a hydrological model, even fewer have studied a basin as large and complex as the DMW. An objective of this project is to use a hydrological model to quantify water balance components of the DMW and to analyze how land use changes may affect them. The next section describes the role of land use in the hydrological cycle and examines the body of literature on the subject.

2.4 Land Use Changes

Land use is the purpose served by an area of land. The second main objective of this study (see Section 1.2) is to identify the degree to which a land use change may alter the baseline hydrological conditions of the DMW. A wide range of studies have shown how land use can affect a region's hydrology, so it expected that any land use changes within the DMW will be manifested in changes to its local hydrology.

Most relevant to the DMW are studies of prairie land use changes. While not analyzing changes, specifically, Euliss and Mushet (1996) examined water level fluctuations in prairie pothole wetlands as a function of the land use in their upland areas. Results show that water levels fluctuate more in wetlands with agricultural uplands than those with natural grasses since the agricultural uplands yield more runoff into the wetlands. However, this study did not examine the physical explanation for this result in detail. van der Kamp et al. (2003) studied the St. Denis National Wildlife area in southern Saskatchewan, examining the hydrological impacts of a land use change from cultivated agricultural land to prairie grasses. It was found that this land use change increased snow trapping on the land as well as frozen soil infiltration. Small wetlands in the area closest to the grassed area dried out over a short period of time due to decreased local runoff, while those in the vicinity of the agricultural areas remained wet. This study illustrates how a prairie land use change directly affected the local water balance and the hydraulics of prairie wetlands. Hedstrom et al. (2001) used a hydrological model to demonstrate the impact of the converse land use change: from grassland to cultivated. Model results showed an increase in sublimation and runoff and decreased infiltration. Another study on soil properties of different prairie land uses confirms that native grasses have higher infiltration capacities than do cultivated fields (Bodhinayake and Cheng Si, 2004). Results from these studies confirm the influence of agricultural land use change on prairie the prairie water balance.

Changes from undisturbed or agricultural land use to that of an urban environment are common on the prairies, and these changes can be expected to modify the local hydrological cycle to some degree. A study in Washington examined the hydrological impacts of changing from forest to urban land uses (Cuo et al., 2011). Results showed that these changes can be expected to impact local hydrology even more than climate change, depending on the spatial distribution of the alterations. Hydrological impacts of climate changes are mainly found to yield changes in the seasonal distribution of runoff, while urbanization can be expected to actually increase the amount of runoff experienced. Many other studies have also demonstrated increased runoff with a change to more urbanized land use, largely due to associated decreases in both infiltration and evapotranspiration (Arnold and Gibbons, 1996; Paul and Meyer, 2001; Pauleit et al., 2005; Poff et al., 2006). However, no studies have examined the impact of urbanization on prairie hydrology or coastal wetlands in particular.

Land use changes can be applied to calibrated hydrological models and compared to the unaltered condition to form an understanding of the impacts these changes have made. Conly and van der Kamp (2001) suggest that a detailed understanding of the hydrological impacts of prairie land use changes can only be found via physically-based models and comprehensive field monitoring. Mao and Cherkauer (2009) modeled land use changes in the Great Lakes region of the United States. This study used the physically-based Variable Infiltration Capacity (VIC) model to simulate the hydrological impacts of land use changes that have already occurred in the area (i.e. change from pre-settlement to modern land use). Changes analyzed in this study were mainly deforestation and introduction of agriculture to natural grasslands. Results of the study show that a change in land use from grassland to row crop increased ET by 10-15% and decreased total runoff by 20-30%. Discussions on row crops on their impact on DMW hydrology can be found in Subsection 4.6.2. As with the current study, Im et al. (2008) used the physically-based MIKE SHE hydrological model to simulate land use changes on a basin scale. While the basin area compares to that of the DMW, the study location in Im et al. (2008) is a somewhat mountainous watershed in South Korea that experiences a temperate monsoon climate. Despite the differences in study areas, this study provides some valuable insight on land use change modelling using MIKE SHE. The authors changed a number of vegetation and ET parameters in the MIKE SHE model to simulate changes seen in satellite land use data. Modeled water balance results show increases in overland flow and total runoff along with decreases in ET, infiltration, and groundwater recharge as urbanization increased. Modelling methodology described in Chapter 4 generally agrees with that of Im et al. (2008). However, that study does not focus on a prairie region like the DMW and therefore hosts different hydrological processes. The study was performed on a somewhat typical river basin with a well-defined drainage network and singular outlet. As will be discussed in detail in Chapter 4, the DMW is a very unique basin of the type that has not been studied extensively in the past.

2.5 The Delta Marsh

The Delta Marsh has long been a popular hunting and recreation area, but has also hosted research efforts since the 1930s. A detailed history on the Delta Marsh and the research efforts it has hosted is described in a book entitled *Delta: A Prairie Marsh and its People* (Sugget et al., 2015). This book details wildlife research that dates to the late 1930s with conscientious hunters working towards waterfowl sustainability. With the establishment of the Delta Waterfowl Research Station in 1938, the University of Manitoba field station in 1966, and the Delta Marsh Bird Observatory in 1995, the Delta Marsh was solidified as a world-renowned wetland, waterfowl, and biology field research facility. Although each of these facilities have now been closed, research efforts at the Delta Marsh are ongoing.

While countless journal articles and graduate theses have been published on Delta Marsh waterfowl, vegetation, aquatic species, and water quality, few have specifically examined marsh and watershed hydrology or hydraulics. However, the impact of water level fluctuations on marsh condition has been recognized since the mid-1960s. Marsh management explorations at that time even included the possibility of complete control of marsh water levels by partitioning the marsh into separate impoundments (Technical Committee for Development of the Delta Marsh, 1968; Sugget et al., 2015). However, this proposal was never realized and it was determined that more extensive and scientific study on the marsh would be required to manage it effectively.

The initiative to build a fundamental understanding of the Delta Marsh began in earnest in the late 1990s. Many studies at this time focused on fish community and submerged vegetation, but analysis of marsh hydrology was also deemed a priority. However, detailed study of Delta Marsh and DMW hydrology and hydraulics were never performed. Analyses of water levels and local water balances were performed as part of the Marsh Ecology Research Program (MERP) that aimed to study the effects of wet-dry cycling on wetlands. Kadlec (1993) recorded water levels, precipitation, ET, and groundwater seepage within the diked marshes constructed for the MERP. However, this study focused on the wetland cells themselves and did not consider any localized runoff in the water balance analyses. Hydrology was also a component of a PhD thesis by Bortoluzzi (Bortoluzzi, 2013), but this study focused mainly on hydrology within the marsh itself and interactions with Lake Manitoba. No detailed hydrological modelling or water balance analyses were performed on the marsh watershed in this research. Stanley (2017) analyzed the relationship between watershed land use and nutrient loading to the marsh. Results of this research showed that nutrient export is correlated to land use and crop type, and also identified regions of the DMW that exhibited the greatest nutrient exports in 2015 and 2016. While Stanley (2017) included land use analyses and discharge measurements, this research was focused on nutrient loading within the watershed. Section 6.4 provides recommendations on harmonizing the research of Stanley (2017) and the current project. Not until the inception of the *Delta Marsh - Restoring the Tradition* project in 2013 did a detailed study on DMW hydrology come to fruition (see Section 3.2 for more details). This thesis describes the first extensive study on the hydrology of the Delta Marsh Watershed and the impacts of land use changes therein.

Chapter 3

Study Area and Data Collection

This chapter describes the geographic location of the DMW, highlights a few of its key features, and describes some of the data collected for the purposes of this project. Both field measurements and digital data were required to meet the objectives outlined in Section 1.2.

3.1 Location and General Background

Formation of the Delta Marsh began some 4,500 years ago when the Assiniboine River used to flow into Lake Manitoba, depositing deltaic sediments in the process. Over approximately 2,000 years these sediments were slowly pushed by waves to form a thin ridge of land, effectively isolating a portion of the lake on the south side of the ridge.

The water isolated by the beach ridge eventually became what is now known as the Delta Marsh (Teller and Last, 1981; Rannie et al., 1989). Figure 3.1 illustrates how the marsh, outlined in yellow, hugs the southern edge of Lake Manitoba and remains separated from the lake by the narrow beach ridge.

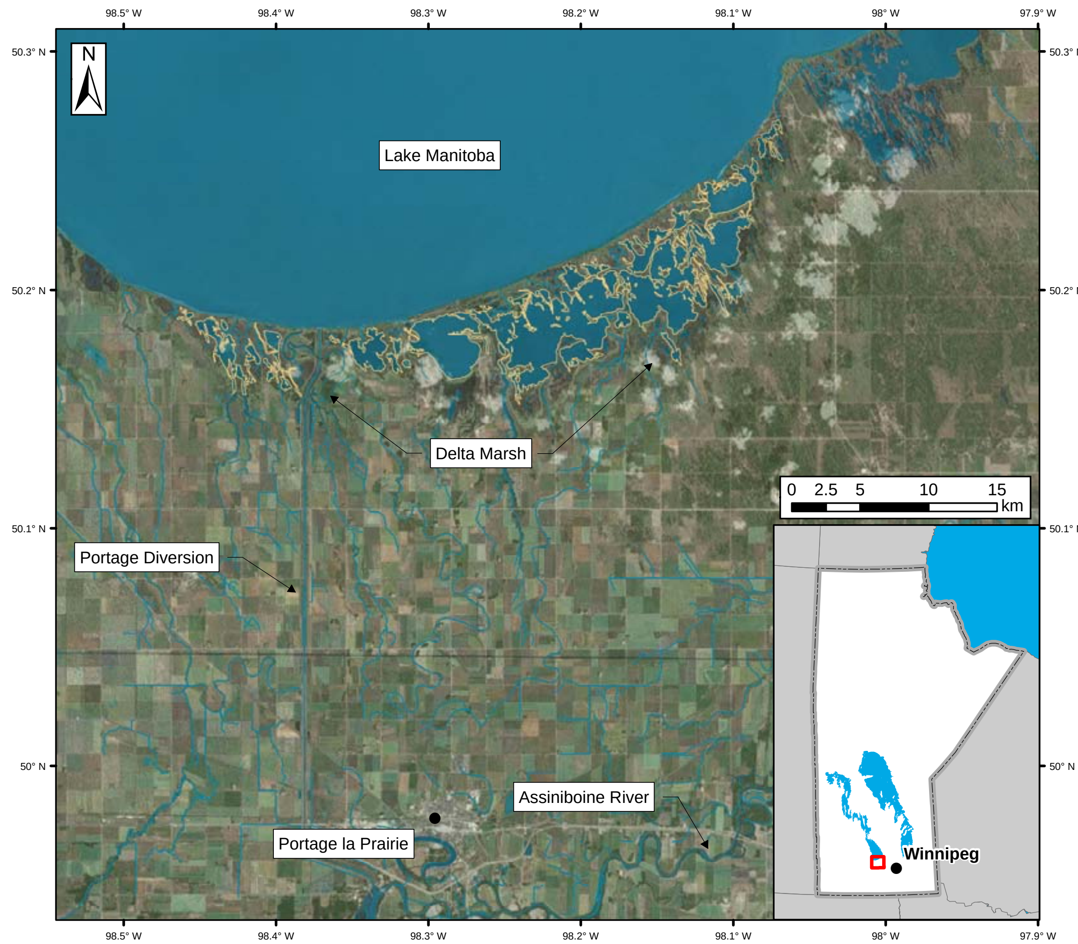


FIGURE 3.1: Study area location plan (Imagery source: ESRI)

This study is predominantly concerned with the area upland of the Delta Marsh (the DMW) rather than the marsh itself. Approximate extents of the DMW were provided in Ducks Unlimited Canada (2013) while Section 4.2 details how the DMW was more precisely delineated for the purposes of this project. From Ducks Unlimited Canada (2013) and from experience in the field (see Section 3.3), it is known that the DMW covers much of the area between Portage la Prairie and Lake Manitoba (see Figure 3.1). Comprising the downstream end of the Assiniboine River Basin until the river changed direction approximately 2,000 years ago, this area slopes very gently towards Lake Manitoba. The city of Portage la Prairie (Portage) has a population of approximately 13,000 (`http://www.statcan.gc.ca/`) and is the largest commercial hub in the region. The city's rural municipality (RM) is the largest in Manitoba by area and has a population of nearly 7,000 (`http://www.rmofportage.ca`) scattered across small towns, hamlets, and family farmsteads. This region is known for its productive agricultural land with favorable conditions for a range of crops as well as livestock.

3.2 Delta Marsh - Restoring the Tradition

There has been motivation for scientific study of the Delta Marsh since at least the 1960s (Technical Committee for Development of the Delta Marsh, 1968); details on the development of research efforts at the marsh can be found in Sugget et al. (2015). The efforts of previous researchers and marsh stakeholders have culminated into a scientific initiative known as *Delta Marsh - Restoring the Tradition*. This multi-disciplinary project was inaugurated in January of 2013 by a variety of stakeholders; Ducks Unlimited Canada

(DUC) manages and directs the research initiative. “Restoring the tradition” refers to the Delta Marsh’s storied tradition of wildlife abundance, marsh prosperity, and conservation efforts. It has been shown that the Delta Marsh has experienced significant degradation of water quality as well as reduced wildlife production, diversity, habitat, and food sources (Watchorn et al., 2012; Ducks Unlimited Canada, 2013). The causes of marsh degradation are not yet fully understood, but it is suspected that a number of factors have contributed. Regulation of Lake Manitoba water levels has attenuated the natural cycling of high and lower water levels (Bortoluzzi, 2013; Aminian, 2015). It has been shown that a natural wet-dry cycle leads to productive emergent wetland vegetation (van der Valk, 2005), so declines in vegetative growth at the Delta Marsh may be attributed to water level regulation. Invasion of exotic species is also expected to be a factor in the degradation in marsh health. Both hybrid cattail and common carp have proliferated in the Delta Marsh in recent decades, but these species have been linked to the declining health of the marsh (Watchorn et al., 2012; Ducks Unlimited Canada, 2013). Other factors such as nutrient runoff from adjacent fields, operation of the Portage Diversion, and artificial dredging of marsh waterways have yet to be explored in detail but may also be contributing to problems at the Delta Marsh (Watchorn et al., 2012).

The overall goal of the *Restoring the Tradition* project is to regain many of the functions that have been lost at the marsh. This includes improvements to marsh biodiversity, fish and wildlife habitat, water quality, and carbon sequestration (Ducks Unlimited Canada, 2013). However, achieving these goals first requires detailed study on the processes occurring at the Delta Marsh and identifying any deficiencies that are responsible for declining marsh health. Restoring marsh functionality hinges on an understanding of local topography, physiography, hydrology, hydraulics, and biology. Therefore, the second main goal of the *Restoring the Tradition* project is to better understand these features and fully characterize factors of each that have led to marsh degradation. DUC has assembled a diverse science team to carry out these investigations. Details on the science team and objectives for each member can be found in Ducks Unlimited Canada (2013), as can details on methodologies taken by each research group. This thesis describes the watershed hydrology component of the *Restoring the Tradition* project.

3.3 Field Data Collection

Field measurements and surveys were crucial aspects of both this project and that of Aminian (2015). A great deal of time was spent in the field to measure the hydraulic and hydrologic processes occurring within the Delta Marsh and its watershed and to witness them first-hand. This section describes the field data that were collected to inform the analysis of DMW hydrology. Aminian (2015) details data collected for the hydraulics component of the larger *Restoring the Tradition* project. A thesis by Marija Glavonić (Glavonić, in progress) explains data collected for the isotope hydrology component of the project.

3.3.1 Hydrometry

The DMW is drained by a series of channels and streams that generally flow northward and drain into the Delta Marsh; water features in the DMW region are outlined in Figure 3.1. Note that none of these channels are gauged by Water Survey of Canada (WSC) for either streamflow or water level. One component of the DMW water balance is surface runoff, and it is an objective of this project to quantify hydrologic contribution from the DMW to the Delta Marsh. Therefore, water movement within the DMW was measured throughout the open-water season of 2014, with an emphasis on the spring freshet, as well as during the spring of 2015. Knowledge of prairie hydrology (see Section 2.1), experience in the field, and communication with DUC staff led to the assumption that freshet flows would dominate the annual hydrograph throughout the DMW.

Starting on April 16, 2014, water movement through DMW channels was monitored via two different methods. The first hydrometric device was the SonTek Argonaut Shallow Water Acoustic Doppler Velocimeter (ADV). This device can be placed at the bottom of a river or stream for continuous recording of streamwise velocity (accuracy ± 5 mm/s) and water depth (accuracy ± 3 mm) (SonTek, 2009). If channel dimensions are known, the velocity and depth can be used to calculate discharge through the channel. Since velocity is measured continuously (every 10 minutes) with the Argonaut, one can therefore estimate a continuous channel discharge. With only one Argonaut available for continuous discharge measurement in the spring, it was decided that the device should be placed in the most hydrologically active channel (i.e. the channel with the largest expected inflow contribution). Field observations and communication with experienced DUC staff led to the placement of the Argonaut in Portage Creek at the culvert crossing under Provincial Road (PR) 227, approximately 7.5 kilometers upstream of the Delta Marsh (flow Station E7 - see Figure 3.2 for location and Figure 3.3 (B) for an image of the station). A double concrete box culvert (opening dimensions approximately 2 x 2 m) carries Portage Creek flow from the upstream watershed towards the marsh, so the Argonaut was placed within one of the two culvert boxes for velocity and depth measurement. Measurement locations at Portage Creek and the other inflow channels are shown in Figure 3.2.

The second flow measurement device used at the DMW was the SonTek FlowTracker handheld ADV. This instrument differs from the Argonaut in that it can be used to take a composite discharge measurement across a channel, rather than simply measuring velocity at a single point. The FlowTracker is a handheld device that is placed into the channel, submerged into the flow at a predetermined depth, and held in place until the measurement of stream velocity is completed. This process is repeated across the width

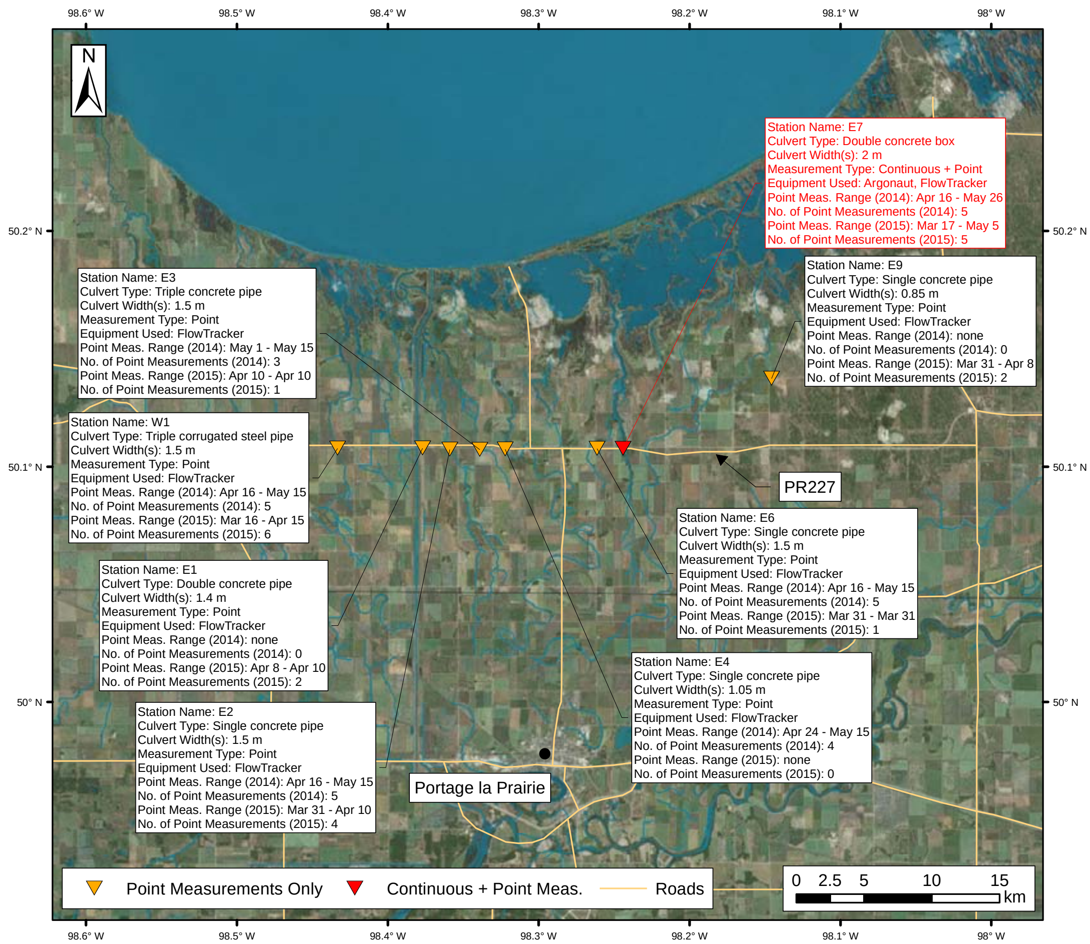


FIGURE 3.2: Points of discharge measurement in the DMW (Imagery source: ESRI)

of the channel at a predetermined interval until the entire cross-section has been profiled. The FlowTracker automatically determines composite discharge across the channel using the velocity and area measurements collected during the profiling. SonTek specifications report a velocity accuracy of ±1% of measured velocity or 0.25 cm/s and that the device is able to measure velocities in the 0.001 to 4.0 m/s range (SonTek, 2016). The FlowTracker was used alongside the Argonaut at Portage Creek to intermittently

FIGURE 3.3: (A): Field measurement of point discharge with the FlowTracker at Station E2 (B): Site layout at Station E7

verify the discharge measurements being collected continuously by the in-stream ADV. It was also used to measure velocities in the other inflow channels shown in Figure 3.2 - also see Figure 3.3 for an image of the FlowTracker in use at Station E2. Flow through these channels were found by simply multiplying a single velocity measurement by the approximate cross-sectional area of flow at the time of measurement (found knowing the depth of flow and culvert dimensions). Flow measurements were taken for the spring melt period in both 2014 and 2015. Measurement date ranges were April 16, 2014 to May 26, 2014 and March 17, 2015 to May 5, 2015 (see information on Figure 3.2 for measurement date ranges and frequency at each station). These periods were chosen to cover the spring freshet period as best as possible within the constraints of field work operations. Results of the discharge measurement program can be found in Subsection 4.4.1 and Subsection 4.5.1.

3.4 Digital Data Collection

The development of a complete hydrological model requires information on the physical characteristics of the area in question. While the previous section describes the field data collected first-hand in the DMW, this section describes the digital information produced by other organizations that was compiled to complete the model construction.

3.4.1 Topography

Topography is an important component of a hydrological model since it defines the domain of the model itself. Watershed delineation is predominantly based on identifying topographic minima and maxima within a region of interest; see Section 4.2 for more information on how topography data were used to delineate the DMW. Topographic information is a key building block for any hydrological model as the surface features of a watershed dictate where water flows on the surface and where it may meet with a larger body of water or flow into the ground. Surface slope is a key factor in the hydraulics of overland flow (see Subsection 2.1.5). Therefore, topographic information is also required for the hydrological model to define rates of overland flow and to determine the pathways of this water balance component. Finally, elevation data also describe surface depressions that collect water and become a source of evapotranspirative production.

Data from three separate topographic data sources were combined to form a complete topographic description of the DMW. These sources were DUC elevation contours, LiDAR Digital Elevation Model (DEM) data, and GeoBase DEM data; each digital dataset is described below.

DUC Elevation Contours

A project was initiated by DUC to collect and assimilate both bathymetric and topographic data for the Delta Marsh and surrounding areas (Wrubleski and Witherly, 2014). This project was carried out as a part of the larger *Delta Marsh - Restoring the Tradition* initiative described in Section 3.2. DUC provided one foot digital elevation contours for the purposes of the current project. These contours were originally produced in paper form from ground surveys performed in 1979 and 1980 by DUC staff and informed by air-photo interpretation (Wrubleski and Witherly, 2014). The maps were scanned and georeferenced for use in GIS software. Spatial coverage of the DUC contours is shown in Figure 3.4. Note that the original topographic survey covered the marsh water bodies and some of the surrounding upland areas, but not the entire marsh watershed.

Note that Geard (2015) performed detailed sonar surveys of the Delta Marsh in 2011, yielding high-resolution bathymetry of the East Marsh region. While this information

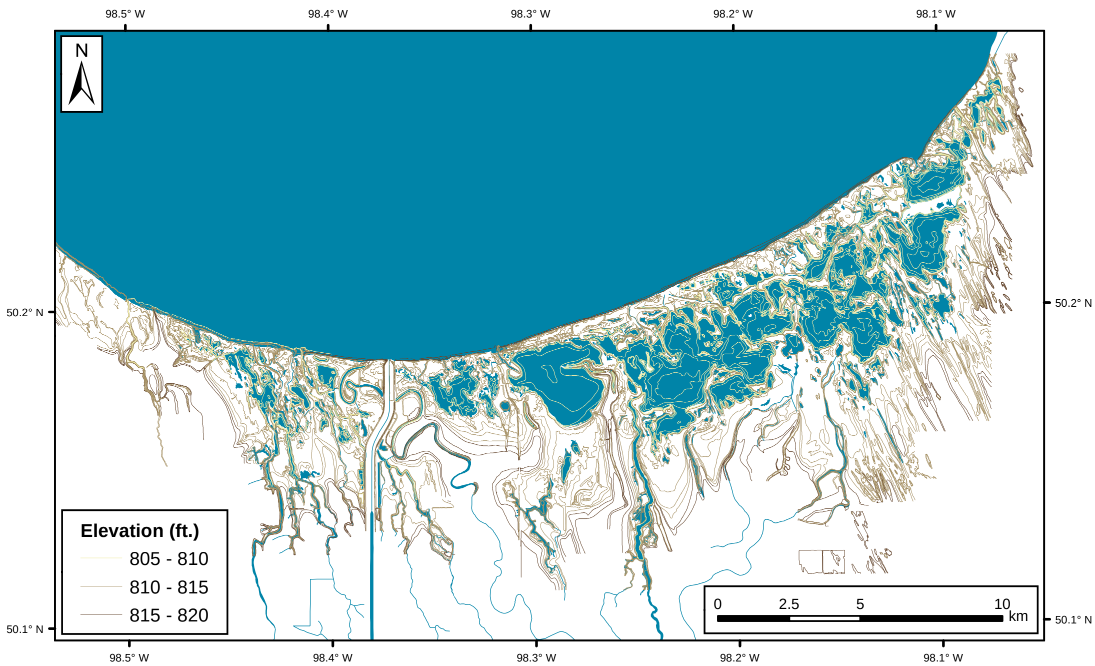


FIGURE 3.4: Spatial coverage of DUC elevation contours

supersedes the contour data described above, and is more accurate in overlapping areas, it was not incorporated as part of the watershed DEM. The hydrological model was not intended to simulate marsh hydraulics so higher-resolution marsh bathymetry data were not required.

LiDAR DEM

The Province of Manitoba collected high resolution topographic data during the fall of 2011 via airborne LiDAR (light detection and ranging) technology. Airborne LiDAR is a remote sensing technology that uses pulses of light sent from an airplane to measure the relief of the ground surface below (Liu, 2008). The LiDAR data collected by the

Province of Manitoba were provided at both one and five meter resolutions (M. Méthot, personal communication, April 2014); the five meter raster product is used throughout this project for computational efficiency. Note that only topographic LiDAR data were collected; no bathymetric information was obtained since topographic LiDAR cannot penetrate the water surface (NOAA Coastal Services Center, 2012). Spatial coverage of the LiDAR collection is described in Subsection 4.2.1. Note that this DEM product covers much of the Delta Marsh itself as well as upland areas. However, it should also be noted that this information collected during a time of high water. Significant flooding of the Assiniboine River and subsequent operation of the Portage Diversion in the spring of 2011 led to increased water levels in Lake Manitoba and the Delta Marsh. These high water levels were sustained throughout the summer and into the fall. Therefore, collection of topographic LiDAR data in this region is subject to inaccuracies in areas that were flooded at the time of capture (M. Méthot, personal communication, April 2014).

CDED DEM

Publicly available DEMs exist for most of Canada and can be obtained from databases hosted by Natural Resources Canada. At the initial time of access, this information was available via GeoBase (`http://www.geobase.ca/`) which has since been migrated to Open Government (`http://open.canada.ca/`). This DEM information is known as Canadian Digital Elevation Data (CDED) and is available at two scales: 1:50,000 and

1:250,000. The 1:50,000 scale DEM translates to a resolution of approximately 16 m wide by 23 m high (0.75 × 0.75 arcseconds) while the 1:250,000 scale DEM has a resolution of approximately 93 m wide by 65 m high (3 × 3 arcseconds) (Natural Resources Canada, 2007). Both the 1:50,000 and 1:250,000 scale DEMs cover the entire Delta Marsh region including the marsh itself and its upland watershed. Given the relatively small size of the DMW, it was determined that the 1,50:000 scale DEM would be appropriate for this study.

Merging topographic information from the three sources to form a complete DEM of the DMW can be referred to as *DEM harmonization*. This process is described in Subsection 4.2.1 and the finalized DEM is shown as part of Figure 4.2.

3.4.2 Land use

In MIKE SHE, a variety of overland flow and ET parameters are grouped by land use class such that these hydrological processes vary in space in the same way that land use does (see Subsection 4.3.5). Therefore, determining the land use distribution is an important step in building a MIKE SHE model of the DMW.

Natural Resource Canada's "Land Cover circa 2000-vector" (LCC2000-V) land cover data for the DMW region were originally downloaded via GeoBase (`http://www.geobase.ca/`) which has also since been migrated to Open Government (`http://open.canada.`

ca/). This land cover imagery is derived from the Landsat 5 and 7 ortho-images and is temporally centered around the year 2000, though data availability results in some variability (Natural Resources Canada, 2009). Spatial resolution of the land cover data is 1:50,000 and it is available in polygon shapefile format for all of Canada. LCC2000-V is formatted as polygons covering a certain area in the country, with each polygon having its own land cover attribute. There are approximately 45 different land cover classes available as part of this data set, all of which are based on the Earth Observation for Sustainable Development of Forests (EOSD) land cover classifications (Wulder and Nelson, 2003). The synthesis and preparation of land cover data for the purposes of this project is described in Subsection 4.3.5.

3.4.3 Hydrography

Understanding the surface water characteristics of any study area requires some knowledge of the water features in the region. For the DMW, hydrographic information is of particular importance for informing the watershed delineation in such a flat, prairie region (see Subsection 4.2.3). Hydrographic information is also used throughout this project to form a general reference of the creeks, rivers, lakes, and even ditches within the DMW that regularly or irregularly hold water. While experience in the field provides some knowledge of local hydrographic features, analyzing existing hydrography data is helpful for better understanding the distribution of surface water within the DMW.

Hydrographic data are available through Natural Resource Canada's "National Hydro Network" (NHN) that was established to provide a high-quality description of Canada's inland surface waters. These data were developed jointly by the federal and provincial governments of Canada and is provided at the 1:50,000 scale or better, where available. Organization of the NHN data is based on Water Survey of Canada's defined drainage areas. Downloaded as polyline or polygon shapefiles, the NHN hydrography data illustrates major water features across the country; lines and polygons representing channels and lakes near the Delta Marsh can be seen in Figure 3.1.

3.4.4 Meteorology

Environment and Climate Change Canada collects meteorological data at thousands of locations across the country and makes them available to the public online (`http://climate.weather.gc.ca/`). Climate stations near the DMW and their attributes are shown in Figure 3.5.

Section 1.2 explains how the initial goal of this project is to establish a baseline model for current conditions. Therefore, the time period for model calibration was chosen to be as current as possible. With first-hand hydrometry and other field data available only within the 2013 to 2015 time frame (see Subsection 3.3.1), it was desirable to have current meteorological data as well. Additionally, Section 4.3 outlines the benefits of hourly

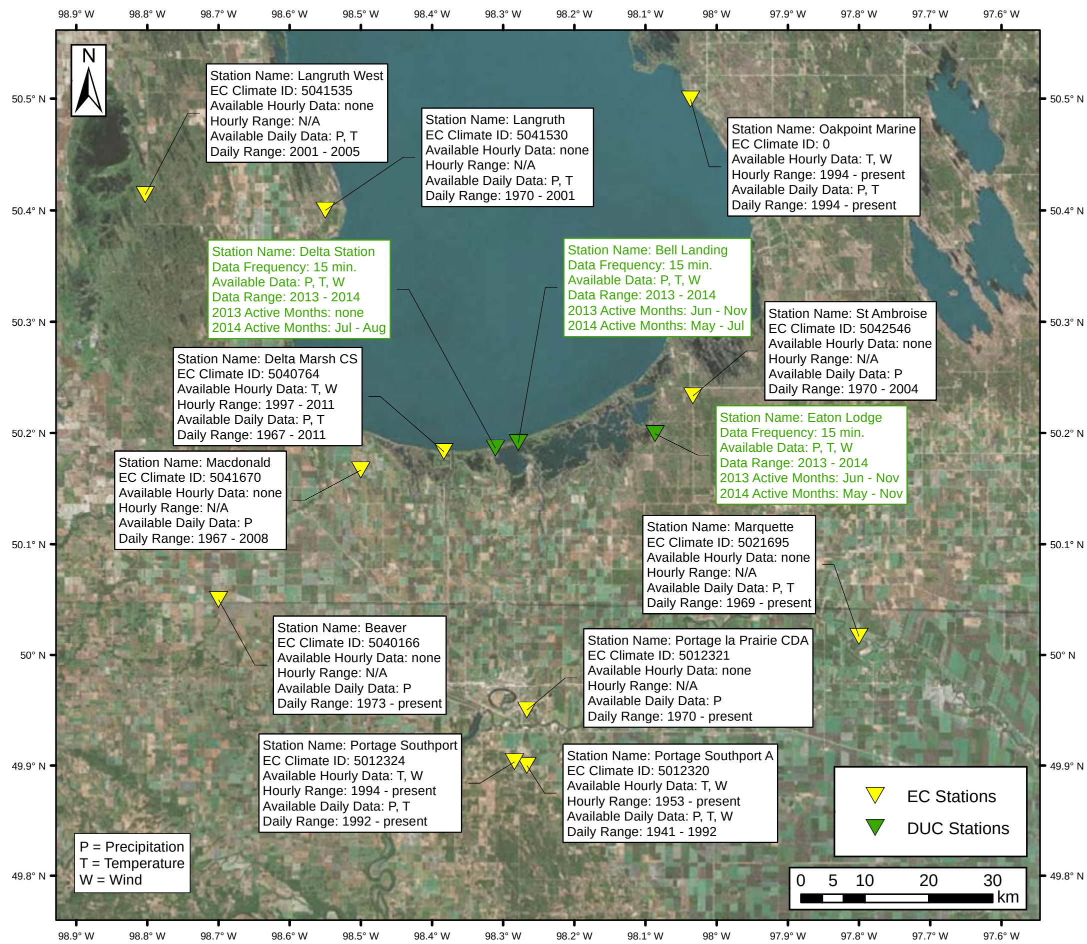


FIGURE 3.5: Climate stations and data availability near the DMW (Imagery source: ESRI)

weather data as model input and for calculation of potential ET. Therefore, the methodology for selecting climate stations for incorporation into the model was to: (1) use stations that best represent the DMW in terms of spatial coverage, (2) use the most current data available, and (3) use hourly data if possible.

Note that meteorological data including precipitation, temperature, wind speed and direction, relative humidity, and solar radiation were also collected at the Delta Marsh by DUC staff and students. The Bell Landing, Eaton Lodge, and Delta Station gauging stations are also shown in Figure 3.5. The Eaton Lodge station operated somewhat continuously during the summers of 2013 and 2014. The Bell Landing station was active through summer of 2013 but in 2014 a large storm on July 1, 2014 and associated flooding resulted in the transfer of this climate gauging equipment to the nearby Delta Station where it could continue operating and remain dry. While these stations provide valuable information on weather much closer to the Delta Marsh itself, their discontinuous and seasonal nature make them somewhat more difficult to incorporate into the hydrological model. Personal communication with DUC staff also noted that wind direction data from these stations are erroneous due to improper device orientation. Figure 3.5 shows that climate stations with hourly data are limited, as are those with data for the modelling time period (i.e. 2013-2015). Therefore, data availability and minimizing complexity led to the use of only the "Portage Southport" climate station within the hydrological model.

The Portage Southport climate station (Climate ID: 5012324) is located at Southport, Manitoba, approximately seven kilometers south of Portage la Prairie and 30 kilometers south of the Delta Marsh. This station is currently active and has daily climate data (minimum, maximum, and mean temperature; total daily rain and snow depths; snow-on-ground etc.) available since 1992 and hourly data (hourly average temperature, wind speed and direction, pressure, etc.) available since 1994. Data for the Portage Southport station were downloaded for this project from Environment Canada's online climate data repository at `http://climate.weather.gc.ca/`. Details on how these data were analyzed and incorporated into the MIKE SHE model of the DMW are provided in Chapter 4.

3.4.5 Geology

The MIKE SHE model is used to model groundwater processes in the DMW by partitioning the subsurface into an unsaturated zone (UZ) and a saturated zone (SZ) - see Section 4.3 for more details. Modelling of these subsurface layers are based on user-inputted geological regions that each exhibit different groundwater movement characteristics. Therefore, defining the subsurface conditions at the DMW is an important step in model development.

Subsurface information for the DMW was based on two Government of Canada sources: surficial geology (available through Open Government - `http://open.canada.ca/`) and the Detailed Soil Service (DSS) compilations (available from Agriculture and Agri-Food Canada's National Soil Database - `http://sis.agr.gc.ca/cansis/nsdb/index.html`). The surficial geology product illustrates, with relatively coarse polygons, the general subsurface category of a given region. As seen in Section 4.3, the classes given for the DMW are organic deposits, alluvial deposits, till blanket, and fine grained (glacio) lacustrine. The DSS compilations are of a much finer detail and were used in conjunction with the surficial geology information to aid in parameterization of the UZ and SZ components of the MIKE SHE model. This step in the modelling process is described in detail in Section 4.3.

Chapter 4

Project Methodology

This project aims to describe the water balance of the DMW using a comprehensive hydrological model of the region. Developing this model is a multifaceted undertaking that incorporates a range of geospatial and hydroclimatic information. This chapter describes the compilation and development of the important input data used as a foundation for the model. It outlines the methods used to identify the boundary of the DMW itself and how the model was built starting from this watershed delineation. This chapter details the steps taken to calibrate and validate the hydrological model, illustrating what is required to ensure the model is an accurate representation of reality. Finally, the application of the hydrological model for simulating future land use changes is described.

4.1 Hydrological Model Selection

A wide range of hydrological models exist, each with its own strengths and limitations. For the purposes of modelling DMW hydrology, the selected model must meet the following criteria:

- Simulate both surface and subsurface hydrological components;
- Incorporate and accurately represent prairie hydrology features such as snowmelt, flat topography, and depressional storage;
- Efficiently generate water balance results on both total watershed and sub-basin levels;
- Use physically-based parameters to allow for efficient calibration and modifications to reflect land use changes; and,
- Integrate effectively with other project components such as marsh hydraulics and nutrient loading/solute transport.

MIKE SHE (2012 release) was chosen as the model used for analyzing the hydrology of the DMW, characterizing its water balance, and examining the impacts of land use changes. As outlined in Subsection 2.2.1, the choice of hydrological model for a given project depends on the intended purpose of this model, the questions it is being used to answer, and some practical considerations such as cost and computational requirements. The US Army Corps of Engineers' HEC-HMS was also considered during the model selection process given its usability, accessibility, and ability to meet some of the criteria listed above. However, the main drawback of HEC-HMS in the context of the larger *Restoring the Tradition* project is its inability to seamlessly integrate with a two-dimensional hydraulic model of the marsh or simulate detailed water contaminant movement within the watershed. Importantly, HEC-HMS is also a lumped hydrological model with limited ability to incorporate detailed topographical and runoff features, and cannot incorporate depressional storage. An advantage of MIKE SHE over HEC-HMS is the fact that it is fully supported; MIKE SHE experts are available to help guide the user and troubleshoot any issues. HEC-HMS, while free to download and use, is unsupported and closed source, which can make troubleshooting more cumbersome.

MIKE SHE, originally named just "SHE" (*Système Hydrologique Européen*, or European Hydrological System) was developed by a collection of three European organizations in the mid-1970s. The SHE was first introduced in two companion papers: Abbott et al. (1986a) explains the history of this model and details of its conception while Abbott et al. (1986b) describes the structure of the model in more detail.

The current formulation of MIKE SHE can be classified as a physically-based, deterministic, and fully-distributed hydrological modelling system (Abbott et al., 1986a; DHI, 2012). The model represents each of the main land components of the hydrological cycle: interception, evapotranspiration, snowmelt, overland flow, channel flow, unsaturated zone flow, and saturated zone flow (Abbott et al., 1986b). The inclusion of subsurface components (unsaturated and saturated zone flow) and more detailed surface flow components (overland and channel flow) are some of the main benefits of MIKE SHE over some of the other prairie catchment or coastal wetland hydrology study methodologies discussed in Chapter 2. The benefits and capabilities of MIKE SHE and why it was selected for modelling the DMW are summarized by the following points:

- MIKE SHE was developed to study the impact of anthropogenic changes on a watershed, aligning directly with the second objective of this project (Section 1.2)
- The physically-based formulation allows for direct parameterization and more efficient calibration
- A fully distributed model takes advantage of the high resolution DEM data available for most of the DMW (see Subsection 3.4.1) since the model domain can be finely discretized
- The model includes both surface and subsurface components, which is important when characterizing the water balance in a study area with active infiltration and subsurface hydrology components (see Section 2.1)

- The flexibility of MIKE SHE allows for customized complexity in representing each hydrological process (i.e. a process may be represented by a physically-based algorithm when the necessary data are available or by a more conceptual calculation if there is less data available)
- MIKE SHE allows for calibration to different parameters (e.g. phreatic surface levels) than the traditional use of streamflow at basin outlet (see Section 4.4)
- MIKE SHE facilitates some of the future applications of the DMW hydrological model (e.g. nutrient or environmental tracer transport through the watershed and marsh, connection to hydrodynamic model of the marsh)
- Practicalities such as computational efficiency, a user-friendly graphical user interface, and full user support

Some potential disadvantages of using a physically-based, distributed model such as MIKE SHE are also discussed in Abbott et al. (1986a). These include the requirement for large amounts of data for parameterization (if using the physically-based and more data-intensive sub-routines) and the potential for extended simulation times and/or heavy computational requirements. These concerns are addressed in subsequent sections. Additionally, proprietary software such as MIKE SHE may be cost prohibitive to some users.

Having selected MIKE SHE for this project, the remainder of this chapter details the steps taken to develop a complete hydrological model of the DMW.

4.2 Watershed Delineation

Building a MIKE SHE model of the DMW begins with identifying the area from which the marsh receives surface water. This process is known as watershed delineation and is commonly one of the first exercises undertaken in a hydrological study. Watershed delineation sets the limits of the study. Furthermore, since runoff is proportional to area it is important to delineate the basin accurately. It was known at the onset of this project that the Delta Marsh drainage basin was relatively small. A DUC report on the Delta Marsh project estimated the watershed area to be approximately 575 km^2 and provided approximate basin extents (Ducks Unlimited Canada, 2013). The current project aims to refine this delineation based on updated topographic and hydrographic information and use the new delineation as the boundary for the hydrological model of the DMW.

The DMW is not a river basin where one can identify a single outlet point along the channel and delineate the area contributing to that location. Indeed, it can be seen in Figure 3.1 that multiple channels and creeks carry water towards the different bays comprising the Delta Marsh. It can be expected that the Delta Marsh also receives water directly off of the adjacent land. The DMW is essentially a collection of multiple, small watersheds or sub-basins that are either drained by a channel or simply by the slope of the land itself. Therefore, determining the contributing watershed for the Delta Marsh is not as simple as defining a single outlet point and delineating upstream. Contribution to this coastal wetland from the watershed takes place along a lineal outlet face which is essentially a line connecting the southern edges of each bay within the marsh. Delineating the DMW means determining the region within which all surface water passes into the marsh through this outlet face. Additionally, it will be shown that the region upland of the Delta Marsh is extremely flat and features a dynamic or poorly-defined drainage network; these characteristics also make automated delineations more difficult (Martz and Garbrecht, 1992; Bera et al., 2013). These complexities specific to the DMW led to a unique and intensive delineation process; details of this process are provided in the following sections.

4.2.1 DEM harmonization

Building a DEM for the DMW relied upon information from each of the three data sources described in Subsection 3.4.1. Given the desire for a high resolution DEM product, it was determined that using as much of the available LiDAR data as possible would benefit the development of a hydrological model of the DMW. However, some of the Delta Marsh's contributing channels are not covered by the LiDAR. Additionally, as discussed in Subsection 3.4.1, the LiDAR data are not useful in areas inundated by high water. LiDAR backscatter intensity data (also provided by the Province of Manitoba) were useful in illustrating areas for which LiDAR-derived elevation data would be inaccurate due to standing water. This information essentially traced the extents of Lake Manitoba and the Delta Marsh under the high water conditions of 2011. Fortunately, these inundated areas were mostly covered by the elevation survey performed by DUC in the 1980s, so the DUC contours discussed in Subsection 3.4.1 (extents shown in Figure 3.4) could be used instead of LiDAR in and around the marsh. Finally, the CDED DEM data were used on the east and west edges of the LiDAR to complete the DEM for the entire region.

Combining, or *harmonizing* DEM information from these three sources required geospatial processing in ArcGIS. The format of each elevation source were unified; ArcGIS tools were used to convert the DUC contours from shapefile (polylines) to gridded raster to match the formats of both the CDED and LiDAR DEMs. The CDED and DUC contour rasters were then resampled to match the five meter resolution of the LiDAR DEM. Finally, the mosaic tool was used to combine the three DEMs into one. The final, harmonized DEM is shown along with the resulting watershed delineation in the following sections. Note that the slope of this extremely flat watershed, from the furthest upland point to the southern marsh boundary, was found to be approximately 0.07%.

4.2.2 Wetland DEM Ponding Model

The Wetland DEM Ponding Model (WDPM), developed by the Centre for Hydrology at the University of Saskatchewan, is a program used to simulate the distribution of surface water in regions with prevalent depressional storage (Shook and Pomeroy, 2011). The WDPM is used to simply apply a uniform depth of water over a high resolution, LiDAR DEM and determine how surface depressions are filled and emptied (Shook et al., 2013). This tool is particularly useful in low relief prairie catchments where flow direction and contributing areas can vary with changing levels of depressional storage (Shook and Pomeroy, 2011; Shaw et al., 2012). Using the WDPM to aid in watershed delineation, however, is perhaps an extension of its original purpose. As described in Section 4.2, watershed delineation is typically focused on identifying the watershed divide, or localized high points where water does *not* pond. The WDPM, on the other hand, identifies regions in which water water *does* pond. Therefore, this model can be used to aid watershed delineation through the process of elimination: if areas where water ponds are the low points, then areas where water does *not* pond should therefore be the high points, or the watershed divide. Use of the WDPM for watershed delineation was brought upon by the aforementioned characteristics of the DMW: given that it was developed to identify distribution of surface water in flat, prairie regions, it was hoped that the WDPM could aid in delineating the DMW by better defining its drainage network.

Accessing climate normals for Portage la Prairie, it was found that 50 mm is a reasonable value to represent an average, multi-day rain event or spring melt. Therefore, 50 mm of water was added to the DEM within the WDPM to represent baseline conditions. Note that sensitivity analyses were also performed on depth of water added and it was determined that depth of water added is somewhat inconsequential since the purpose of the WDPM in this application was to locate relative high and low points. Figure 4.1 illustrates WDPM results in a selected region of the DMW with two different depths of applied water: 50 mm and 100 mm. Areas without ponding are indicated by the light blue color; these are the regions of higher local elevation that would represent a watershed or sub-watershed divide since water would not typically traverse these raised areas of land. Tracing all of these local high points within the Delta Marsh region was carried out to completely define the marsh watershed. Manual delineation techniques described in Section 4.2 were used alongside WDPM output to complete the delineation.

4.2.3 Delineation and ground-truthing

A hybrid delineation approach was necessary for this study: components of both manual and automated watershed delineation were used with output from the WDPM used to aid the manual effort. Beginning with the automated delineation, the harmonized DEM was entered as a layer in the Green Kenue hydrological modelling tool (Canadian Hydraulics Center, 2010). Although it has many uses and sub-components, Green Kenue

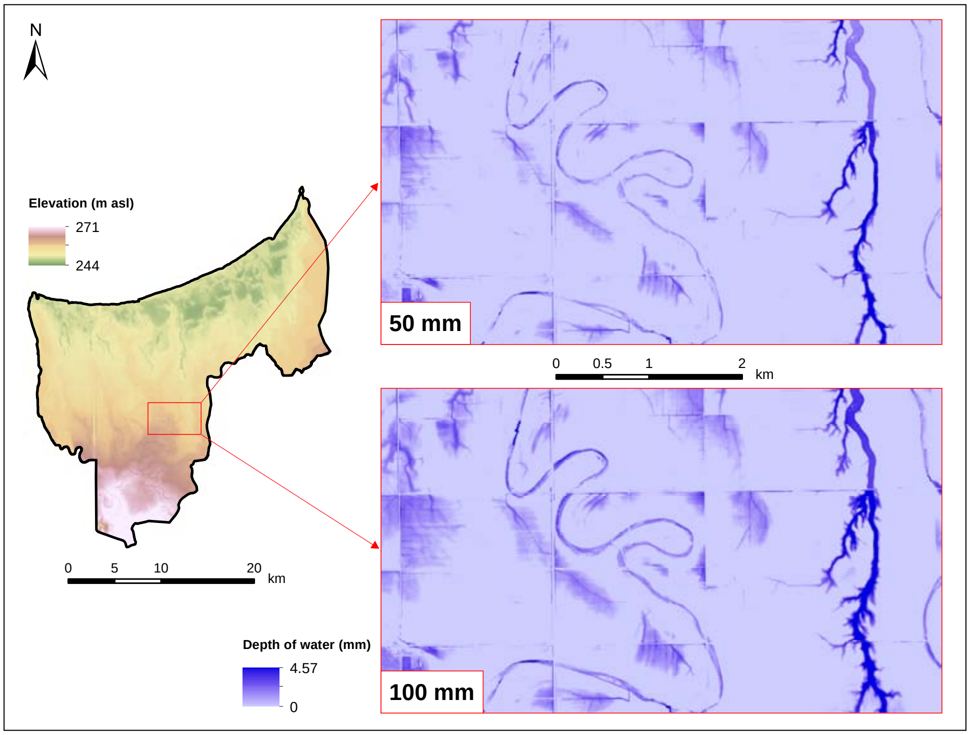


FIGURE 4.1: WDPM output for a selected region: 50 mm and 100 mm water added

was only utilized for its watershed delineation tools in this instance. After adding the DEM to Green Kenue, the embedded A^T Search delineation algorithm (Ehlschlaeger, 1989; Canadian Hydraulics Center, 2010) was implemented to attempt an automated delineation of the DEM. The resulting basin outline showed some similarities to that which was expected (comparing to estimated basin boundary shown in Ducks Unlimited Canada, 2013), but it appeared as though both the Portage Diversion and the flat topography resulted in an incomplete delineation.

Beginning with the approximate basin boundary from Green Kenue output, the manual delineation first addressed the issue of the Portage Diversion. The Diversion is another unique feature of the region, bisecting the DMW as it carries water from the Assiniboine River to Lake Manitoba (see Figure 3.1). For the purposes of this project, it is assumed that the Portage Diversion does not play a role in the hydrology of the DMW. Bounded on both sides by substantial dikes, the Diversion forms a physical barrier for any water that would ordinarily flow east-west within the watershed. Despite any connections between the Diversion and the DMW that may exist in reality (i.e. culverts, agricultural drain inputs/pump withdrawals, groundwater flow, etc.), it is assumed that there are no hydraulic connections between the Diversion and the DMW or that their role in the hydrology and water balance of the DMW is negligible. For the purposes of this study, the Diversion is conceptualized as a closed conduit, essentially transporting water *over* the DMW and directly into Lake Manitoba. Interactions between the Diversion, Lake Manitoba, and the Delta Marsh itself are discussed extensively in Aminian (2015).

Despite making this assumption, the physical presence of the Portage Diversion does exist within the DEM so it has to be considered upon delineating. It is acceptable for the watershed boundary to cross the Portage Diversion and its banks under the assumptions made. Therefore, the delineation proceeded as though the Portage Diversion was not present in the DEM; the basin boundary was manually drawn across the Diversion in accordance with the elevations in the region. This portion of the boundary separates the DMW from the Assiniboine and Whitemud River basins.

The manual delineation continued with the help of the hydrographic information described in Subsection 3.4.3 as well as the WDPM output. This information allowed for a more hydrologically conditioned delineation in which the channel network and locations of local ponding informed the delineation. Basin and sub-basin boundaries were traced within ArcGIS with DEM, WDPM output, and hydrography layers (rivers and water bodies) displayed to inform the process. Sub-basins were delineated for most of the definable channels that convey water toward the marsh. A collection of the areas that contribute surface water to these channels forms the complete DMW delineation as the exterior sub-basin boundaries are shared by the DMW boundary. Note that the sub-basins were all delineated upstream of PR227 and followed DUC naming convention. All of the channels being considered cross beneath PR227 as they flow north towards the marsh. Although PR227 runs approximately five kilometers south of the Delta Marsh, delineating upstream of the road crossings was deemed appropriate given the streamflow measurements taken at these crossings and matched. See Subsection 3.3.1 for more details on hydrometric measurements.

Finally, efforts were made to ensure that the digital delineation was accurate and representative. Ground-truthing by visual inspection was carried out to verify the basin boundary and some of the decisions or assumptions made while delineating. A number of "trouble spots" were identified from the available digital data during the manual delineation. These included locations where the drainage direction was difficult to discern, regions of unknown connectivity (i.e. presence of a culvert or ditch unknown), and locations where roads or other unnatural high-points may interfere with overland flow. The majority of these concerns were located near Portage la Prairie and the DMW's headwaters as it was initially difficult to determine the partition between land that drains towards the Delta Marsh and that which drains into the Assiniboine River. However, visually inspecting the locations in question allowed for a better understanding of basin connectivity and where the boundary is located. Ground-truthing also allowed for verification of the WDPM output. Fortunately, there was rain in the region shortly before the ground-truthing excursion and it was therefore possible to identify areas of actual surface ponding. The qualitative survey found that WDPM output did indeed agree with actual ponding conditions, affirming that this tool was useful in informing the watershed delineation. Information gathered during ground-truthing was incorporated into the watershed delineation and corrections were made where necessary. This yielded the finalized DMW and sub-basin delineations displayed in Figure 4.2. The area of the DMW was found to be 558 km^2. Also shown in the figure is the finalized DEM and the data sources from which each portion was derived (see Subsection 4.2.1).

4.3 MIKE SHE Model Development

MIKE SHE allows the user to make selections for how they wish to simulate the hydrology of a given area based on their requirements, objectives, data availability, and the

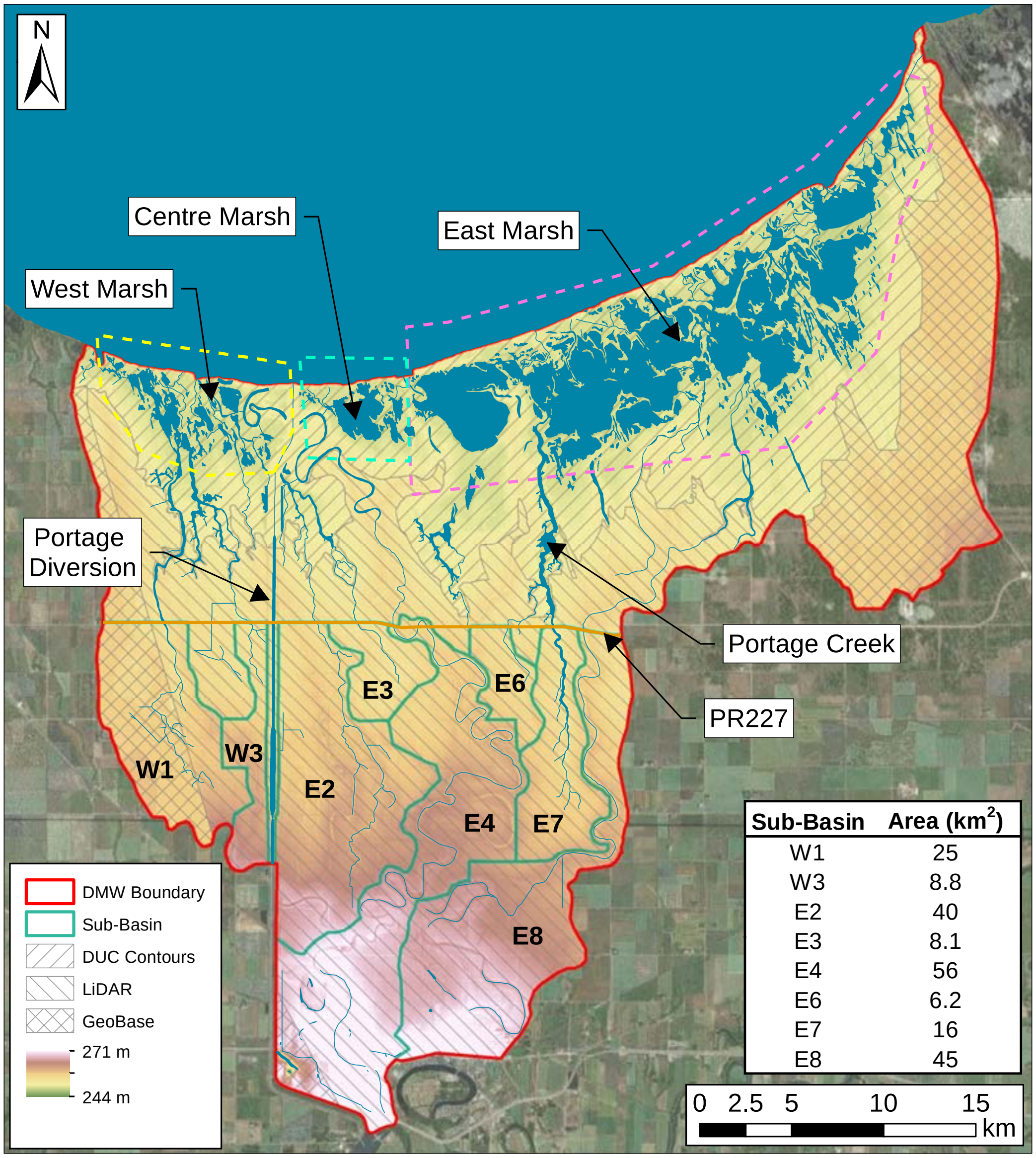


FIGURE 4.2: Delineated DMW and sub-basin boundaries and DEM sources

computational power they have at their disposal. Previous chapters have discussed each of these from a DMW context, and this section is therefore a recounting of the model setup process itself.

4.3.1 Simulation specification

Simulation specification is where the user makes selections on which processes to include in the model and how to go about simulating them. The user also specifies the temporal components of the simulation such as the start and end dates for the simulation and time steps for the various calculations that take place during a simulation.

The simulation period (i.e. start and end dates and times) for the DMW model generally depended on whether the model was being used for model calibration, model validation, or perhaps an analysis of a specific event or process as part of the calibration and validation process; see Section 4.4 and Section 4.5 for more details.

Simulation specification for the DMW model activated each of the five available components: overland flow (OL), rivers and lakes, unsaturated zone (UZ) flow, evapotranspiration (ET), and saturated zone (SZ) flow. Details on each component (i.e. solution method, conversion criteria, optional sub-components, etc.) are provided in the following subsections.

4.3.2 Model domain and grid

The DMW model and each of its components were set up in the Universal Transverse Mercator (UTM) coordinate system, zone 14N, using the North American Datum 1983 (NAD1983). Use of the distance-based UTM system (as opposed to angle-based one) is applicable for the MIKE SHE model since calculations take place on a uniform, rectangular grid, and the domain is within a single UTM zone. The *Model Domain and Grid* component allows for the definition of this model grid as well as the model domain itself. MIKE SHE represents any shape of watershed with a complete rectangle and then the actual basin outline is defined within that rectangle. For the DMW model, the domain is defined by a GIS shapefile of the watershed as delineated (see Section 4.2). MIKE SHE automatically interpolates the input basin boundary line to the defined model grid, essentially rasterizing the boundary shapefile at the specified grid size resolution.

Grid size is an important parameter of any discretized hydrological model since it determines how many "pieces" the watershed is broken down into; hydrologic calculations are performed within each of these pieces. A gridded model such as MIKE SHE simulates individual hydrological processes for each grid cell and essentially passes volumes of water from one grid to the next according to the water balance of each cell. Model discretization typically involves the evaluation of both model results and simulation time for a range of grid sizes. In the case of the DMW model, qualitative analyses found that a 200 m square grid size would be appropriate to represent the region. This grid size is appropriate for the resolution of different data inputs (described in the following subsections), and was also expected to provide simulation results in an appropriate amount of run time. As a test, the model was also set up using a 50 m grid and results were compared to the 200 m output. It was found that the finer grid did not yield substantially different results than the 200 m model although the simulation did take significantly longer to run. Therefore, it was determined that a 200 m grid size would be sufficient for modelling of the DMW.

The MIKE SHE rectangular representation of the entire model domain originates at approximately 14N 537164.6m E, 5533166.6m N and covers a total of 170 grid cells in the X direction and 200 in the Y (with each of these square cell spanning 200 x 200 meters). The DMW itself is represented by the delineated basin boundary; a total of 14,567 grid cells cover the watershed.

Finally, although the DMW model uses 200 m square cells, MIKE SHE allows for these cells to be further discretized for the purposes of the overland (OL) flow model component only in an option called “Multi-cell Overland Flow”. Using a finer grid for the OL model, specifically, allows the model to take better advantage of higher resolution topography data, if available, therefore better representing the flow of water over complex surface features. As described in Subsection 3.4.1 and Section 4.2, there is high resolution (5 m) LiDAR DEM coverage for the majority of the DMW, so using a 200 meter grid size may not fully incorporate the level of detail provided by the LiDAR. Therefore, the multi-cell overland flow option was activated and the 200 meter grid cells were further discretized by a factor of four (i.e. into 100 x 100 m square sub-cells). While further discretizing the model grids implies increased simulation time, it was found that a multi-cell factor of four did not compromise overall modelling efficiency.

Figure 4.3 depicts the model domain and grid, including the resolution of the underlying DEM, the 200 m model grid, and the 100 m sub-cells used for the OL component only.

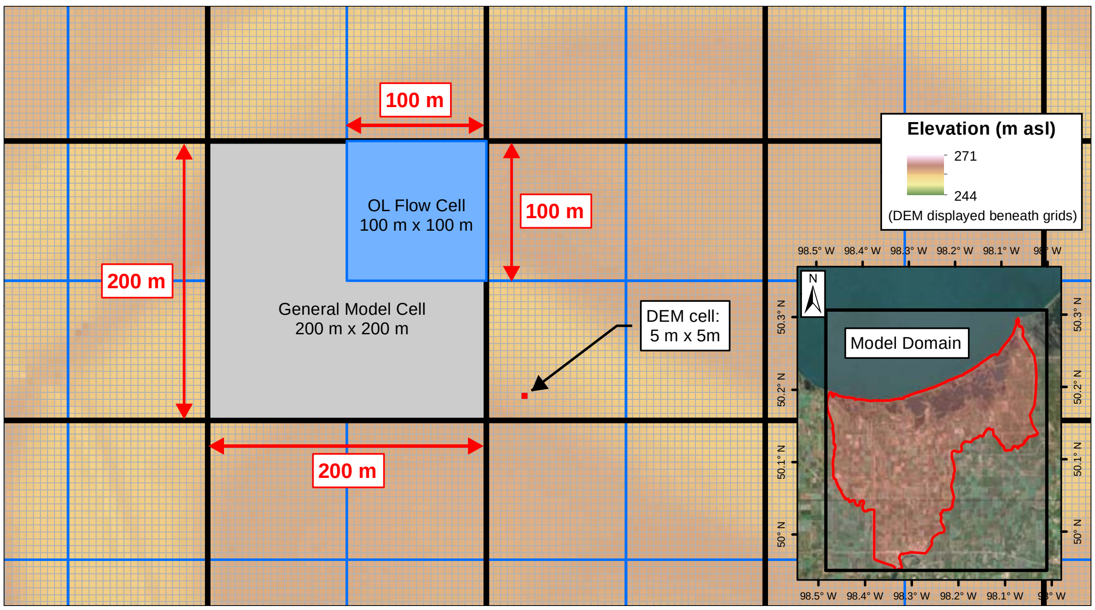


FIGURE 4.3: MIKE SHE model domain and grid layout/sizing

4.3.3 Topography

The DEM developed during the watershed delineation process (Section 4.2) was added to the MIKE SHE model to form the ground surface component of the model. In MIKE SHE, the topography input defines the upper boundary of the model: precipitation inputs are applied onto this digital surface and the hydrological calculations proceed across and beneath this boundary. The model references the inputted topography information such that the calculated hydrological processes are relative to ground elevation across the entire model domain.

As discussed in Subsection 4.2.1, the finalized DEM for the DMW has a resolution of five meters. However, it was determined that a 200 m grid size was appropriate for the DMW MIKE SHE model (see Subsection 4.3.2). Therefore, the five meter input DEM is resampled to a final resolution of 200 m, matching the model grid size and facilitating the hydrological calculations on a uniform spatial scale (with the exception of the finer discretization for overland flow - see Subsection 4.3.2). MIKE SHE's pre-processor performs resampling of spatial input files (including the DEM, land use data, etc.) prior to executing the hydrological calculations. When the user inputs the DEM as a previously-gridded raster, the pre-processor uses bilinear interpolation to convert the input resolution (five meters) to the model grid resolution (200 m). This is illustrated in Figure 4.3: the input DEM with a five meter resolution (i.e. one elevation value per 5 x 5 m cell) is resampled via bilinear interpolation to the 200 m grid resolution (i.e. one elevation value per 200 x 200 m cell) for use within the MIKE SHE model.

4.3.4 Climate

Hydrological models generally require the input of climate data to "drive" or "force" the model to simulate the watershed's hydrological response to these climatic conditions.

Just as the actual hydrologic cycle is driven by the climate, so to is the simulated hydrological cycle within a model. In the case of the DMW model, inputs of precipitation, air temperature, and reference evapotranspiration are used as forcing data.

Note that although 16 years of climate data (January 1, 2000 to May 15, 2015) were entered into the model, the user can choose to execute the model for any time period within the date range of the climate data inputs. Also note that hourly climate data was preferred as model input since model calculations were made on an hourly basis wherever possible.

Precipitation

MIKE SHE requires that precipitation input be a timeseries of *total* precipitation (i.e. snowfall and rainfall depths combined); temperature and snowmelt parameters within the model are used to differentiate between liquid and solid precipitation. For the DMW model, daily precipitation measured at the Portage Southport climate station (see Subsection 3.4.4) was used as a uniform precipitation input over the entire DMW. This climate station includes a 'total precipitation' field representing the sum of total rainfall depth and snow water equivalent depth (in millimeters) recorded at the station for the entire 24 hour period. A daily timeseries (from January 1, 2000 to May 15, 2015) of total precipitation recorded at Portage Southport was entered into the model; any missing data was filled using linear interpolation (for a single missing daily entry) or estimated from the nearest climate station with data (for multiple days without data).

Temperature

Air temperature data were used by MIKE SHE to calculate the hydrological processes of evapotranspiration and snowmelt and to determine if precipitation input is in solid (snow) or liquid (rain) form. Hourly air temperature data are available from the Portage Southport climate station for the same time period as the precipitation data (January 1, 2000 to May 15, 2015), with missing data again filled by linear interpolation or estimation from a nearby station. Figure 4.4 illustrates the 16-year daily total precipitation and hourly temperature timeseries inputted to the DMW model.

Reference Evapotranspiration

Potential evapotranspiration (PET) is defined as the maximum amount of water that could theoretically evaporate and transpirate from a vegetated surface with no limitations besides energy (i.e. with unlimited moisture available) (Lu et al., 2005; Burn and Hesch, 2007). The amount or rate of actual evapotranspiration (AET) is usually less than the PET due to the amount of water available for ET as well as vegetative properties that limit transpiration, specifically. MIKE SHE begins its AET calculation from a user-inputted timeseries of *reference evapotranspiration*, ET_0, defined as the PET

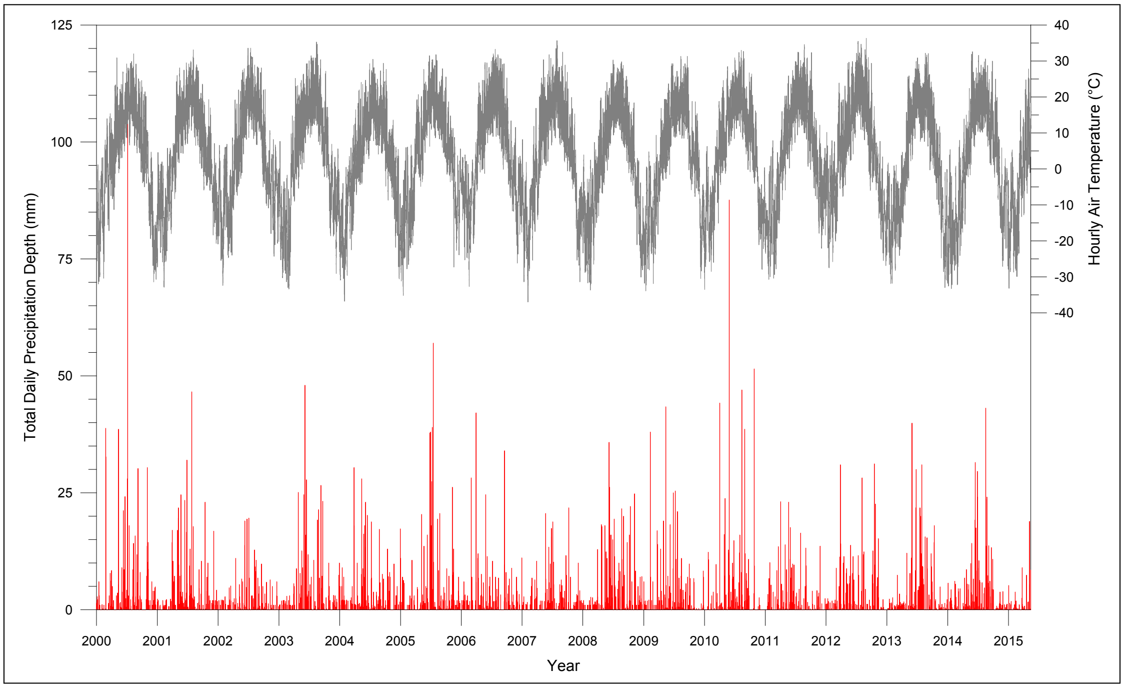


FIGURE 4.4: Input precipitation and temperature timeseries (Portage Southport ECCC gauge)

from a specific reference surface, usually a certain crop or grass type. MIKE SHE recommends calculating ET_0 using the United Nations Food and Agriculture Organization (FAO) Penman-Monteith method (FAO, 1998). Hourly records of air temperature, relative humidity, and wind speed from the Portage Southport station were used within the FAO Penman-Monteith method to derive estimates of ET_0 that were then input into MIKE SHE. Figure 4.5 illustrates the estimated hourly ET_0 timeseries for a total of 16 years, as inputted to the DMW model.

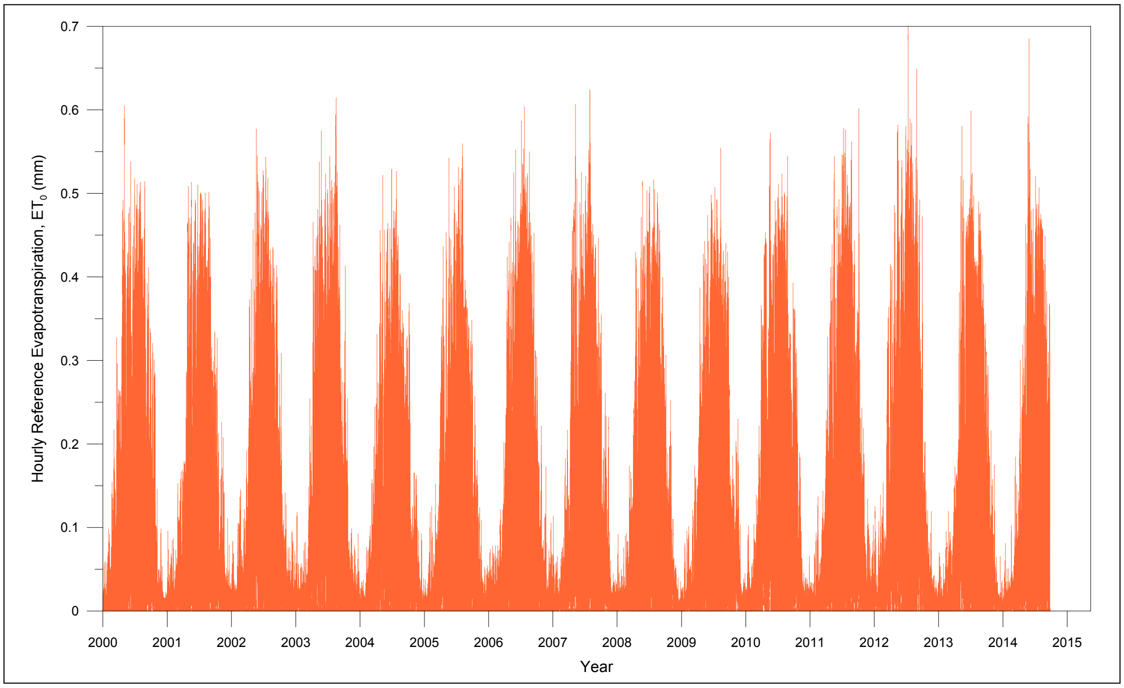


FIGURE 4.5: Input reference evapotranspiration timeseries

Snowmelt

The DMW model includes specific consideration of snowmelt and its associated processes. MIKE SHE utilizes a modified degree-day snowmelt calculation method (Abbott et al., 1986b) in which snow accumulates when air temperature is below a defined reference temperature and where snow melts above this temperature. As mentioned previously, MIKE SHE requires input of *total* precipitation depth (i.e. recorded total rainfall plus snow water equivalent); the snowmelt reference temperature is used to determine both the state of the precipitation input and the temperature at which snowmelt begins.

The modified degree-day method incorporates a snowmelt rate (in mm/°C/day) that increases as the air temperature increases above the reference temperature. The model's snowmelt method also considers snow moisture content, re-freezing of water within the snowpack with temperature changes, sublimation (i.e. evaporation of dry snow), and evaporation of liquid water entrained in the snowpack. A detailed description of MIKE SHE's snowmelt calculation method can be found in the user's reference manual (DHI, 2012). Details on input parameters and their calibration is provided in Section 5.1.

4.3.5 Land use

MIKE SHE uses inputs of land use characteristics to calculate hydrological processes such as evapotranspiration and overland flow. Land use processes are defined in the model through input of a vegetation map with a specific code for each land use type. The LCC2000-V land use data collected from Natural Resource Canada (see Subsection 3.4.2) were processed and entered to define the different land use types that exist in the DMW. The LCC2000-V data contain many different land cover fields that were either combined or excluded to create a representative yet concise description of DMW land use. The original polygon land use features were also rasterized at a 200 m cell size for input to the model. The resulting land use map includes six different fields: water, wetlands, impervious, shrub/grass land, cropland, and deciduous forest. These six land cover classes adequately describe the distribution of DMW surface features within the MIKE SHE model.

Figure 4.6 displays land use coverage of the DMW, as inputted to the MIKE SHE model. Table 4.1 describes the amount of the DMW covered by each class and provides further detail on the types of surface features found within each class. Appendix A includes a dissection of land use coverage by DMW sub-basin.

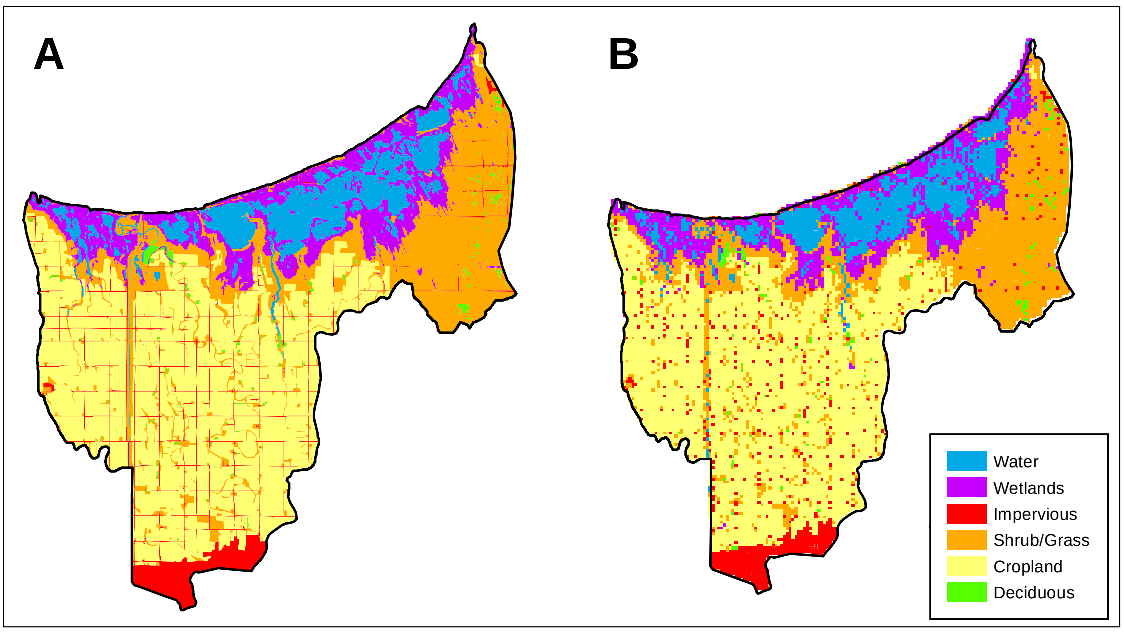


FIGURE 4.6: Land use map of the DMW. (A): Land cover classes merged from LCC2000-V data (B): Rasterized to 200 m cell size for input to MIKE SHE

Vegetation parameters are defined by the user are used to convert from reference evapotranspiration, ET_0, to actual evapotranspiration, AET (see Subsection 4.3.4). The main vegetation parameters are Leaf Area Index (LAI), Rooting Depth (RD), and Crop Coefficient (K_c), each of which can vary over time and with land use type. LAI is defined as the ratio of vegetation leaf area (e.g. total area of leaves, petals, needles, branches, etc.) per unit ground area (Hedstrom and Pomeroy, 1998), which typically ranges from zero

TABLE 4.1: Breakdown and description of DMW land use classes

Land Use Class	Surface Features	Area (km^2)	% of DMW
Water	Perennial lakes, rivers, and streams	57.7	10.3
Wetlands	Marshland or other vegetated standing water features	67.7	12.1
Impervious	Roads, urban areas, farmsteads, bare soil	31.2	5.6
Shrub/Grass	Pastureland, un-maintained grasslands, small shrubs or brush	138.0	24.7
Cropland	Seasonally-seeded agricultural lands (row crops, cereals, vegetables)	258.3	46.3
Deciduous Forest	Small bluffs of broadleaf trees, treed farmyards	5.3	0.95
	Total DMW Area	**558.2**	

to seven, depending on vegetation type (DHI, 2012). RD is the maximum depth below ground reached by the active roots of a given plant (DHI, 2012). K_c is a crop coefficient ratio used to relate ET_0 to AET where K_c = 1 means that the maximum simulated ET rate will equal ET_0 (DHI, 2012).

In the DMW model, vegetation parameters were defined via a *vegetation development table*. Vegetation coverage and rooting depths vary throughout the growing season; the vegetation development table allows the user to define a typical growing season as well as time-varying vegetation parameters associated with each land use type. For the DMW model, a typical prairie growing season was assumed to begin in mid-May and continue until the end of August. The growing season is reflected in the time-varying vegetation parameters: as vegetation grows, its LAI, RD, and Kc increase until the vegetation begins to expire or is harvested in the fall. Many studies have been carried out on these vegetation parameters: FAO (1998) describes all three parameters for agricultural land uses, Canadell et al. (1996) and Merrill et al. (2002) describe RD for a range of vegetation types, and Asner et al. (2003) synthesizes LAI observations for a range of plant types around the world. Review of this literature and number of simplifying assumptions were made while establishing vegetation property values for the DMW model. Note that determining appropriate vegetation properties was a component of the overall model calibration, described in detail in Section 4.4.

Figure 4.7 displays vegetation development properties for each of the four vegetated land use types: cropland, shrub/grass land, wetlands, and deciduous forest. No vegetation growth was assumed for the water and impervious land use classes; constant values of zero for both LAI and RD were applied to these classes to force no transpiration from these areas. Free-water evaporation is calculated separately from areas of standing water, defined within the overland flow/detention storage item in MIKE SHE (see Subsection 4.3.7).

The land use map presented in this subsection is also used for calculating overland flow since a different surface roughness value can be attributed to each land use class. Subsection 4.3.7 includes further detail on calculation of overland flow.

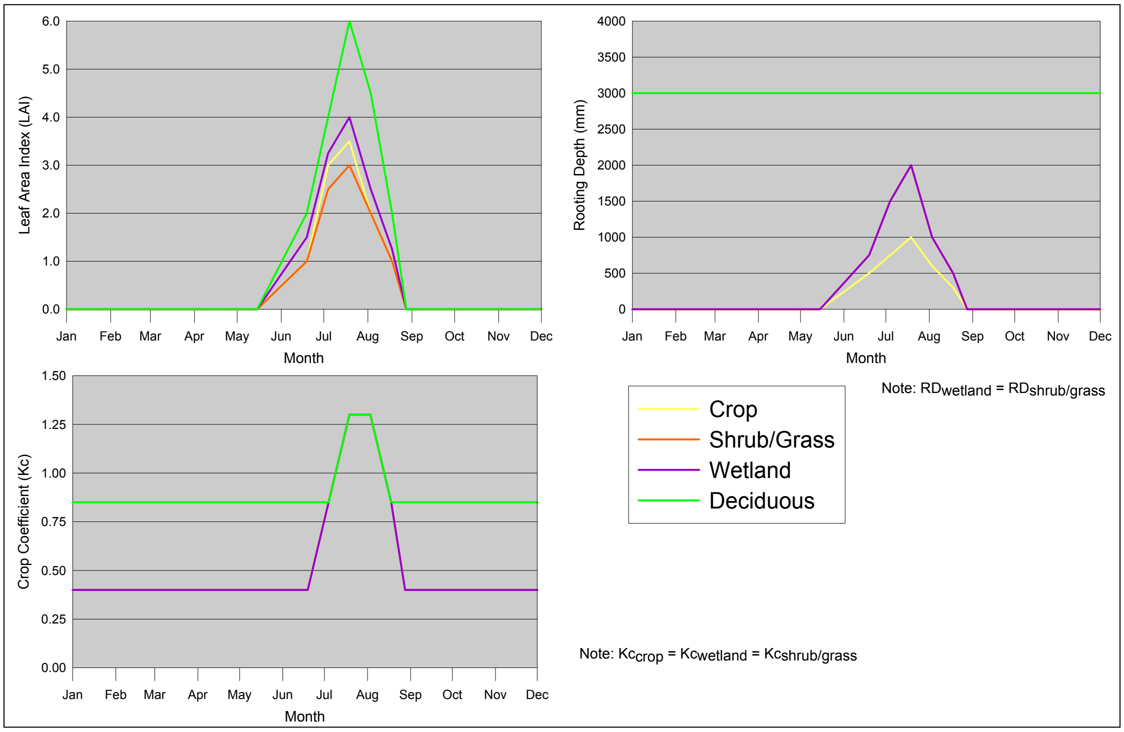


FIGURE 4.7: Calibrated vegetation properties for the DMW model

4.3.6 River and lakes

MIKE SHE uses MIKE 11, a one-dimensional hydraulic model, for simulation of channel flow within the watershed being analyzed. Coupling MIKE 11 with MIKE SHE allows for separate calculation of channel hydraulic processes with streamflow inputs sourced from the hydrological model. MIKE SHE calculates each component of the watershed's hydrological cycle and determines the quantity of water available for runoff. Once runoff is generated, it is routed overland towards local surface depressions and eventually to the watershed's rivers and lakes (see Subsection 4.3.7). After water enters a river, MIKE 11 takes over and performs the appropriate one-dimensional hydraulic calculations for routing the water downstream towards its endpoint.

In the DMW, there are a number of small rivers and streams that carry water - generally from south to north - towards the Delta Marsh. These channels are illustrated in Figure 3.1. Hydraulic simulation with MIKE 11 requires cross-sectional (i.e. bathymetric) geometry, hydraulic parameters including roughness, and boundary condition data for each channel under consideration. Calibrating the MIKE 11 model also requires observed streamflow or water level data for each channel to determine the model's accuracy in representing actual hydraulic conditions. Subsection 3.3.1 details the hydrometric field program at the DMW; Figure 4.8 and Figure 4.9 present streamflow data collected at the various hydrometric gauging locations (see Figure 3.2) for the spring seasons of 2014 and 2015, respectively.

Figure 4.8 and Figure 4.9 show that site E7 (Portage Creek) carries much more spring streamflow towards the Delta Marsh than any other channel at which measurements were taken. Personal communication with DUC staff also confirmed that Portage Creek is generally the most significant source of channelized inflow to the Delta Marsh in a given year. Given the hydrological significance of Portage Creek, the scope and objectives of this project, as well as data limitations, it was determined that only Portage Creek would be set up in MIKE 11 for detailed hydraulic modelling. The plots of measured

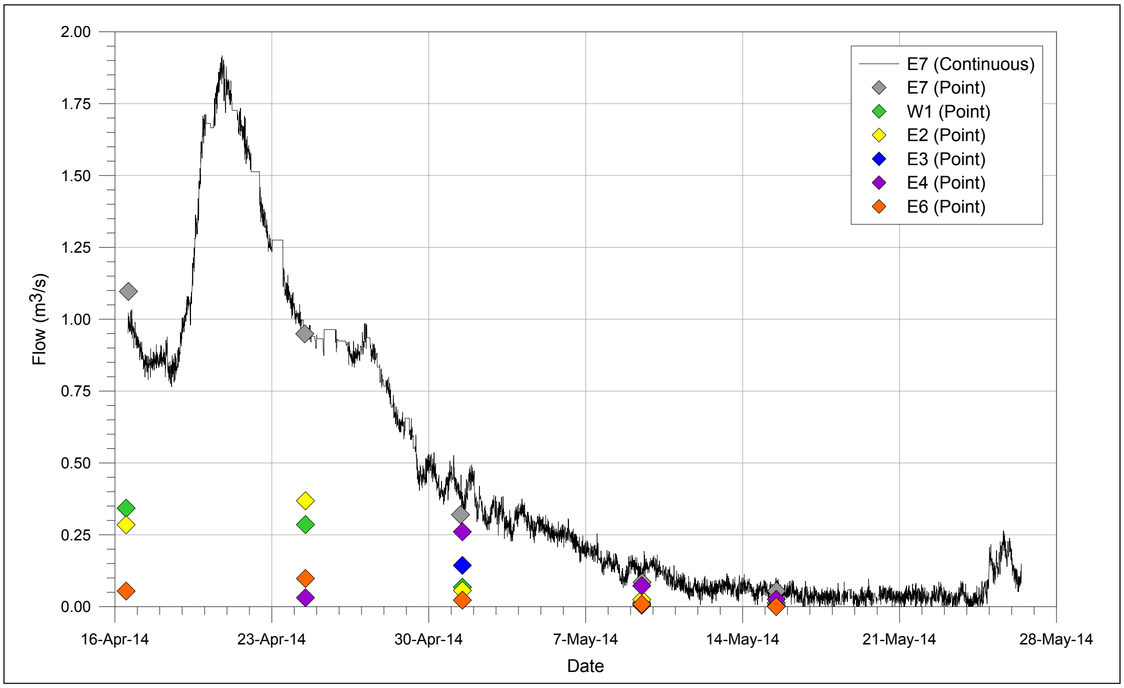


FIGURE 4.8: Measured streamflow data, spring 2014

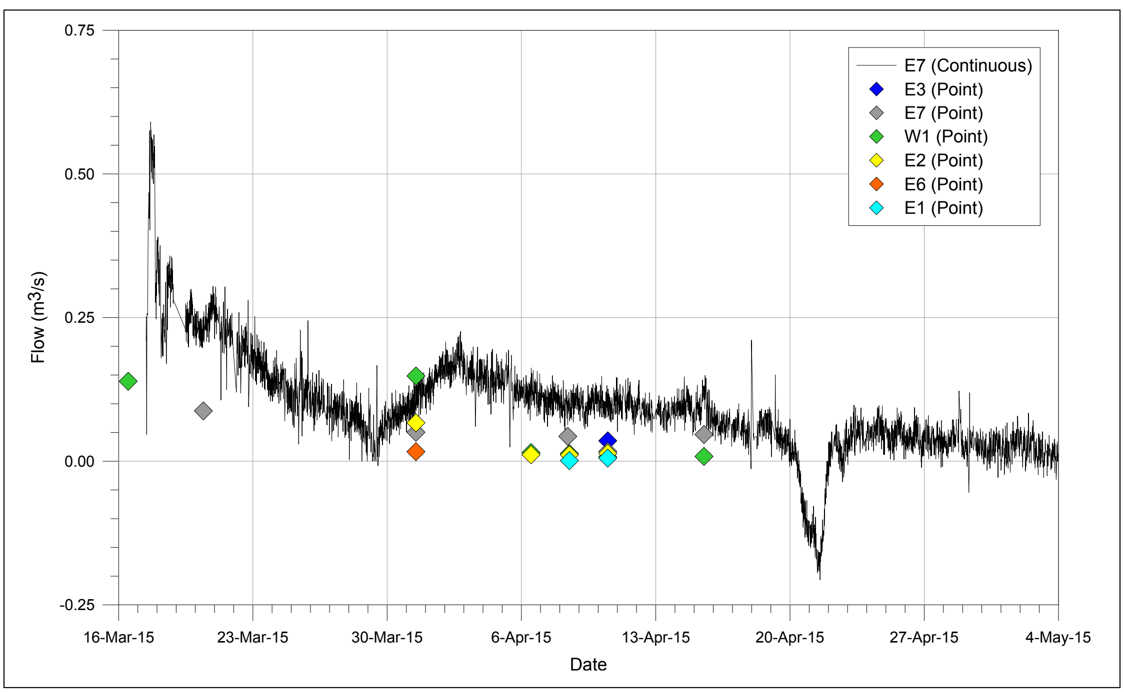


FIGURE 4.9: Measured streamflow data, spring 2015

hydrographs indicate a general shortage of streamflow data, especially the continuous streamflow data that is most useful for model calibration. Additionally, bathymetric data were not available for Portage Creek or any of the other channels within the DMW, so development of cross-sectional geometry inputs becomes a somewhat laborious process based on DEM data that may introduce additional uncertainty. Aminian (2015) provides details on the setup of the MIKE 11 model of Portage Creek including the channel definition itself as well as its cross-sectional geometry.

The MIKE 11 model of Portage Creek, established by Aminian (2015), was refined for inclusion within the MIKE SHE model of the DMW. The primary objective of the hydraulic model is to adequately simulate the channel as a part of the larger DMW model and to use results from the MIKE 11 component for comparison to measured data (i.e. model calibration). As such, a relatively simple approach was taken for the Portage Creek hydraulic model. After establishment of the model and its geometry by Aminian (2015), hydraulic parameters and boundary conditions were determined.

While MIKE 11 offers a wide ranging functionality, only the one-dimensional hydrodynamic routing component was activated for the DMW model. No ice formation, sediment transport, groundwater leakage, or climatic components were activated in this application. A Manning's roughness (n) value of 0.04 was used for the entire Portage Creek hydraulic model to reflect the relatively straight but vegetated nature of the channel.

Model sensitivity analysis and calibration confirmed 0.04 as an appropriate Manning's n value.

Since Portage Creek flows north and eventually enters the Delta Marsh at Portage Creek Bay, the marsh water level was used as a downstream boundary condition for the embedded MIKE 11 model. Aminian (2015) provides details on the Delta Marsh open water field program, including the collection of water level data at various points around the marsh. While water level collection on the marsh covered only the 2013 and 2014 open water seasons, a longer record was desired as a boundary condition for Portage Creek. However, long-term water level data on Lake Manitoba are available from Water Survey of Canada ("Lake Manitoba at Westbourne", WSC station 05LL012) and it was shown through Aminian's research that Lake Manitoba and Delta Marsh water levels are heavily correlated (Aminian, 2015). Therefore, a simple statistical exercise was performed where overlapping water level data at both Portage Creek Bay (into which Portage Creek flows), WL_{PC} (collected by Aminian and others) and Lake Manitoba at Westbourne, WL_{LakeMB} (available online from WSC) was first compared and a linear regression equation was fit, as shown in Equation 4.1 (R^2 = 0.93).

$$WL_{PC} = 0.97 \times WL_{LakeMB} + 6.48 \tag{4.1}$$

This regression equation was then applied to the full water level record from the WSC gauge to create a synthetic water level timeseries for Portage Creek Bay to be used as the downstream boundary condition for the MIKE 11 Portage Creek model. No upstream boundary condition was applied to the Portage Creek model since it is embedded within MIKE SHE, receiving lateral runoff along its entire length.

4.3.7 Overland flow

The overland flow component of MIKE SHE simulates the movement of surface water within a watershed and is mainly defined by inputs of topography (see Subsection 4.3.3), surface roughness, and detention storage. For the DMW model, MIKE SHE's finite difference overland flow module was activated. This method approximates the two-dimensional St. Venant Equations using an explicit numerical diffusive wave approximation and is recommended for complex local overland flow regimes (DHI, 2012). This method translates water overland while accounting for attenuation due to surface roughness and interaction with depressional storage. Additionally, the "Multi-cell Overland Flow" option was activated to further discretize calculations given the importance of this model component and the availability of high resolution elevation data (see Subsection 4.3.2).

The finite difference method uses a surface roughness parameter to calculate overland flow between each grid cell. For the DMW model, grid cell surface roughness was defined based on land use class (see Subsection 4.3.5) such that each class has a unique roughness value. Determining an appropriate surface roughness value for each land use class is an iterative process within the sensitivity analysis and calibration of the model parameters (see Section 4.4). The calibrated surface roughness values for each land use class are shown in Table 4.2. Note than an n value of 1.0 is applied to the water class so that MIKE SHE does not calculate overland flow through these permanently wet areas but can still receive overland flow from adjacent cells.

TABLE 4.2: Calibrated surface roughness parameters

Land Use Class	**Manning's n**
Water	1.000
Wetlands	0.300
Impervious	0.028
Shrub/Grass	0.060
Cropland	0.040
Deciduous Forest	0.100

Detention storage is defined in MIKE SHE as shallow surface depressions that must fill with water before surface flow can begin. In MIKE SHE, water contained in depressional storage can infiltrate into the ground or evaporate to the atmosphere but does not flow overland into an adjacent cell. In addition to watershed delineation (see Subsection 4.2.2), WDPM was used to define detention storage depths for the DMW. WDPM uses topographic data to determine quantity and location of surface water ponding in response to a defined amount of rainfall. Therefore, WDPM output from a 50 mm rainfall addition (see Subsection 4.2.2) was used to define detention storage depths for the DMW model.

A primary goal of this study is to quantify the amount of water passing from each sub-basin of the DMW into each bay of the Delta Marsh (see Section 1.2). As discussed in the Introduction (see Chapter 1), the DMW passes water into the marsh through multiple creeks as well as via local overland runoff. Subsection 4.3.6 describes how only Portage Creek was modeled as an actual river in MIKE 11. Streamflow through the remaining channels, as well as runoff via local drainage, are only captured by MIKE SHE's overland flow calculations. While calculated overland flow quantities can be exported at a given grid cell, a MIKE SHE extension called *FlowThroughLine* was implemented to determine overland flow across a user-defined line or profile. Figure 4.10 displays the defined flow lines for the DMW model. In the *FlowThroughLine* application, the user defines grid cells across which the total overland and/or saturated zone flow is determined. Referring to Figure 4.10, *FlowThroughLine* calculates total overland and saturated zone fluxes from the green cells to the red cells, the border between these cells forming the actual "flow line". The figure depicts each line with a different colour to illustrate where they stop and start; each line is also labeled with an identification number. These flow lines were established to define total overland flow entering the marsh along its southern boundary, but were separated into the 21 lines shown in Figure 4.10 to identify flow fluxes into specific regions of the marsh and to capture flow entering the marsh through known creeks and channels.

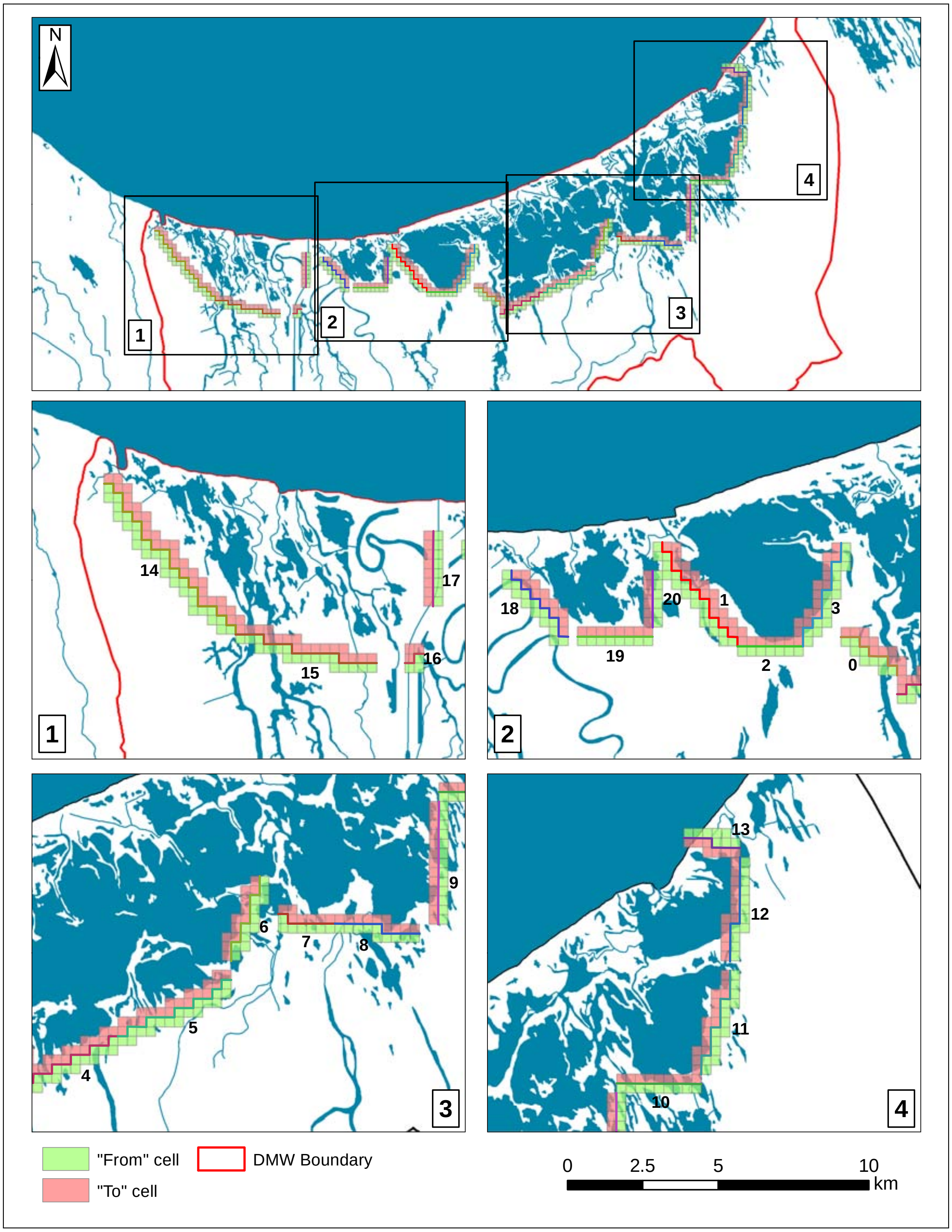


FIGURE 4.10: Flow Lines for *FlowThroughLine* application

4.3.8 Unsaturated zone

The unsaturated zone (UZ) is defined as the region below the ground surface and above the water table. Soil moisture in the UZ is added when water infiltrates into the ground and is removed when it evapotranspirates or flows downwards to the saturated zone. Therefore, MIKE SHE defines UZ flow as vertical/one-dimensional only. Of the three available UZ calculation methods, the two-layer water balance method was chosen for modelling the DMW. This method is applicable in regions of shallow groundwater where AET is approximately equal to PET (DHI, 2012). The first layer represented by this method is the vegetation layer, defined by LAI and rooting depth properties associated with each land use class (see Subsection 4.3.5). Interception and UZ evapotranspiration are calculated based on these vegetation properties. The second layer is the unsaturated soil itself where a constant infiltration capacity is defined by water content parameters and vertical hydraulic conductivity. The Green & Ampt method (Mishra et al., 2003) was selected for infiltration calculations as a physically-based approximation of the Richards Equation DHI (2012). Macropore flow calculations were not included in the model.

The UZ of the DMW was classified into five different regions based on the geological data described in Subsection 3.4.5. Each subsurface class has its own set of parameters with which to represent UZ processes; it is assumed that soil properties are uniform within a given subsurface class. Figure 4.11 illustrates the spatial coverage of the five subsurface classes used for the DMW.

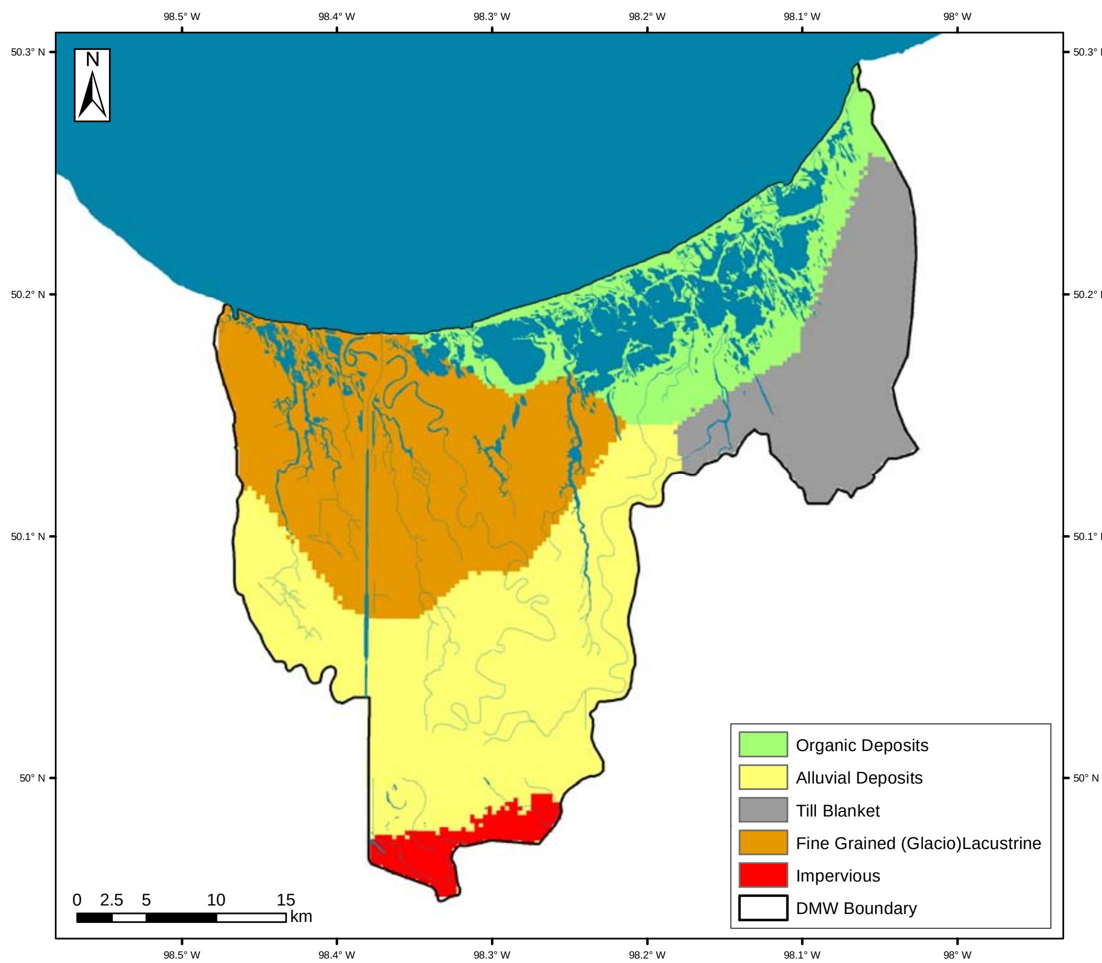


FIGURE 4.11: Spatial coverage of DMW subsurface classes

The two-layer UZ component requires input of five parameters for each soil class: water content at saturation; water content at field capacity; water content at wilting point; saturated vertical hydraulic conductivity, K_{sat}; and soil suction at wetting front. These soil properties are defined in Table 4.3 (DHI, 2012).

TABLE 4.3: Definitions of UZ soil properties

Soil Property	Unit	MIKE SHE Manual Definition
Water content at saturation	—	Max. water content; approx. equal to porosity
Water content at field capacity	—	Water content at which vertical flow becomes negligible/drains freely
Water content at wilting point	—	Lowest water content at which plants can extract water
Saturated hydraulic conductivity, K_{sat}	m/s	Max. vertical infiltration rate
Soil suction at wetting front	m	Capillarity factor for adjusting K_{sat}

Since MIKE SHE uses physically-based soil parameters, parameterizing each UZ class began with tabulated values associated with the general soil types. Textbook hydraulic conductivity and soil suction values for a range of soil types were accessed from Mays (2011); water content/holding capacity values were accessed online from Agvise Laboratories `http://www.agvise.com/`. The sources provided soil properties that were used as a starting point in the calibration process (see Section 4.4). Parameters were altered slightly from their textbook values to achieve reasonable simulation results while remaining physically representative. Table 4.4 displays final, calibrated soil parameters (except for K_{sat}) used for simulating the DMW's unsaturated zone. Saturated vertical hydraulic conductivity details are included in Table 4.5, following discussion of frozen soil infiltration.

The DMW is subject to frozen or partially frozen soils during the winter months, as detailed in Subsection 2.1.3. As such, mid-winter or even spring snowmelt runoff may not

TABLE 4.4: Calibrated UZ soil parameters

	Water Content at:			Soil Suction at
	Saturation	**Field Capacity**	**Wilting Point**	**Wetting Front (m)**
Organic	0.38	0.29	0.11	-0.2
Alluvial	0.33	0.24	0.13	-0.2
Till	0.33	0.24	0.13	-1.0E-04
Fine grain	0.38	0.29	0.13	-0.05
Impervious	0.01	1.0E-05	1.0E-06	-1.0E-06

infiltrate at the same rate as in the summer time. MIKE SHE does not include an option for frozen or partially frozen soil infiltration but erroneous infiltration rates may be calculated if summer infiltration rates are applied to the winter or spring. However, the model does include an option for a time-varying *surface-subsurface leakage coefficient*. This option is normally used to limit infiltration in locations where soil compaction or fine sediment deposits form a nearly impervious "crust" at the ground surface, such as a lake bottom or flood plain. The user is able to manually define a leakage coefficient which replaces vertical horizontal conductivity for infiltration calculations and can vary in both time and space. Therefore, this option was applied for frozen soils by setting the leakage coefficient to a very low value over the winter months. Similarly, a reduced leakage coefficient was applied for the early spring season when partially frozen soils can be expected. For the rest of the year, however, normal hydraulic conductivities were used for infiltration calculations. Table 4.5 illustrates the time-varying hydraulic conductivities/leakage parameters for each soil class.

TABLE 4.5: Calibrated hydraulic conductivities and leakage coefficients

	K_{sat} (m/s)	Leakage Coefficients (m/s)	
		Partially Frozen	**Frozen**
Organic	2.6E-04	2.6E-05	1.0E-15
Alluvial	1.5E-04	1.5E-05	1.0E-15
Till	1.1E-04	1.1E-05	1.0E-15
Fine grain	1.4E-04	1.4E-05	1.0E-15
Impervious	1.0E-15	1.0E-15	1.0E-15

MIKE SHE requires a consistent leakage coefficient time step throughout the simulation; a 31 day time step was selected for the DMW model (i.e. a given set of leakage coefficients may only change once every 31 days). This constraint causes the transition dates (i.e. from normal to frozen, frozen to partially frozen, and partially frozen back to normal) to vary slightly from year to year within the 15 year simulation period. Table 4.6 displays the range of transition dates used within the surface-subsurface leakage coefficient model component. The table illustrates how "normal", unfrozen soil conditions typically extend from May 1 to November 12, frozen soils last from November 12 to March 31, and partially frozen soils extend from March 31 to May 1. These dates were based partially on climate normals for the region (see Subsection 2.1.1) and were part of the overall model calibration process. Note that no partially frozen soil was simulated during the fall/winter transition because sensitivity analyses showed little infiltration during this time of year.

TABLE 4.6: Transition date ranges for surface-subsurface leakage coefficients

Transition	Earliest	Median	Latest
Normal to frozen	Oct 26	Nov 12	Nov 27
Frozen to partially frozen	Feb 16	Mar 31	Apr 16
Partially frozen to normal	Mar 19	May 01	May 17

4.3.9 Saturated zone

The saturated zone (SZ) component of MIKE SHE describes saturated groundwater flow. The Finite Difference SZ method was chosen for modelling the DMW as it is a fully three-dimensional representation of saturated subsurface flow. This method numerically solves the Darcy equation via an iterative finite difference technique (DHI, 2012). For the DMW model, a single geological layer was assumed to represent the saturated zone. In the vertical plane, this layer is bounded by the dynamic phreatic surface above and a defined "lower level" elevation below; the three-dimensional finite difference flow calculations are performed within this vertical layer and across the horizontal plane. A lower level of 10 m below the ground surface was chosen for the DMW model as it was assumed that any interaction between surface and groundwater, and any seepage from the SZ into the Delta Marsh, would occur within a 10 m thick subsurface layer. This geological layer, representing the vertical (z) plane, is separated into five "geological units", representing the horizontal (x and y) plane. These geological units are identical to the unsaturated zone classes (see Figure 4.11), under the simplifying assumption that the

DMW subsurface is consistent throughout its depth. In the horizontal plane, the SZ is assumed to be confined by the DMW boundary around the south, east, and west sides and by Lake Manitoba to the north. A no-flux boundary was selected for the DMW boundary so that no groundwater may pass into or out of the DMW along its south, east, and west sides. It is assumed that groundwater levels near Delta Marsh and Lake Manitoba are very close to the surface. Therefore, a fixed head condition was set for the northern SZ boundary: recorded Lake Manitoba water levels (from WSC gauge 05LL012) were applied as the northern SZ boundary condition.

SZ groundwater calculations are dependent on four hydrogeologic parameters for each geological unit: specific yield; specific storage; horizontal hydraulic conductivity, K_x; and vertical hydraulic conductivity, K_z. These soil properties are defined in Table 4.7 (DHI, 2012). Final, calibrated SZ parameters are shown in Table 4.8.

TABLE 4.7: Definitions of SZ hydrogeologic properties

Hydrogeologic Property	**Unit**	**MIKE SHE Manual Definition**
Specific Yield	—	Volume of water released per unit surface area of aquifer per unit decline in head
Specific Storage	m^{-1}	Volume of water released per volume of aquifer per unit decline in head
K_x	m/s	describes ease of horizontal water passage through soil (typ. 5 to 10 times greater than K_z)
K_z	m/s	describes ease of vertical water passage through soil

TABLE 4.8: Calibrated SZ hydrogeologic parameters

	Specific Yield	**Specific Storage (m^{-1})**	**K_x (m/s)**	**K_z (m/s)**
Organic	0.09	0.0001	1.0E-02	2.6E-04
Alluvial	0.09	0.0001	2.0E-04	1.5E-04
Till	0.09	0.0001	1.0E-03	1.1E-04
Fine grain	0.09	0.0001	1.5E-04	1.4E-04
Impervious	0.09	0.0001	1.0E-07	1.0E-15

4.4 Model Calibration

Hydrological model calibration is the process of refining the model parameters to ensure the model adequately represents reality or serves its intended purpose. Calibration is typically an iterative process that involves examining the model's sensitivity to certain parameters and comparing model results to measured data. The calibration process depends on how the model is being applied; the methodology used to calibrate the DMW hydrological model is summarized in the following subsections.

4.4.1 Calibration data

Hydrological model calibration relies on measured, real-world data. The objective of model calibration is not only to ensure that simulated results match measured data as closely as possible, but also that the real hydrological processes involved are being accurately described by the model (i.e. getting the "right answers for the right reasons")

(Kirchner, 2006). As such, it is important to define the measured data that will be used for calibration as it is the only confirmation that a model is accurately or adequately representing reality.

The DMW model was primarily calibrated to measured streamflow in Portage Creek at the PR227 crossing location. An objective of this project is to quantify overland flow from the DMW into the Delta Marsh (see Section 1.2). As such, Portage Creek streamflow was used as the primary calibration variable to emphasize the surface components of the DMW water balance.

Subsection 3.3.1 describes how Portage Creek discharge data were collected during the springs of 2014 and 2015. Figure 4.8 and Figure 4.9 illustrate that spring 2014 Portage Creek streamflow is significantly greater than the 2015 record. The 2014 streamflow also more closely resembles a typical spring hydrograph (i.e. rising limb, peak, and recession to near zero streamflow). Therefore, spring 2014 (specifically April 10, 2014 to May 26, 2014) was used as the Portage Creek streamflow calibration period. Spring 2014 streamflow measured in Portage Creek at the PR227 location is presented in Figure 4.12; this hydrograph was used as the primary calibration data for the DMW model.

In comparing the original measured data (Figure 4.8) to the calibration data (Figure 4.12), it should be noted that a linear rising limb was artificially added to the measured flow record. When streamflow data collection began in the spring of 2014, the first data point

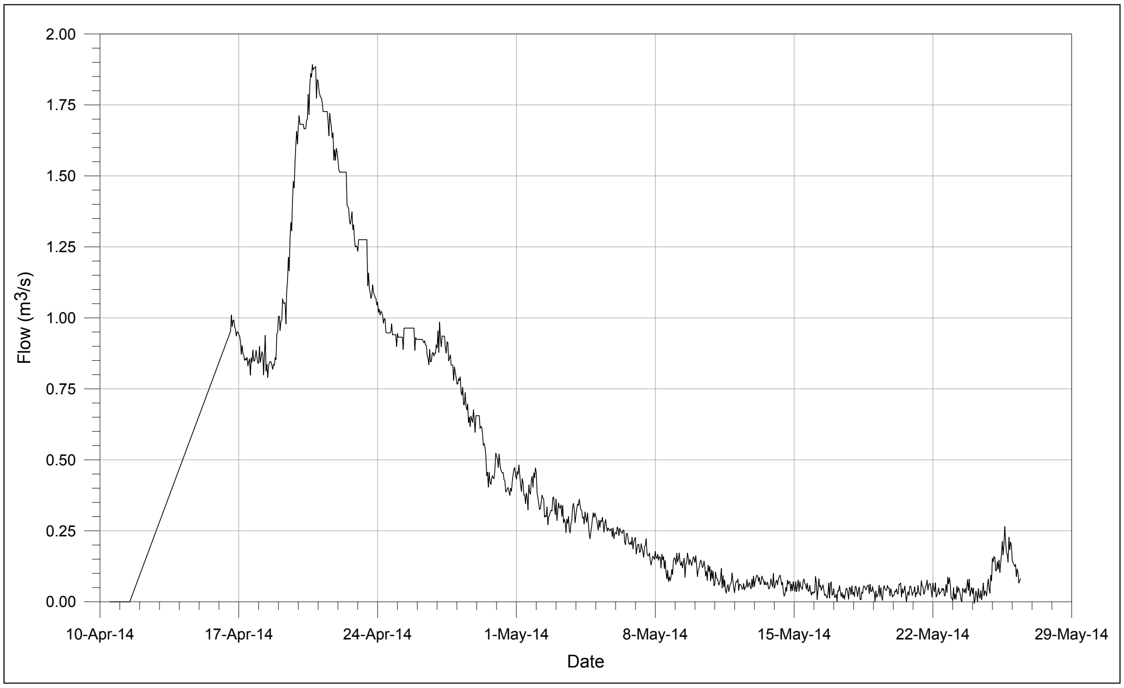


FIGURE 4.12: Spring 2014 calibration data - Portage Creek streamflow

collected showed a streamflow of approximately 1.0 m^3/s on April 16, 2014. However, separate data collection by DUC staff showed that streamflow in Portage Creek was zero or near-zero on April 10 and 11. Therefore, it was concluded that streamflow in Portage Creek rose from zero on April 11 to approximately 1.0 m^3/s on April 16. Having no actual measured data between these dates, a linear interpolation between zero and 1.0 m^3/s was assumed to fill this gap. Adding this artificial rising limb allowed for a more accurate model calibration: if actual Portage Creek streamflow rose from zero to approximately 1.0 m^3/s the simulated streamflow should display similar hydrological behavior.

In addition to the Portage Creek streamflow data, select groundwater data were also used for model calibration. Groundwater data were provided by Manitoba Sustainable Development; provincial groundwater well "G05LL001 R-1" is located within the DMW and has been recording daily phreatic surface elevation (i.e. depth to groundwater) since 1970. This wire-wound monitoring well is installed at the base of an unconfined sand layer, approximately 24 ft deep. Figure 4.13 displays the recorded groundwater data and the location of well G05LL001 R-1 within the DMW. This groundwater data are copyright to the Province of Manitoba and was obtained from Manitoba Sustainable Development staff (G. Phipps, personal communication, 8 July 2015).

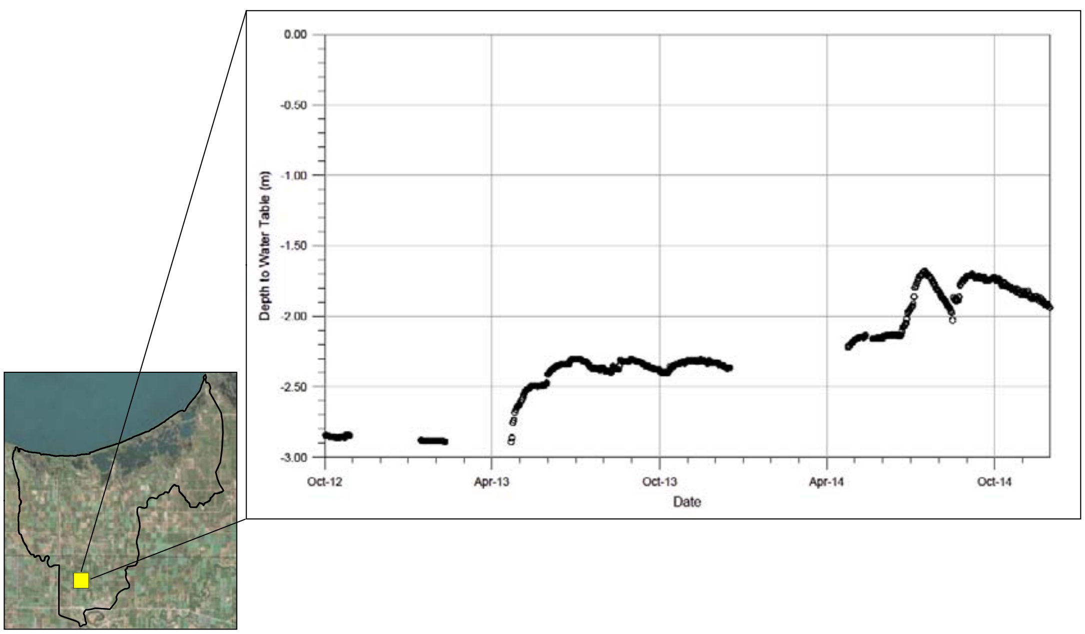


FIGURE 4.13: Groundwater calibration data and well location

Note that while the groundwater depth record spans more than 40 years, only October 2012 until November 2014 was used for calibration of the DMW model. Comparing simulated to measured phreatic surface depths at the provincial well location provides feedback on the model's groundwater processes; a match between simulated and measured groundwater depth would suggest that the UZ and SZ parameters used within the DMW model are representative of reality.

4.4.2 Calibration statistics

While hydrological model calibration typically involves visual comparison of a simulated hydrograph to a measured hydrograph, or some other "simulated versus measured" visual comparison, this type of "face-value" inspection alone may not be descriptive enough to judge calibration progress. Calibration statistics are commonly used to consistently describe the degree to which simulated results match measured data. Several goodness of fit statistics were used during calibration of the DMW model to: (1) provide an index of calibration "cause and effect" (i.e. to examine the effect of changing a certain model parameter) and (2) define stopping criteria for the calibration (i.e. when it can be deemed that the calibration objectives have been met). Each of these statistics was applied to the comparison of simulated to measured streamflow in Portage Creek at PR227.

The first statistic used to describe the fit between simulated results and measured data was *percent deviation* in streamflow, or $\%Dv$. This parameter reflects the total discharge volume difference between simulated and measured streamflow, but does not describe any timing discrepancies between the two. $\%Dv = 0$ indicates no difference between simulated and measured flow volume; a negative $\%Dv$ indicates an under-estimation of discharge volume by the model; a positive $\%Dv$ indicates an over-estimation of discharge volume by the model. $\%Dv$ is calculated as per Equation 4.2.

$$\%Dv = \frac{\sum_{i=1}^{N} \left(Q_{sim,i} - Q_{meas,i}\right)}{\sum Q_{meas,i}} \times 100 \tag{4.2}$$

where:

$Q_{sim,i}$ = simulated streamflow at i^{th} time-step

$Q_{meas,i}$ = measured streamflow at i^{th} time-step

i = time-step index

N = maximum time-step index = total number of time-steps

Root Mean Square Error (RMSE) was also used as a calibration statistic. RMSE quantifies the average difference between simulated and measured streamflow at the same time-step, quantifying both volume and timing discrepancies. RMSE approaches 0 for a perfect match between simulated and measured streamflows and is calculated as per Equation 4.3.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(Q_{sim,i} - Q_{meas,i}\right)^2} \tag{4.3}$$

The Nash-Sutcliffe Efficiency (NSE) describes both timing and volume discrepancies between simulated and measured streamflows and quantifies the efficiency of the model at describing the variance in measured data (Nash and Sutcliffe, 1970). The NSE relates the simulated results to the average measured streamflow and its value reflects which is a better “predictor” of the measured flow record. For example, a positive NSE value indicates that the simulated streamflow results are a statistically superior predictor of the measured flow record than is the average measured flow. Conversely, a negative NSE value indicates that the average observed flow is a more reliable predictor of measured flow than is the model. A NSE value of 1 reflects a perfect match between simulated and measured flows. NSE is calculated as per Equation 4.4.

$$NSE = 1 - \frac{\sum_{i=1}^{N} \left(Q_{sim,i} - Q_{meas,i}\right)^2}{\sum_{i=1}^{N} \left(Q_{meas,i} - \overline{Q}_{meas}\right)^2} \qquad (4.4)$$

where:

$\overline{Q}_{meas}$ = average measured streamflow

All of these statistics have their shortcomings: $\%Dv$ does not describe timing differences between simulated and measured flows while RMSE and NSE tend to over-emphasize the peak flows and disregard lower flows. Therefore, all three statistics were used in combination with visual inspection of the results to fully assess the calibration.

4.4.3 Calibration procedure

Calibration began once the MIKE SHE model was created, meteorological and geospatial inputs were added, initial model parameters established, and the appropriate settings were chosen so the model was operational and outputting results for comparison to measured data (see Section 4.3 for details on hydrological model setup). During the calibration process, the overall MIKE SHE model simulation period was from October 1, 2012 until May 15, 2015. However, streamflow calibration (simulated versus measured streamflow in Portage Creek at the PR227 crossing) was from April 10, 2014 to May 26, 2014 and groundwater calibration (simulated versus measured groundwater depth at Provincial well G05LL001 R-1) was from October 1, 2012 to November 30, 2014. These two calibration exercises occurred iteratively and concurrently, following the simplified calibration flow chart shown in Figure 4.14.

This flow chart is simplified as a number of additional “checks” were also performed after each model execution. Throughout calibration, water balance results were also analyzed to gain insight into how the model is representing each hydrological component and how parameters affect them. For example, model outputs of infiltration and groundwater recharge depths were examined and compared to precipitation depths to determine the proportion of precipitation that enters the UZ and then the SZ. In this way, the model calibration focused on the internal hydrological processes as well

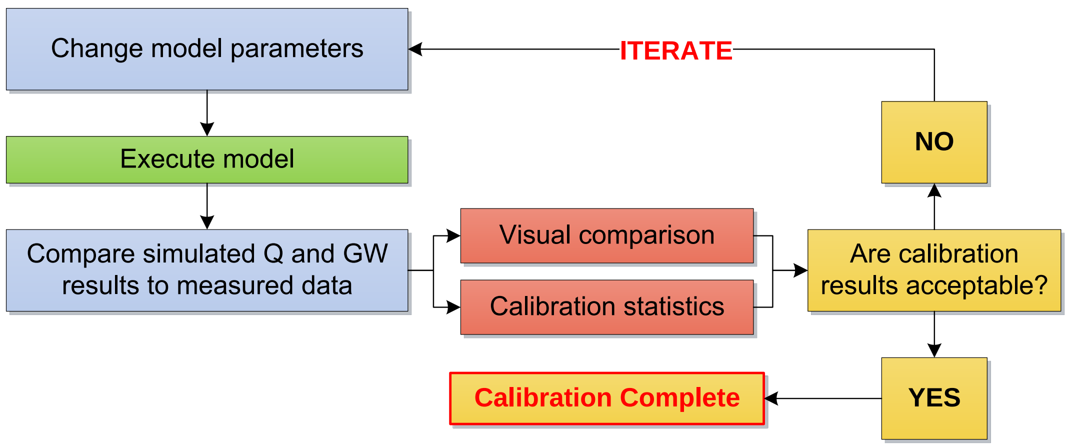


FIGURE 4.14: Simplified model calibration flowchart

as the "simulated vs. measured" comparisons described previously and shown in Figure 4.14. Note that the "decision point", *Are calibration results acceptable?* shown in Figure 4.14 introduces some subjectivity into the calibration process. Theoretically, calibration should continue until simulated results exactly match measured data and each calibration statistic is maximized. In reality, hydrological models are not expected to perfectly represent the myriad of complicated natural processes present within a watershed (see Section 2.2). Therefore, the modeller must use their judgment to determine when the calibration process can be concluded; Section 5.1 displays calibration results and describes the point at which results were deemed acceptable for the DMW model.

The sensitivity analyses performed on model parameters were holistic in nature; parameters were manually altered within a representative range and the resulting impacts on the overall simulation results were scrutinized. Through this method, parameters with the greatest impact on calibration results were identified and were further refined towards the final calibrated parameter set. The primary model calibration parameters are shown in Table 4.9 along with references to where each is explained. Note that the order of these parameters corresponds to the general order in which they were analyzed and calibrated within the MIKE SHE model, with some revisiting of parameters involved during the various iterations.

TABLE 4.9: Primary model calibration parameters

Calibration Parameter	Model Component	Thesis Reference
K_z, K_x	SZ	Subsection 4.3.9
Initial potential head	SZ	Subsection 4.3.9
K_{sat}	UZ	Subsection 4.3.8
Specific yield	SZ	Subsection 4.3.9
Water contents	UZ	Subsection 4.3.8
LAI, RD, K_c	Land Use	Subsection 4.3.5
Manning's n	OL	Subsection 4.3.7
Surface-subsurface leakage coefficients	OL	Subsection 4.3.7
Degree-day coefficient	Climate	Subsection 4.3.4

4.5 Model Validation

Hydrological model validation is the process of "testing" a model by simulating outside of its calibration range. Validation allows the modeller to test the robustness of the model and the applicability of its calibrated parameters for a time period to which it was not initially compared. By executing the model outside of its calibration range - without altering the calibrated parameters - one can determine if a model is true to reality and robust enough to be used for further analyses.

4.5.1 Validation data

The DMW model was validated against Portage Creek streamflow data, but for a different time period to which it was calibrated. Streamflow data collected from March 17 to May 5, 2015 were used as the validation dataset (see Subsection 3.3.1 for details on streamflow data collection). Figure 4.15 illustrates the streamflow data used for validation of the DMW model. Note that the calibration statistics described in Subsection 4.4.2 were also used to describe the statistical fit of validation results.

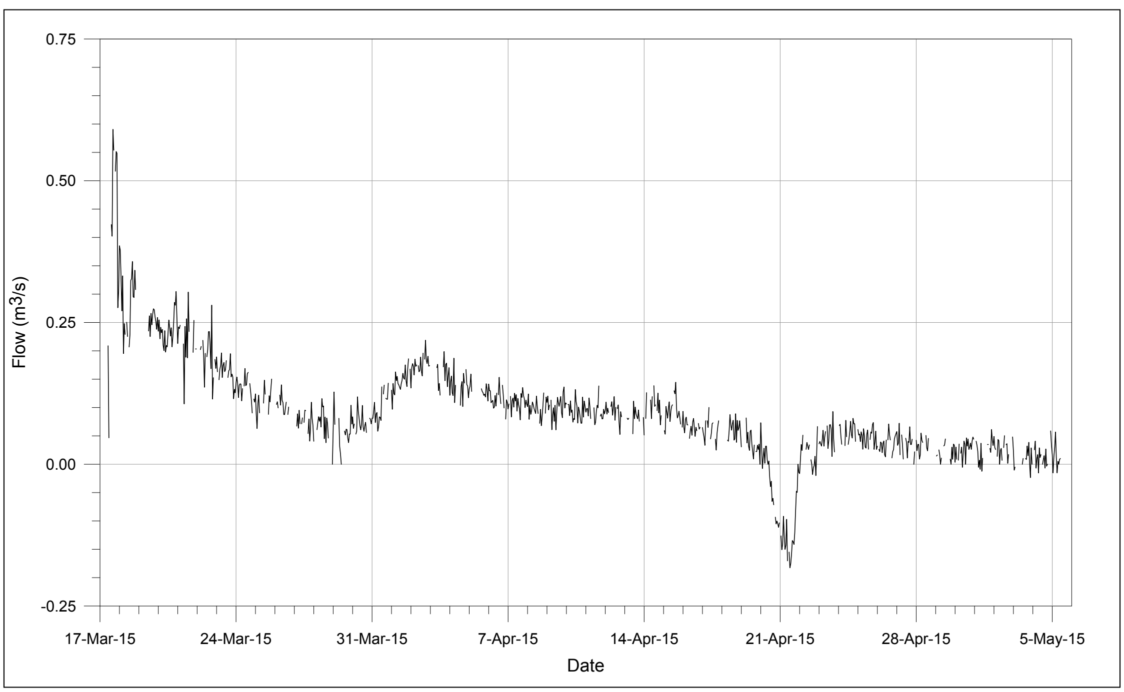


FIGURE 4.15: Spring 2015 validation data - Portage Creek streamflow

4.6 Land Use Change Scenarios

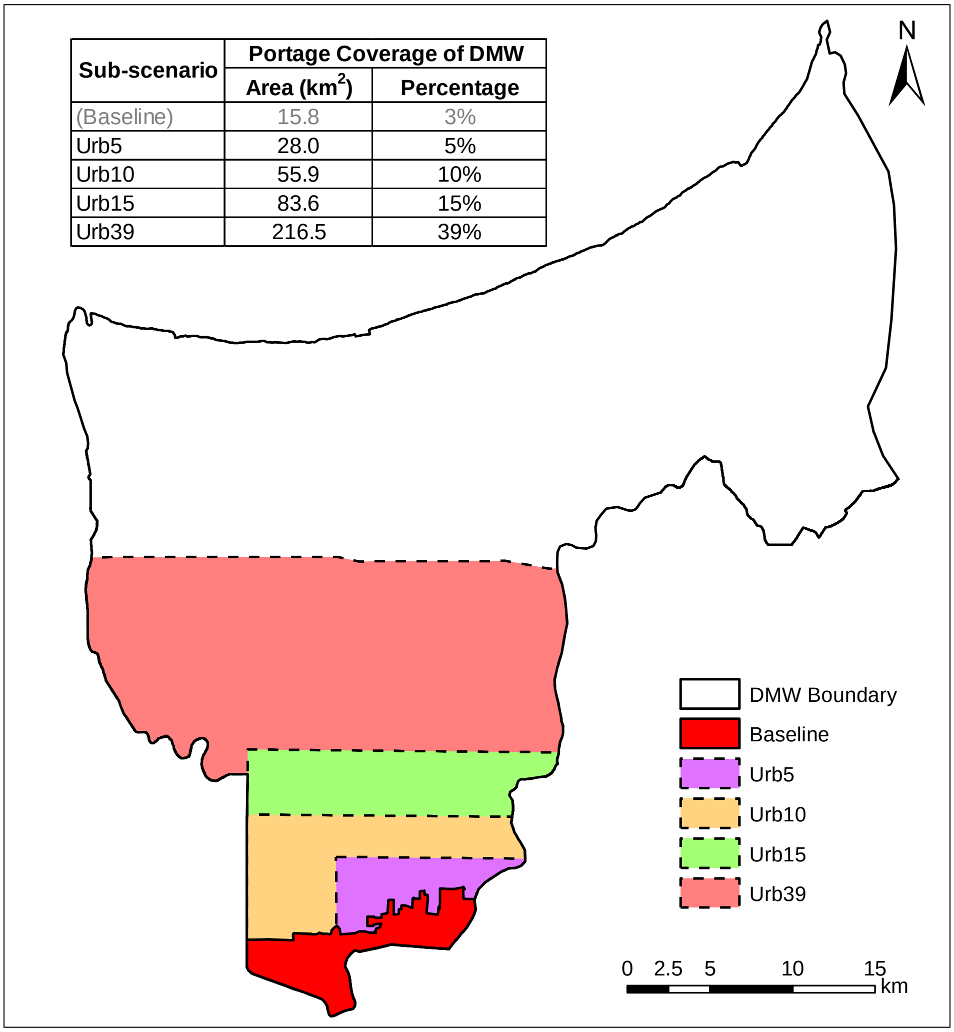
An objective of this project is to examine the relative hydrological response of the DMW to various potential land use changes. While it should be noted that the land use changes presented here are hypothetical in nature, they were developed in conjunction with DUC as being the most plausible changes that could theoretically occur within the DMW in the future. The objective of these scenarios was to provide upper and lower limits to the theoretical range of land use changes and the corresponding hydrological responses. Note that the current land use composition, and corresponding MIKE SHE representation, is referred to as the *baseline* scenario. Refer to Subsection 4.3.5 for details on current land use classes in the DMW and to Section 4.3 in general for descriptions of how the current characteristics of the DMW are described within the MIKE SHE model. The three land use change scenarios were examined for this project are referred to by the following titles: *urbanization*, *row crop*, and *naturalization*.

4.6.1 Urbanization

The urbanization (“Urb”) scenario centers around the potential northward expansion of Portage la Prairie. While no imminent urban expansion is expected for the city, it is conceivable that increases to local industrial activity and/or population may cause an increase to the city’s footprint. It is hypothesized that urban expansion would result in significant changes to runoff processes: urban environments are usually paved and somewhat de-vegetated, having an impact on infiltration, ET, and other hydrological processes.

Currently, the city of Portage la Prairie covers approximately 15.8 km^2 or 3% of the DMW (shown as the red impervious area at the south end of the DMW in Figure 4.6) and the area north of Portage is predominantly cropland. Lacking any detailed information of potential urban expansion of Portage, four simplified urbanization sub-scenarios were developed and are depicted in Figure 4.16. These sub-scenarios simulate incremental expansion of Portage la Prairie further into the DMW to totals of 5%, 10%, 15%, and 39% coverage. Note that the urban expansion extents were set somewhat arbitrarily. The Urb5 sub-scenario represents urban expansion of the northeast portion of Portage la Prairie, given that some industrial activity already takes place in this part of the city. For simplicity of implementation, the Urb10 and Urb15 sub-scenarios assume a “straight-line” northern limit to their respective expansion extents. For the most “extreme” - and therefore most improbable - urbanization sub-scenario (Urb39), Portage la Prairie was expanded all the way to PR227, which results in 39% total watershed coverage.

The urbanization land use changes were incorporated into the MIKE SHE model by changing a number of overland flow and vegetation inputs. Each sub-scenario is essentially an expansion of the impervious land use class. As such, the vegetation properties



Sub-scenario	Portage Coverage of DMW	
	Area (km^2)	Percentage
(Baseline)	15.8	3%
Urb5	28.0	5%
Urb10	55.9	10%
Urb15	83.6	15%
Urb39	216.5	39%

FIGURE 4.16: Spatial coverage of urbanization sub-scenarios

(Subsection 4.3.5), Manning number (Subsection 4.3.7), and surface-subsurface leakage coefficients (Subsection 4.3.8) associated with the impervious class were modified to reflect its expanded spatial coverage. Additionally, detention storage (Subsection 4.3.7) was set to 0 across the expanded impervious areas for each sub-scenario. Note that other physical characteristics of the model (i.e. topography and river network) were not changed as a result of the urbanization land use change. Additionally, no urban drainage infrastructure was added to the urbanization scenario models.

It is hypothesized that the urbanization changes will result in increased runoff towards the Delta Marsh in proportion to the degree of northward expansion. Increased impervious area should result in decreased surface ponding and, by extension, decreased infiltration and ET. Holding meteorological inputs constant, decreasing infiltration and ET should lead to increased surface runoff and an overall increase in surface water entering the Delta Marsh.

4.6.2 Row crop

The row crop ("RC") scenario reflects evolving agricultural practices and the possibility of increased row crop predominance in the DMW. Crops such as potatoes, soybeans, and corn are planted in rows to facilitate tilling and cultivation. The raised rows and depressed furrows formed during seeding create a rougher overall field surface as compared to cereals and other non-row crops (i.e. "traditional" crops). As a result, an increase in row crop prevalence may impact runoff processes.

The row crop scenario was recommended by DUC staff with knowledge of agricultural practices and trends in the DMW. To corroborate this recommendation, Agriculture and

Agri-Food Canada (AAFC) crop inventory data were analyzed for any trends in agricultural practices, especially for any apparent increase in row crop prevalence. AAFC crop inventory data describe the distribution of crop types or other agricultural land uses every year and are compiled based on optical and radar-based satellite imagery as well as some ground-truthing (Agriculture and Agri-Food Canada, 2014). This product displays the specific crop types planted across the country in a given year. Figure 4.17 presents crop inventory information from the 2009, 2011, 2012, and 2013 growing seasons, separated into traditional and row crops, as defined within the figure.

Figure 4.17 illustrates how row crop coverage in the DMW (i.e. proportion of cropland land use classified as row crops) increased markedly from 2011 to 2012 and remained at nearly 30% in 2013 as well. While this sample size of growing seasons is too small to discern any statistically significant trends, it can be concluded that increased row crop prevalence has indeed been observed in the DMW. The average row crop coverage overlapping the baseline period (2012 and 2013) is approximately 30%.

As with the urbanization scenario, the row crop scenario was further divided into sub-scenarios. These sub-scenarios reflect increasing percentages of row crop prevalence within the DMW. Therefore, sub-scenarios RC45, RC60, RC75, and RC100 were created, reflecting changes from the baseline of 30% to 45%, 60%, 75%, and 100% row crop coverage, respectively.

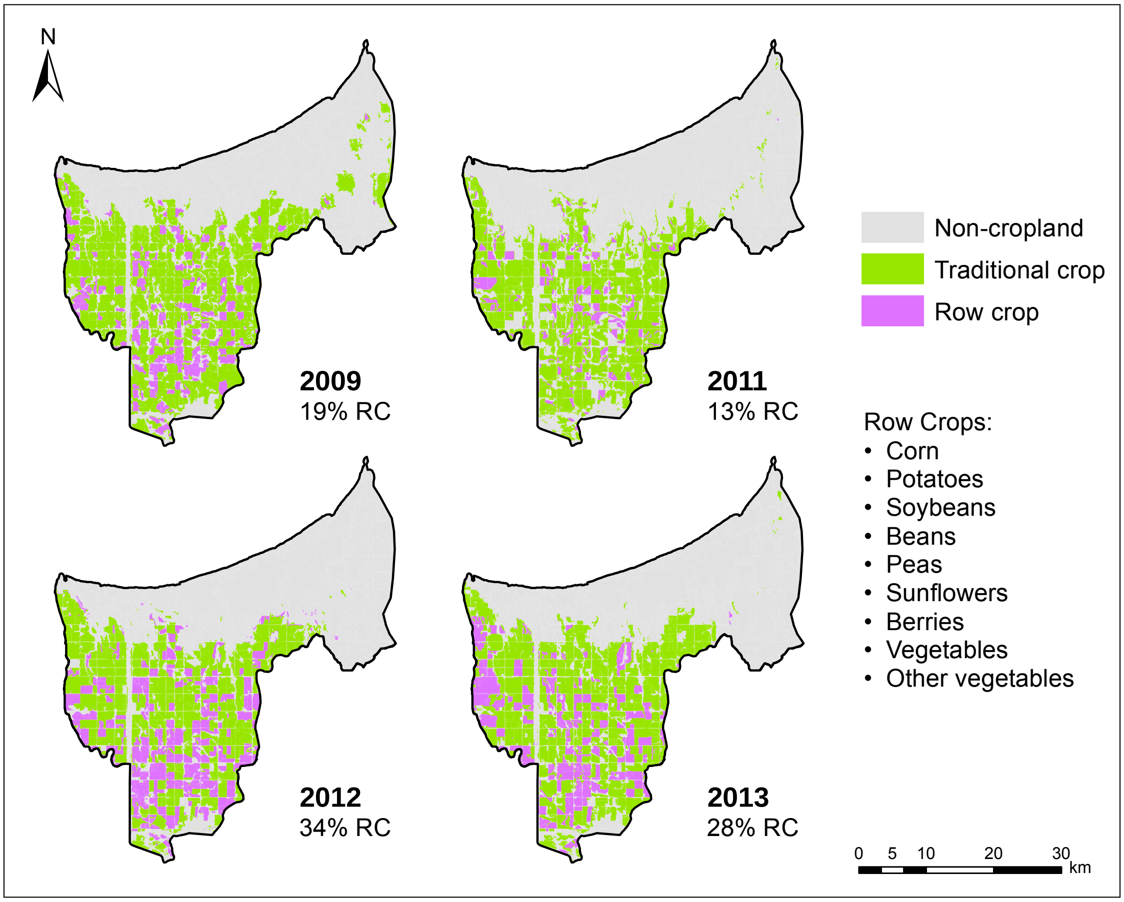


FIGURE 4.17: DMW crop inventory data - traditional vs. row crops

The row crop sub-scenarios were implemented in MIKE SHE model through changes to overland roughness values. While a range of agricultural and vegetation variables would be involved in a transition from traditional to row crops, it was assumed that modifying surface roughness values alone would appropriately represent this land use change and any resulting water balance changes. Although row crops are often irrigated, no additional irrigation component was introduced as part of the row crop scenario. Similarly, vegetation parameters (e.g. LAI, RD) were not altered in this scenario.

As described in Subsection 4.3.7, the calibrated Manning's n value for the cropland land use class is 0.04. The cropland class is not divided into row and non-row crops, meaning that the n value of 0.04 is a "combined" roughness value for the 30% row crop and 70% traditional crop regions of the DMW. To create the row crop sub-scenarios, a roughness value specific to row crops was needed. Literature values for row crop roughness may range from 0.025 to 0.2 (Engman, 1986; Mays, 2011). Having calibrated the baseline model to a combined roughness value of 0.04, a weighted-average technique was used to separate roughness values for row versus traditional crops. Using the aforementioned literature value range and iterating the weighted-average calculation, it was determined that an appropriate row crop roughness value for the DMW is 0.07. With 30% row crop coverage under the baseline scenario, the corresponding traditional crop roughness value is therefore equal to 0.027, which is within the range of literature values as well. These separated roughness values were used to determine combined n values for each of the RC45, RC60, RC75, and RC100 sub-scenarios: 0.046, 0.053, 0.059, and 0.070, respectively. This technique allows for the simulation of each row crop sub-scenario by simply modifying the Manning's roughness value for the entire cropland land use class and facilitates appropriate comparisons to the baseline scenario.

It is hypothesized that the row crop scenario results will show decreased overland runoff into the Delta Marsh. Increased surface roughness should impede overland flow, resulting in increased surface ponding and therefore increased infiltration and ET. Holding meteorological variables constant, the water balance response to increased infiltration and ET should be a decrease in overland runoff.

4.6.3 Naturalization

The naturalization ("Nat") scenario reflects a transition from developed croplands to more natural shrub and grass lands. Agricultural development in the DMW is ubiquitous; Figure 4.6 shows how the cropland land use class covers a significant portion of the DMW. Agriculture is the predominant industry within the DMW and throughout the Rural Municipality of Portage la Prairie in general. While the likelihood of a transition from cropland to natural shrubs and grasses is small, the hydrological response to such a land use change still presents an interesting scenario. As mentioned previously, the land use change scenarios developed for this project should bound the theoretical range of possibilities. While the urbanization scenario is perhaps the "upper range", in terms of maximum urban/industrial expansion and development, the naturalization scenario may be the "lower range", reflecting a transition away from agriculture and towards a naturalized landscape in the DMW. Indeed, the naturalization scenario is more of a past than a future land use change: this scenario reflects DMW land use conditions before the influx of agricultural activity and development.

The naturalization land use change was implemented in MIKE SHE by changing the entire cropland land use class to the shrub/grass class. This change results in both the vegetation surface roughness parameters being modified; Subsection 4.3.5 describes vegetation parameters by land use class and Subsection 4.3.7 describes the surface roughness parameters. For the naturalization scenario, all cropland parameters were simply changed to shrub/grass parameters. No sub-scenarios were developed for the naturalization land use change scenario; this scenario reflects a complete transition from cropland to shrub/grass land.

It is hypothesized that the naturalization scenario will have similar results to the RC60 or RC75 sub-scenario since the Manning's n values are comparable between these scenarios. However, the modification of vegetation parameters is expected to have an impact on water balance results as well.

Chapter 5

Results and Discussion

This chapter presents results of a hydrological modelling study developed to simulate current and potential future water balance conditions within the Delta Marsh Watershed. A large portion of the overall modelling effort was spent on calibration, ensuring that the MIKE SHE model is representative of real hydrological conditions in the DMW. Calibration results are one in the same with the baseline scenario results: the MIKE SHE model was calibrated to current conditions, so the final calibrated model is assumed to represent the DMW under current land use conditions. Model validation results are also presented in this chapter, indicating the model's ability to represent hydrological conditions outside of its calibration range. This chapter also includes the land use change modelling results, all of which are presented on a "relative change" basis. Rather than analyzing the land use change scenario results themselves, the results are compared against the baseline scenario to display relative increases or decreases. The objective is to estimate the degree to which a hypothetical land use change may alter the baseline water balance of the DMW.

5.1 Calibration Results

Model calibration was carried out following the methodology provided in Section 4.4. The parameters listed in Table 4.9 were manually altered and the model was executed to examine the result. Figure 4.14 illustrates how this process was repeated until the calibration results were deemed acceptable. During this process, simulated results revealed specific components of the model that were not being adequately represented with a given set of model parameters. Therefore, a number of calibration "sub-objectives" arose to which the calibration was tailored: a model shortfall was identified then parameters were altered in attempts to rectify. A simplified list of calibration sub-objectives is as follows:

1. Change UZ and SZ parameters so simulated groundwater depths match measured and soil moisture becomes reasonable
2. Decrease infiltration rate
3. Limit frozen/partially frozen soil infiltration

4. Refine snowmelt rates and volumes

Altering a given parameter and examining the corresponding change to model outputs provided insight on how sensitive the model is to that parameter. In this way, model sensitivity analyses and calibration were essentially performed simultaneously.

Subsection 2.1.3 describes how unfrozen prairie infiltration rates are generally quite high and how frozen and partially frozen soils have a significant impact on a prairie water balance. Much of the calibration effort for the DMW model was therefore spent on refining infiltration processes and ensuring this component of the water balance was being adequately represented. During this process, it was found that the DMW model was particularly sensitive to UZ and SZ parameters: modifying hydraulic conductivity, water contents, and leakage coefficients had a relatively large impact on simulation results, particularly in terms of simulated versus measured depth to water table. For example, average simulated water table depth was nearly 2 m higher than measured early in the calibration. Water content values at saturation, field capacity, and wilting point were doubled to investigate the impact on groundwater depth. Literature values of these physical UZ parameters were accessed to define appropriate ranges (Maulé and Gray, 1994; Dingman, 2002; St. Laurent and Valeo, 2007). As a result, average simulated groundwater depth was lowered to only 0.2 m higher than the average measured value. This qualitative sensitivity analysis revealed the importance of these UZ parameters and the impacts that changes to them can have on simulated results. Water content parameters were further refined to the final values shown in Table 4.4.

Similarly, model results were highly sensitive to snowmelt parameters and the degree-day coefficient in particular. This coefficient defines how much of the snowpack melts for every degree that air temperature is above a reference melt temperature. A constant threshold melt temperature of -2.5 °C was used for the DMW model; this value was established through calibration and based on prior knowledge that snowmelt can commence at slightly negative air temperatures (Harder and Pomeroy, 2013). Literature values for degree-day coefficient/melt rate vary: Clark (1955) reported melt rates from 1.0 to 2.7 mm/°C/day for southern Manitoba; Shaw et al. (2011) quote values ranging from 2.5 to 11.6 mm/°C/day; and St. Laurent and Valeo (2007) used a constant melt rate of 0.5 mm/°C/day in a hydrological model of a northern Manitoba watershed but stated literature values range from 1.0 to 5.0 mm/°C/day. The degree-day method is empirical in its nature and therefore depends on either measured data or detailed calibration to adequately represent snowmelt in a specific region. For the DMW model, calibration found that a time-varying degree-day coefficient was useful to ensure an adequate match between simulated results and measured data. This coefficient increases from 0 mm/°C/day in late March, peaking near 2.0 mm/°C/day in late April, and decreasing back to 0 mm/°C/day by mid-May. Figure 5.1 displays the calibrated time-varying degree-day coefficient used for the spring 2014 streamflow calibration period. A constant degree-day coefficient of 1.0 mm/°C/day was used for the remainder of the simulation period in lieu of additional calibration data.

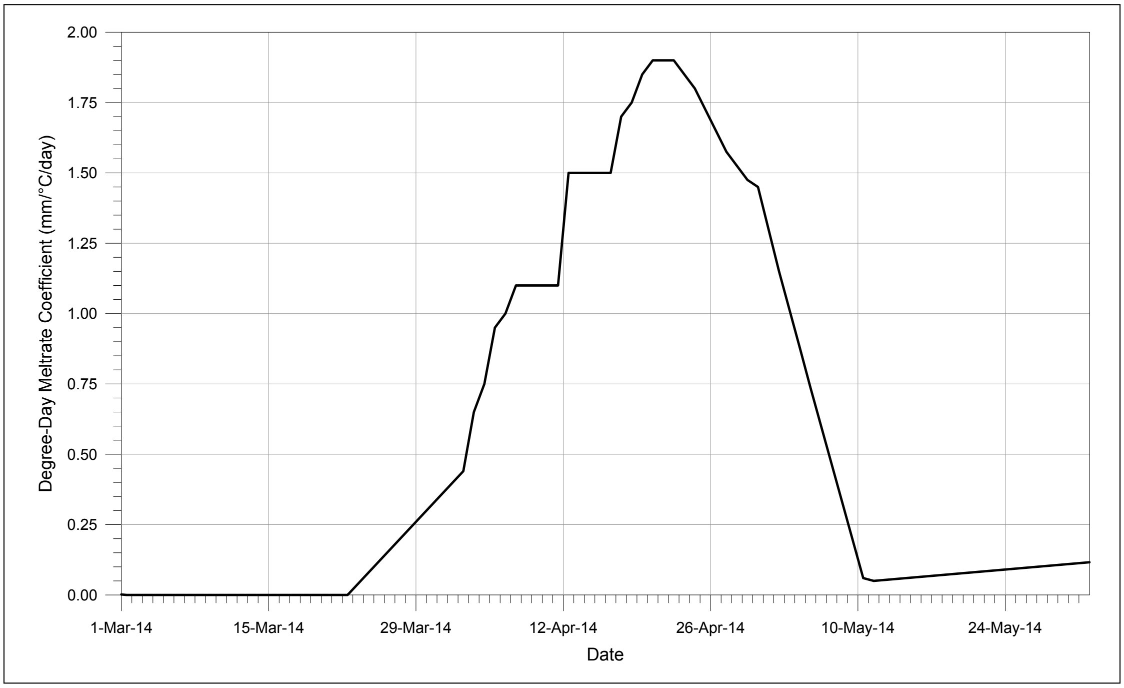


FIGURE 5.1: Calibrated degree-day melt rate coefficient

In addition to the sensitivity analysis details above, a summary of the key sensitivity analysis/calibration results is shown in Table 5.1. This table illustrates the most impactful changes to the calibration parameter set and indicates how sensitive the model was to these parameter alterations, expressed as $\%Dv$ and NSE streamflow calibration statistics. Note that "O.M." denotes order of magnitude as K_{sat} values were adjusted by factors of 10 during the sensitivity analysis process. Parameter set changes described in Table 5.1 occurred incrementally, meaning that a single parameter change was made and the corresponding impact on calibration results were analyzed, then the next parameter change was made, and so on. This process helped to identify parameters to which streamflow results were most sensitive and provided insight into the key hydrological processes of the DMW.

TABLE 5.1: Incremental sensitivity analysis/calibration results by parameter set

Param. Set #	**Parameter**	**Change**	**%Dv Before**	**%Dv After**	**NSE Before**	**NSE After**
14	UZ K_{sat}	decrease 1 O.M.	-103	-42	-0.89	-0.10
15	Water Content @ F.C.	-15%	-42	-23	-0.10	0.14
44	UZ K_{sat}	increase 2 O.M.	-83	-9.4	-0.51	0.40
57	DD melt rate coeff.	change timeseries	-17	-6.9	0.28	0.35

Simulated streamflow results were very sensitive to UZ K_{sat} as this parameter defines the maximum infiltration rate of each soil class. As anticipated, infiltration is a significant component of the water balance (see Subsection 5.4.1), so model sensitivity to K_{sat} is logical. The model is also shown to be sensitive to other UZ parameters, such as water content at field capacity, as these also define infiltration and soil storage capacities. Model sensitivity to the degree-day melt rate coefficient is described above.

Intermediate parameter set changes were made between those listed in Table 5.1. The impact of these changes on the streamflow calibration results were limited and the model was therefore considered largely non-sensitive to these parameters. Non-sensitive parameters include:

- SZ vertical hydraulic conductivity, K_z
- Initial potential groundwater head
- Overland Manning's n
- Detention storage depth
- MIKE 11 channel (Portage Creek) Manning's n

Calibration continued until it was deemed that results were acceptable, in terms of visual fit and calibration statistics, given time and data availability constraints. Final streamflow calibration results are shown in Figure 5.2; this is the type of plot used during calibration to analyze some key water balance components alongside the Portage Creek streamflow comparison. The figure was used to ensure snowmelt results correctly correspond to inputs of threshold melt temperature, air temperature, and degree-day factor; it also demonstrates subsurface processes as incremental infiltration (i.e. surface to UZ) and recharge (i.e. UZ to SZ) depths are included. Note that the water balance terms shown are totals for the entire DMW while streamflow is for Portage Creek at PR227. Streamflow calibration statistics are summarized in Table 5.2.

A percent deviation value of -6.9% indicates that the model is underestimating overall streamflow volume through Portage Creek at PR227 during the spring of 2014. The visual comparison shown in Figure 5.2 confirms this volume underestimation, particularly between April 13 and April 20, 2014: the measured data show that the first streamflow peak

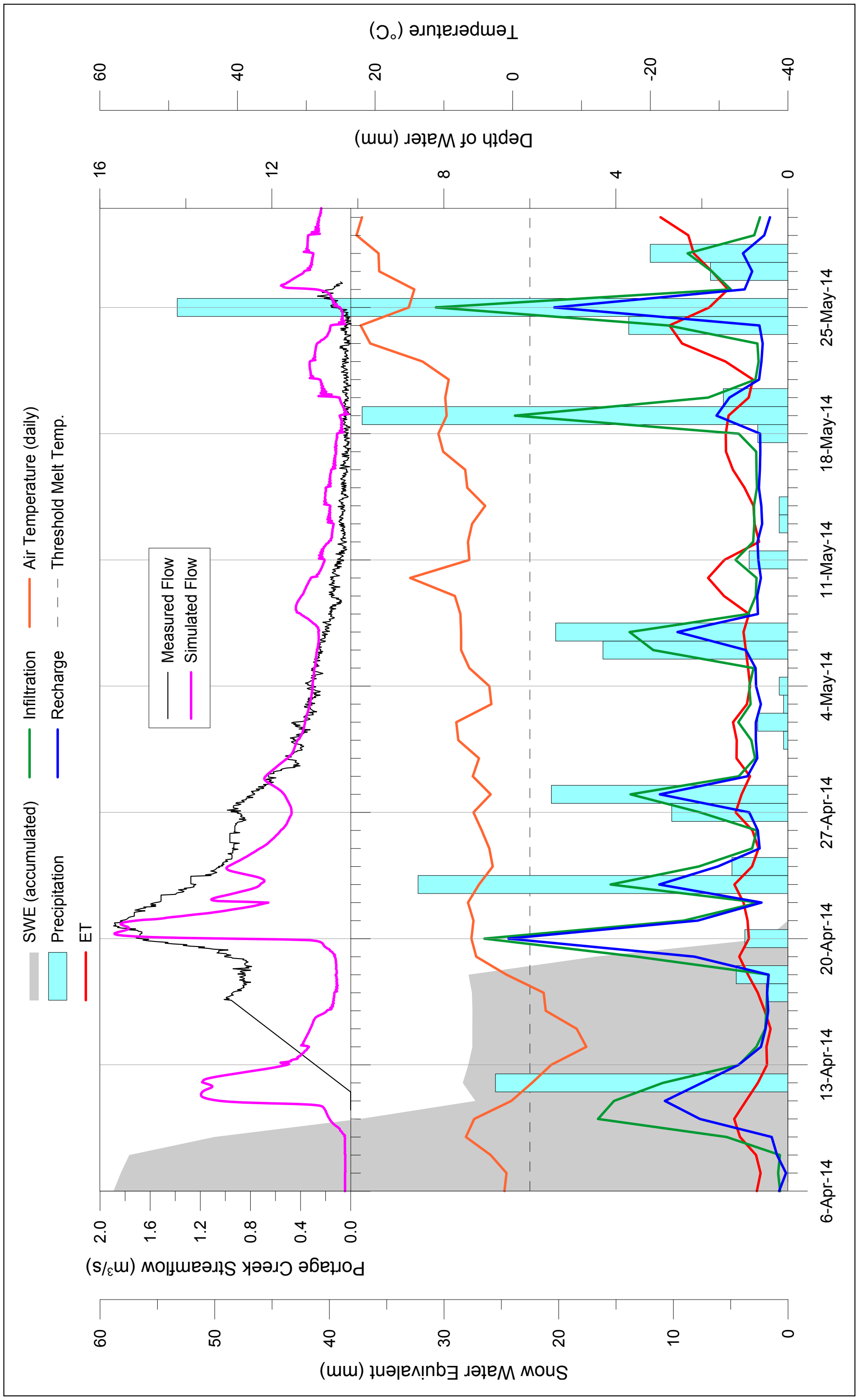


FIGURE 5.2: Portage Creek streamflow and water balance calibration results

TABLE 5.2: Calibration statistics for Portage Creek streamflow calibration

Statistic	Calibration Result
Percent deviation (%Dv)	-6.9
Root Mean Square Error (RMSE)	0.384
Nash-Sutcliffe Efficiency (NSE)	0.350

of approximately 1.0 m^3/s was occurring at this time while simulated results show very little corresponding streamflow. However, the model does simulate a streamflow peak closer to April 11, seemingly in response to a partial snowmelt event (Figure 5.2 illustrates SWE decreasing from nearly 60 mm to 25 mm between April 6 and April 11). Overland and river routing parameters may have also been responsible for the erroneous timing of this peak event. The second and larger measured streamflow peak (occurring around April 21), however, is captured fairly well by the model: peak flows match almost exactly in both timing and magnitude. The simulated receding limb of this peak accounts for additional mismatch in streamflow volume as the simulated streamflow recession occurs somewhat faster than the measured, at least initially (i.e. between April 21 and April 27). The remainder of the simulated receding limb closely follows the observed recession. RMSE and NSE statistics (0.384 and 0.350, respectively) also indicate a reasonable match between simulated and measured Portage Creek streamflow. While NSE values closer to 0.5 are typically indicative of a successful calibration (Moriasi et al., 2007), 0.350 was deemed acceptable in this application given data availability and time constraints. Qualitative review of the internal hydrological processes supported the conclusion that each model sub-component is being reasonably represented and the model calibration was therefore found to be complete.

Results of the groundwater depth calibration are shown in Figure 5.3. Statistics were not calculated for the groundwater calibration as a visual comparison was deemed sufficient for this secondary calibration exercise. The shape of the simulated water table depth generally matches that of the measured data: inflections in the simulated results follow those of the observed data, indicating that groundwater is responding appropriately to inputs and outputs. However, there is a bias of approximately 1.0 m shown in the results that was introduced by an over-estimation of water table rise in the spring of 2013, and is carried through the remainder of the simulation. While surface water is the focus of this study, this model limitation should be noted since groundwater plays a role in the interconnected DMW water balance.

5.2 Validation Results

After completing model calibration, the calibrated parameters were used to generate model output for the streamflow validation period of March 17, 2015 to May 5, 2015. Section 4.5 describes the model validation methodology in detail. Note that no groundwater data were available for the validation period so validation was based on Portage

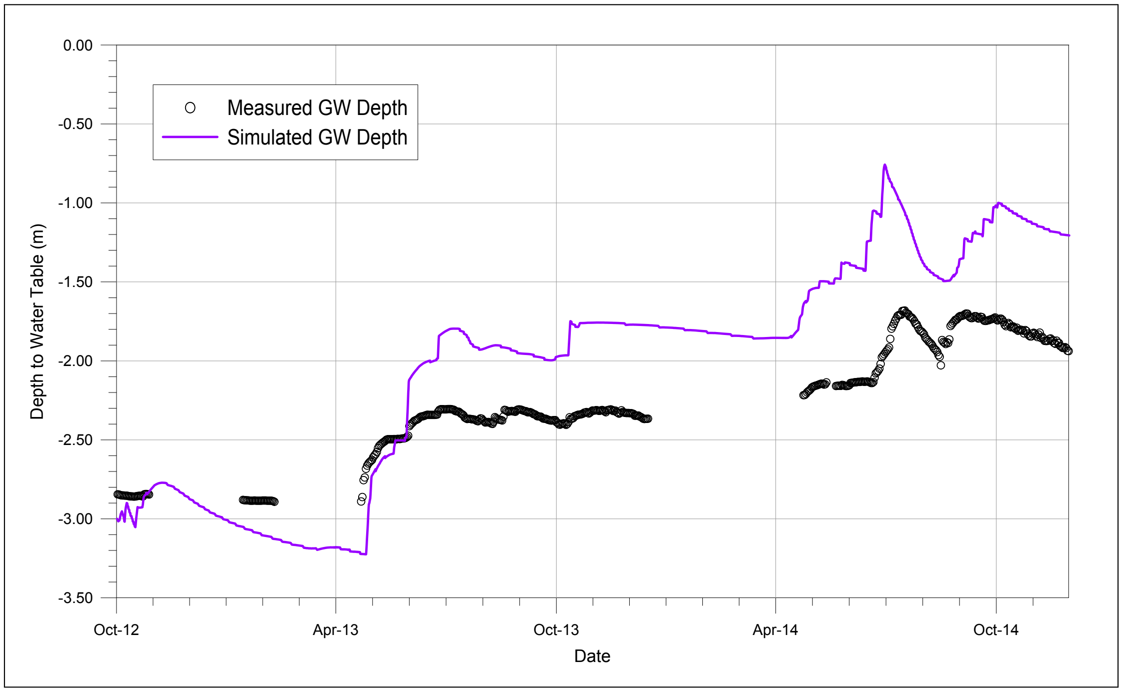


FIGURE 5.3: Site G05LL001 R-1 groundwater depth calibration results

Creek streamflow at the PR227 crossing location only. Figure 5.4 illustrates DMW model validation results; validation statistics are shown in Table 5.3.

TABLE 5.3: Validation statistics for Portage Creek streamflow

Statistic	Validation Result
Percent deviation (%Dv)	45.7
Root Mean Square Error (RMSE)	0.143
Nash-Sutcliffe Efficiency (NSE)	-1.07

Streamflow validation results generally show a poorer fit between simulated and measured as compared to calibration results. The model parameter set was tailored to the limited calibration data available and therefore cannot be expected to represent other time periods to the same degree of accuracy, especially if hydrologic conditions in the

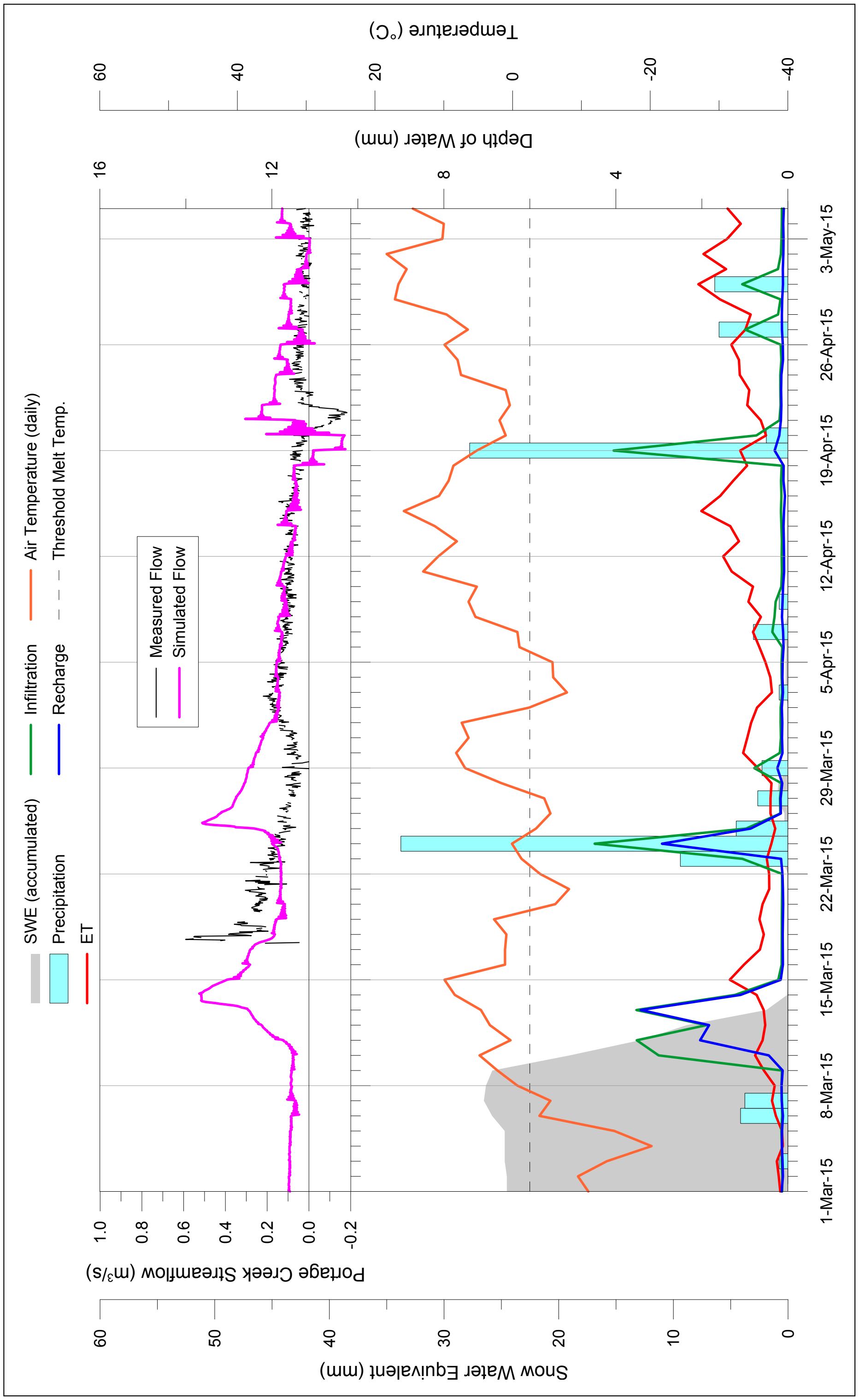


FIGURE 5.4: Portage Creek streamflow and water balance validation results

validation period differ from those of the calibration period. From the limited Portage Creek discharge data available, snowmelt and runoff conditions differ somewhat between the springs of 2014 (calibration) and 2015 (validation). Pre-melt snow water equivalent in 2014 is more than twice as large as than of spring 2015. Correspondingly, Portage Creek discharge measured in 2014 is significantly higher than in 2015. While many more factors contribute to creek discharge than simply pre-melt snow water equivalent, this provides an indication that hydrologic and meteorologic conditions in these two years were indeed different. Therefore, a model established to describe watershed conditions of 2014 cannot be expected to represent those of 2015, or any previous or subsequent year, with the same level of accuracy.

However, further explanation of the discrepancies shown in validation results is required. From the streamflow results shown in Figure 5.4, the first simulated peak flow occurs approximately four days earlier than the measured peak. While the measured streamflow record is somewhat sporadic during the spring of 2015, it appears that the actual peak streamflow was observed on March 17. This result is similar to that observed in the calibration period, where the initial spring peak was accurate in magnitude but arrived too early. Again, it is expected that overland and river routing parameters may have caused the timing error.

Secondly, there is a second simulated streamflow peak on March 25, 2015 (approximately 0.5 m^3/s); no such streamflow peak was shown in the measured data at this time. This discrepancy has a large impact on the validation statistics and is a significant contributor to the general mismatch between simulated and measured streamflow. The water balance terms included in Figure 5.4 were analyzed to understand this discrepancy. A multi-day precipitation event was recorded at the Portage Southport gauge on March 23 (2.5 mm total precipitation), March 24 (9.0 mm total precipitation), and March 25 (1.2 mm total precipitation) and input to the MIKE SHE model. Since air temperature at this time was at or above the threshold melt temperature of -2.5 °C (also used by MIKE SHE to distinguish rainfall from snowfall), the model designated this precipitation event as almost entirely rainfall, as opposed to snowfall (Figure 5.4 illustrates how SWE stays close to zero during this event), and runoff/streamflow response occurs near instantaneously. However, if this precipitation was mixed rain/snow or mostly snowfall, a more attenuated streamflow reaction would be expected. The measured data show a slower rise in streamflow to approximately 0.25 m^3/s on April 3, 2015, which is more indicative of a mixed precipitation or snowfall event. While the Portage Southport climate station applied to the DMW reports only total precipitation (i.e. snowfall and rainfall combined), other nearby gauges provide more detailed precipitation measurements. The "Portage la Prairie CDA" station recorded 9.0 cm of snowfall and 9.0 mm of rainfall on March 24, 2015; the "Brandon A" station recorded 8.0 cm of snowfall and 4.8 mm of rain; and the

"Winnipeg Inlt A" station recorded 5.0 cm of snowfall and 8.0 mm of rain. These supplemental measurements strongly indicate a mixed precipitation event in southern Manitoba at that time. Environment and Climate Change Canada's historical radar information (`http://climate.weather.gc.ca/radar/index_e.html`) was also accessed and confirmed the presence of a mixed precipitation event. Therefore, it can be concluded that the threshold melt temperature of -2.5 °C may apply for the calibration period but is not necessarily representative of the validation period. Research has shown that the snow/rain transition is variable over time and is a function of more meteorological variables than air temperature alone (Harder and Pomeroy, 2013). While MIKE SHE allows a spatially-variable melt temperature, it does not allow it to vary temporally; this model limitation was revealed through model validation. Despite the erroneous simulation of a secondary streamflow peak in the spring of 2015, it has been shown that the underlying hydrological processes are accurate and representative of reality (i.e. the simulated streamflow response would be indicative of a rainfall event even though this was not what happened in reality).

Note that the negative streamflow both measured and simulated around April 20, 2015 are reflective of directionality as described in Subsection 3.3.1. The Argonaut ADV records directional velocity where positive indicates northward velocity (i.e. water flowing towards the marsh) and negative is southward velocity (i.e. water flowing away from the marsh). The derived discharge records are therefore directional as well, following the same sign convention. MIKE SHE (and MIKE 11, in this case) also adopts this convention, outputting negative discharge where water flows upstream. While the flow direction was generally positive through Portage Creek (see Figure 4.8 and Figure 4.9), the flow direction changed around April 20, 2015. Channel slope of Portage Creek is very minimal in the 7 km between PR227 and the marsh, so it is conceivable that a large increase in marsh water level could cause a backwater effect through Portage Creek. Indeed, review of marsh level data confirms that the marsh water level rose by approximately 12 cm near the outlet of Portage Creek between April 18 and April 21. Recorded wind data show a corresponding north wind event, likely causing this marsh level increase. Despite the fact that it is not set up as a hydrodynamic model, the MIKE SHE model captured this event with a slight timing discrepancy. See Aminian (2015) for more information on marsh hydrodynamics and the effects of wind on marsh water levels.

5.3 Model Uncertainty

The ability of a hydrological model to fully represent real-world conditions is inherently limited. Using equations and numerical tools to estimate the natural processes occurring within a watershed is always subject to some degree of uncertainty. Savenije (2009) summarizes, "a hydrological model is not a tool but a hypothesis". Therefore, it is important to understand the limitations of the model results shown in this chapter and to appreciate the associated uncertainties.

Both calibration and validation of the DMW hydrological model were limited by data availability. Essentially, the model was calibrated to less than two months of streamflow data recorded in one of many channels within the watershed. While limited additional streamflow data were available (see Subsection 3.3.1), the lack of a continuous record made calibration to these records unfeasible. Limited groundwater data were useful for calibrating the subsurface components of the watershed, but, again, the record of water table depths was for a single location in the watershed only. While hydrological model calibration to limited or even non-existent data is not uncommon in the engineering practice (Bardossy, 2007; Spence et al., 2013), it is important to understand the uncertainty associated with simulated results. A full uncertainty analysis was not within the scope of this project, but ranges of simulated values are presented, wherever possible. Even the ranges presented should be considered approximate, as they too were model-estimated.

While the calibration and validation results do not closely match the measured data in all instances, the discrepancies can be rationalized and the physical processes in MIKE SHE appear representative of reality. Model validation typically covers a much larger temporal range such that some of the model intricacies and small errors tend to balance out. A long validation period was not possible during this study due to data availability. Therefore, model "robustness", or its ability to represent conditions to which it was not calibrated, should be scrutinized. Additional uncertainty is introduced since the

DMW model was applied over an expanded temporal range for analysis purposes (see Section 5.4). However, the use of temporally-averaged simulation results provides more statistical confidence in the results in the context of defining "typical" or "normal" hydrological conditions in the watershed.

Finally, modifying model parameters that may not completely represent baseline conditions to represent altered land use conditions introduces further uncertainty. However, the objective of analyzing land use change scenarios is not to predict actual hydrologic conditions under these changes, but to understand the degree to which baseline hydrological conditions are impacted by the land use changes. Therefore, *relative* water balance and marsh inflow results are presented in all cases in Section 5.5.

5.4 Baseline Hydrologic Conditions

The MIKE SHE model was calibrated to current land use conditions within the DMW; therefore, the calibrated results represent *baseline* hydrologic conditions. The term *baseline* is used mostly in reference to the land use change scenarios described in Section 4.6 given that land use change results are always compared back to the baseline results.

Note that while the MIKE SHE model was used to simulate October 2012 to May 2015 during calibration, it was determined that a larger temporal range would be preferable for analyzing average baseline conditions. Additional simulation years were desired to provide more insight into the DMW's hydrological characteristics and to add statistical significance to averaged results. Therefore, the calibrated model was modified to simulate the longer period of September 2003 to May 2015, providing approximately 12 years of water balance results for analysis.

5.4.1 Water balance

MIKE SHE outputs water balance results as equivalent water depths, averaged over the basin, associated with a given model component. Water balance results indicate if water is being added or removed from a given model "domain". This domain can be the entire model, or a "Total Water Balance" (i.e. all atmospheric, surface, and subsurface processes), or a specific sub-component of the model (i.e. snowmelt component only, unsaturated zone only, etc.). The sign convention adopted in this thesis is that a positive water depth indicates water being *added* to the domain while a negative water depth is water being *removed* from the domain. Specific sign convention details will be provided along with the results for clarification, if necessary.

To illustrate baseline hydrological conditions within the DMW, the 12 years of model results were first simplified into monthly average values. Analyzing water balance results on a monthly average provides insight on how the various hydrological processes change seasonally. The monthly average water balance plots generally represent a *land surface* water balance. The sign convention used is that positive values represent depths of water added to the DMW ground surface (e.g. precipitation or subsurface exfiltration) while negative values represent water leaving the land surface (e.g. ET, infiltration). Average total monthly water depths, for the entire watershed under baseline conditions, are shown in Figure 5.5.

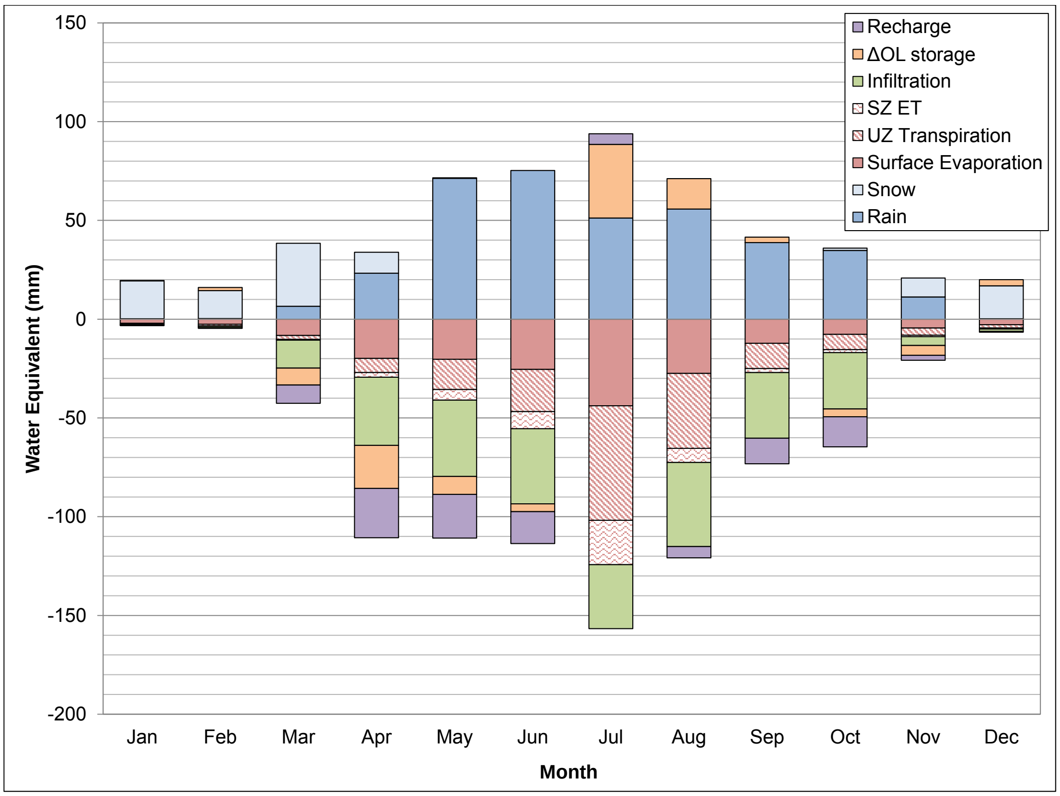


FIGURE 5.5: Average monthly baseline water balance results

Recall that total precipitation depth from the Portage Southport climate station were input to the model for uniform application over the DMW and partitioning into rain versus snow. Actual evapotranspiration is estimated based on inputs of reference ET (see

Subsection 4.3.4). MIKE SHE separates ET by source: either surface evaporation (evaporation from ponded water on the surface or from wet snow plus sublimation from dry snow), unsaturated zone transpiration (plant uptake in the root zone), or total saturated zone evapotranspiration. The remaining water balance items shown in Figure 5.5 are estimated directly by the model. Note that change in overland storage is represented by "ΔOL storage", where a negative value indicates increasing storage of water on the ground surface (i.e. in surface depressions and other topographic low points) and a positive value indicates decreasing surface water storage. Runoff and overland flow components are elaborated upon in Subsection 5.4.2, but the ΔOL storage value provides general insight on the amount of water being added or removed from the DMW ground surface.

The monthly average water balance results confirm that hydrological conditions within the DMW generally conform to typical prairie hydrology, as outlined in Section 2.1. The stacked bar graph allows for comparison of inflows and outflows on a monthly basis. In general, the summer months are shown to be in a net negative water balance wherein more water is removed from the land surface by ET and infiltration than is added by precipitation. Total ET is represented by the combination of surface evaporation, UZ transpiration, and SZ ET bar values; each of these sources of ET are greater in the summer months than in the winter, as can be expected. Surface evaporation is greatest in the months of July and August when temperatures are highest; correspondingly, transpiration depths increase during the summer months as crops and other watershed vegetation take up water from the UZ. As theorized in Section 2.1, transpiration exceeds evaporation during the peak growing months of July and August where it comprises over 50% of total ET. Infiltration is limited during the frozen winter months, as simulated using the surface-subsurface leakage coefficient described in Subsection 4.3.8. Thawing temperatures in the spring result in increased infiltration as well as melting of the snow that accumulates over winter. Significant infiltration continues throughout the summer which, combined with high rates of ET, results in a net decrease in surface water storage (indicated by the positive ΔOL storage values in July and August).

Figure 5.6 illustrates average annual total water balance depths for each of the eight sub-basins; basin-average annual water balance depths (i.e. the sum of water balance components shown in Figure 5.5) are also shown for comparison. Recall that the eight sub-basins examined terminate at PR227; these sub-basin outlet locations are used by DUC for various field monitoring activities and were therefore applied for this study as well. While these sub-basins provide useful insight on the hydrological processes upstream of PR227, they do not provide any indication of conditions between this road and the Delta Marsh itself. This region, however, is captured in "total watershed" results such as those shown in Figure 5.5.

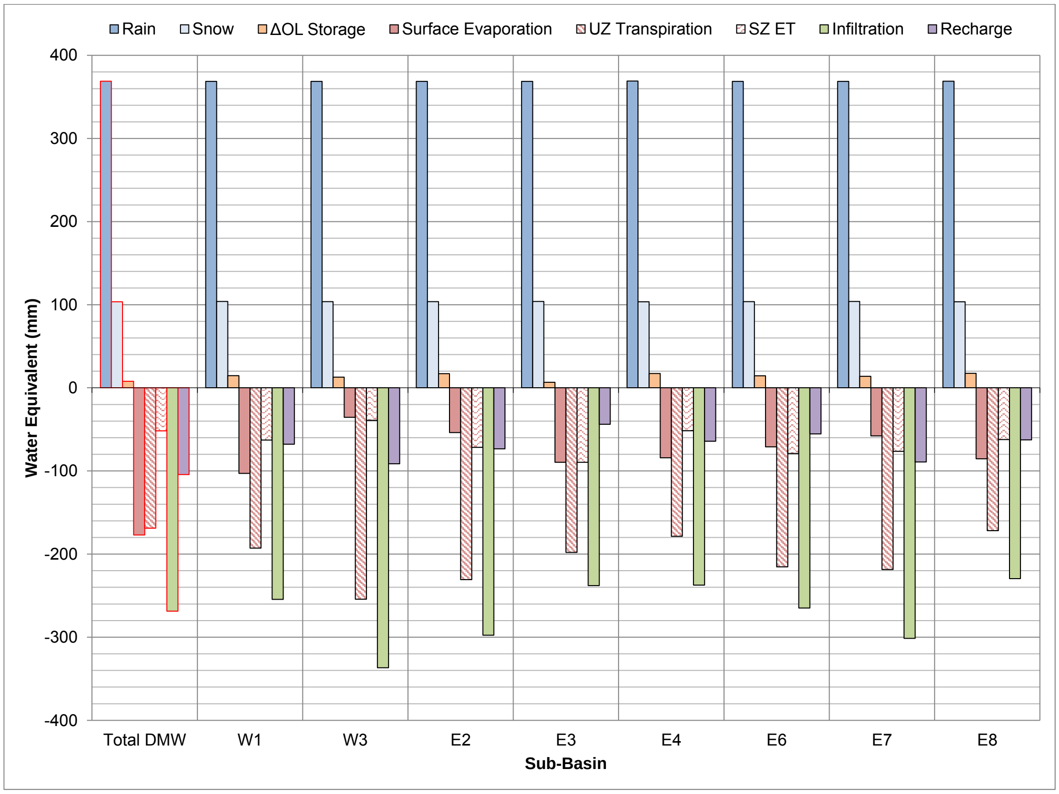


FIGURE 5.6: Average annual total water balance results by sub-basin

Rain and snow inputs are equal across all sub-basins, as precipitation data from the Portage Southport climate station were applied uniformly over the DMW (see Subsection 4.3.4). Sub-basin losses are represented by the negative water balance terms of ET, infiltration, and recharge. Note that DMW-total surface evaporation is somewhat higher than any of the component sub-basins since the area north of PR227 contains a higher concentration of standing water features as well as the Delta Marsh itself. Results show that sub-basin W1 has the largest annual abstraction of surface evaporation (snow plus ponded water evaporation) of the eight sub-basins examined. Snow evaporation is also consistent across all sub-basins, so sub-basin W1 exhibits more evaporation from ponded water than the other sub-basins. Sub-basin W3 shows the largest transpiration, infiltration, and recharge of the analyzed sub-basins. Summing all water balance components gives an indication of which sub-basin may exhibit the largest net gain or loss of water. While all sub-basins analyzed demonstrate a net annual loss in the presented water balance components, sub-basin E8 shows the smallest net loss and W3 the largest. Subsection 5.4.2 presents a more detailed analysis of surface runoff in the DMW in terms of overall inflows into the Delta Marsh itself and which sub-basins are particularly "active" in this regard.

5.4.2 Marsh inflows

The volume of surface water entering the Delta Marsh from the DMW was estimated via MIKE SHE's *FlowThroughLine* model extension. As described in Subsection 4.3.7, this application allows the user to manually define "flow lines" over across which modeled overland flow hydrographs are provided; see Figure 4.10 for an illustration of the 20 flow lines placed across the southern limits of the DMW. As described in Subsection 4.3.6, an embedded MIKE 11 was used to represent the hydraulics of Portage Creek. Therefore, all Portage Creek inflow results shown here were extracted from MIKE 11 model output. Note that flow line FL-0 shown in Figure 4.10 was used only for confirmation that the MIKE 11 model of Portage Creek was fully encompassing inflows for that channel. *FlowThroughLine* and MIKE 11 results were extracted from each of the 11 complete simulation years (2004-2014) to yield annual total inflow volumes at each location. Figure 5.7 presents a box-whisker plot of the annual total flow volumes with inflow locations sorted west to east.

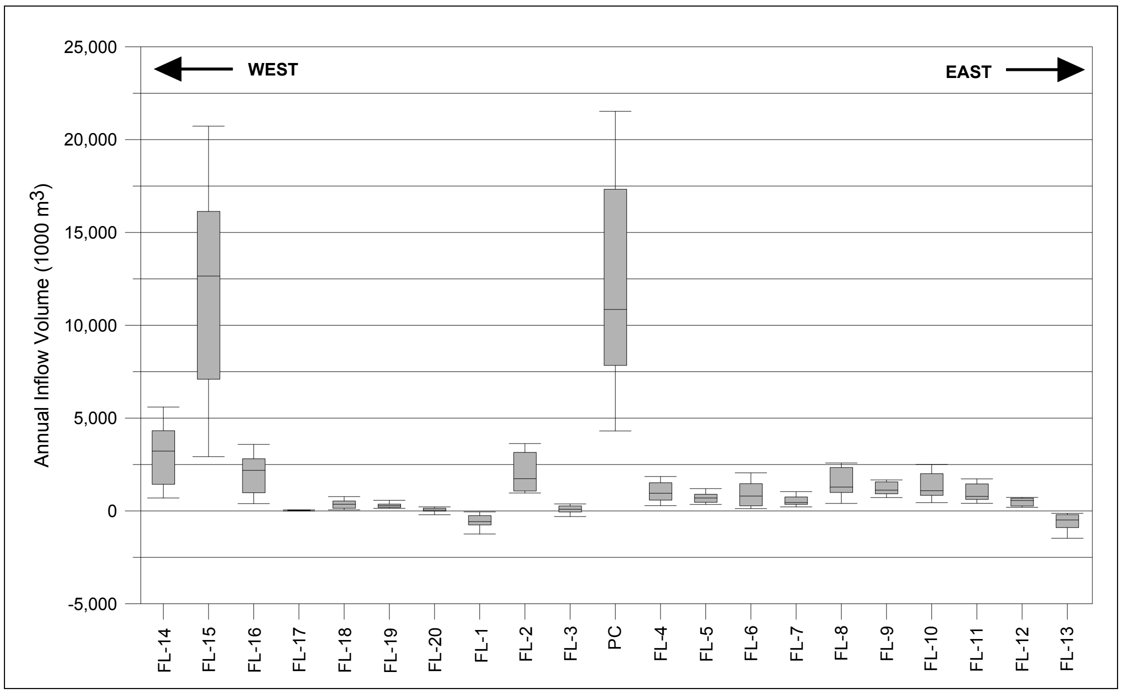


FIGURE 5.7: Box-whisker plot of annual marsh overland inflow volumes

Summing all flow line and Portage Creek inflow volumes, total annual marsh inflows from the DMW are presented in Table 5.4. On average, approximately 40 million m^3 of water runs off the watershed and into the marsh per year. Normalized to the watershed area, total marsh inflow averages 710 m^3/ha/yr, or a total runoff depth of 71 mm/yr. Previous prairie hydrological studies have shown comparable runoff values:

Green and Turner (2002) measured annual runoff rates in southern Manitoba ranging from 29 to 780 m^3/ha/yr; Maulé and Gray (1994) estimated runoff depths across the prairie provinces, with approximately 35 mm estimated in Manitoba during the spring melt alone; McConkey et al. (1996) measured mean annual runoff depths of approximately 30 mm from agricultural fields near Swift Current, SK; and Udawatta et al. (2006) observed three-year mean annual runoff values ranging from 939 to 3,434 m^3/ha/yr, depending on land use, at a test farm in Missouri.

TABLE 5.4: Total annual marsh inflow volumes

Year	Total Marsh Inflow (million m^3)
2004	47
2005	68
2006	49
2007	13
2008	35
2009	56
2010	63
2011	24
2012	18
2013	25
2014	38
Average	**40**

While linkages between DMW hydrology and marsh hydraulics were not fully realized during this study, a contextual comparison can be made between sources of marsh inflows. Aminian (2015) "traced" water volumes from their source location and determined cumulative inflow volumes to the marsh. For the analysis years of 2013 and 2014, it was determined that total marsh inflow contributions from the Portage Diversion were 5.6 and 7.5 million m^3, respectively (P. Aminian, personal communication, 30 November 2017). While many connecting factors are not encapsulated by the two studies, it can be noted that marsh inflows from the DMW are somewhat greater than from the Portage Diversion in 2013 and 2014 (see Table 5.4).

Note that a negative marsh inflow value, as is the case for annual average inflows across flow lines FL-1 and FL-13, indicates flow leaving the marsh across this interface. As detailed in Aminian (2015), marsh water levels rise and fall largely as a function of Lake Manitoba water levels and wind speed/direction. Given the flat topography typical of the marsh-watershed interface, an increased elevation head in the marsh can result in flow being "spilled" out of the marsh and onto the surrounding land. This behavior is typical of a coastal wetland and aids in vegetation growth along the marsh periphery. Flow lines FL-1 and FL-13 are defined very close to the edge of the marsh so an "outward" flow from the marsh to the surrounding land is conceivable; note that model results show these negative discharge rates to be very low (on the order of -0.1 m^3/s).

Marsh inflow results can provide insight on which regions of the DMW are most hydrologically "active" in terms of the amount of overland marsh inflow that originates from each sub-watershed. Estimates of runoff volume were also normalized by contributing area to make comparisons between the different source of marsh inflow. Subsection 4.2.3 describes how sub-watersheds were delineated upstream of PR227 to match with streamflow measurements taken along that road. However, the region between PR227 and the southern extents of the Delta Marsh generate runoff as well. Therefore, manual delineations were approximated for each flow line presented in Figure 4.10, continuing the sub-basins shown in Figure 4.2 all the way to the marsh. These delineations were performed following the general methodology in Section 4.2. Note, however, that difficulty of sub-basin delineation increases closer to the marsh due to flat topography and interconnectedness of hydrographic features. Therefore, these sub-basins should be considered approximate and for the purposes of inflow-per-area comparisons only.

Figure 5.8 illustrates overland marsh inflows by location as annual average volumes, as percent of the total annual average marsh inflow volume, and as volume normalized by contributing area; inflow arrows shown in the figure are sized proportional to average inflow volume in m^3, based on 12 years of model results. Note that flow lines with net negative marsh inflow (i.e. Fl-1 and FL-13) are not shown in this figure. All flow lines surrounding the “Centre Marsh” area (i.e. original flow lines FL-16 to FL-20) were combined given their close proximity to a single arrow representing Centre Marsh inflow.

Model results confirm that the largest single inflow from the DMW to the Delta Marsh is

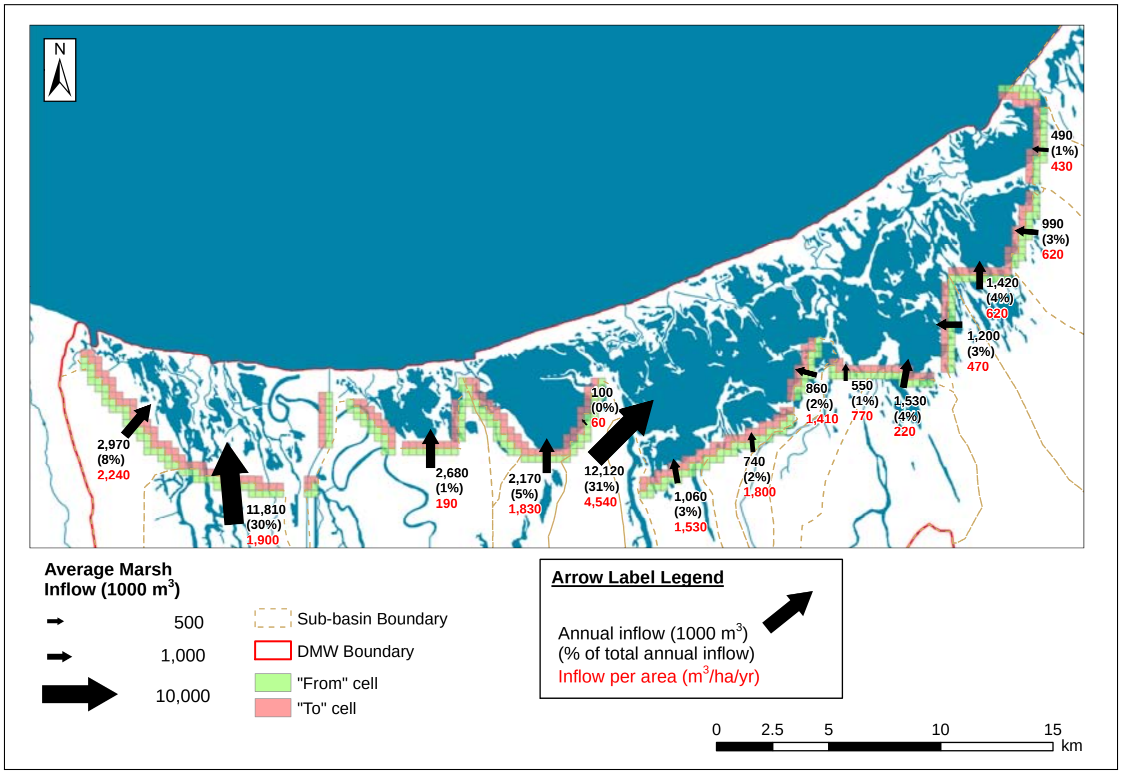


FIGURE 5.8: Marsh inflow results map

Portage Creek, which contributes over 30% of the annual average marsh inflow. Marsh inflows east of Portage Creek are relatively small, in terms of total volume, although inflow per unit area to the Simpson Bay region is significant. The West Marsh (i.e. west of the Portage Diversion) also receives significant overland runoff from the DMW; approximately 37% of annual average marsh inflow from the watershed to the marsh enters into the West Marsh area. Figure 5.9 displays average annual hydrographs for each inflow, either across a flow line or from MIKE 11 hydraulic model output (Portage Creek only).

Model results show that inflows to the marsh are generally low over the winter time until

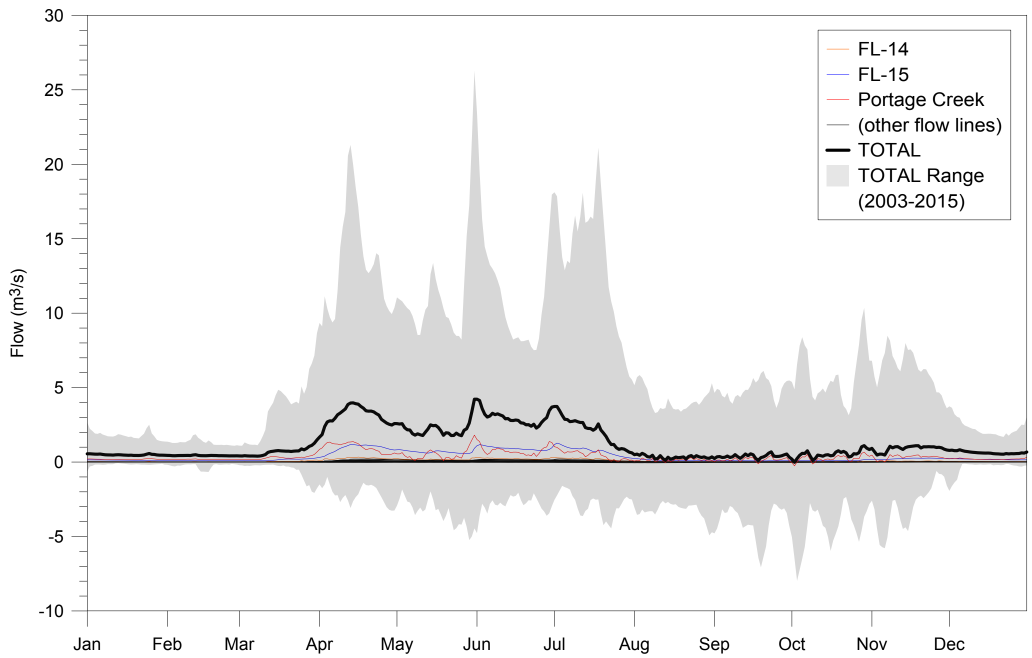


FIGURE 5.9: Marsh inflow results - average annual hydrographs

the spring when inflow increases as the snow melts and runs off the land. Somewhat unexpected is the high marsh inflows over the summer months, on average. Model results show a net negative water balance for the DMW over the summer months (see Figure 5.5), a hydrological behavior that would be expected given experience in the field as well as the body of literature on prairie hydrology. However, water balance results also indicate increasing overland storage through the spring and early summer (March to June) followed by decreasing overland storage from July through the fall. These results suggest that water accumulates in surface storage as snow melts in the spring and rain falls early in the summer. While a large proportion of surface water infiltrates into the subsurface or is evaporated to the atmosphere, much of it is retained in the various creeks, ponds, and other low-lying areas scattered across the DMW. As the summer continues, this retained surface water begins to flow towards the Delta Marsh. While more detailed analyses would be required to confirm, it is expected that the hydraulic connections between the DMW and Delta Marsh could be responsible for draining of the retained surface water. Marsh water levels are expected to be highest in the spring as Lake Manitoba ice and snow surrounding the marsh melts. These meltwater inflows are represented in the first streamflow peak shown in Figure 5.9. Since the DMW surface slopes so gently towards the marsh, high marsh water levels would prevent significant marsh inflow until a northward hydraulic gradient could be re-established as marsh levels drop. Once marsh water levels recede later in the summer, it is expected that water stored on the surface and in the various inflow channels could flow into the marsh, represented by the persistently high marsh inflows throughout the summer months.

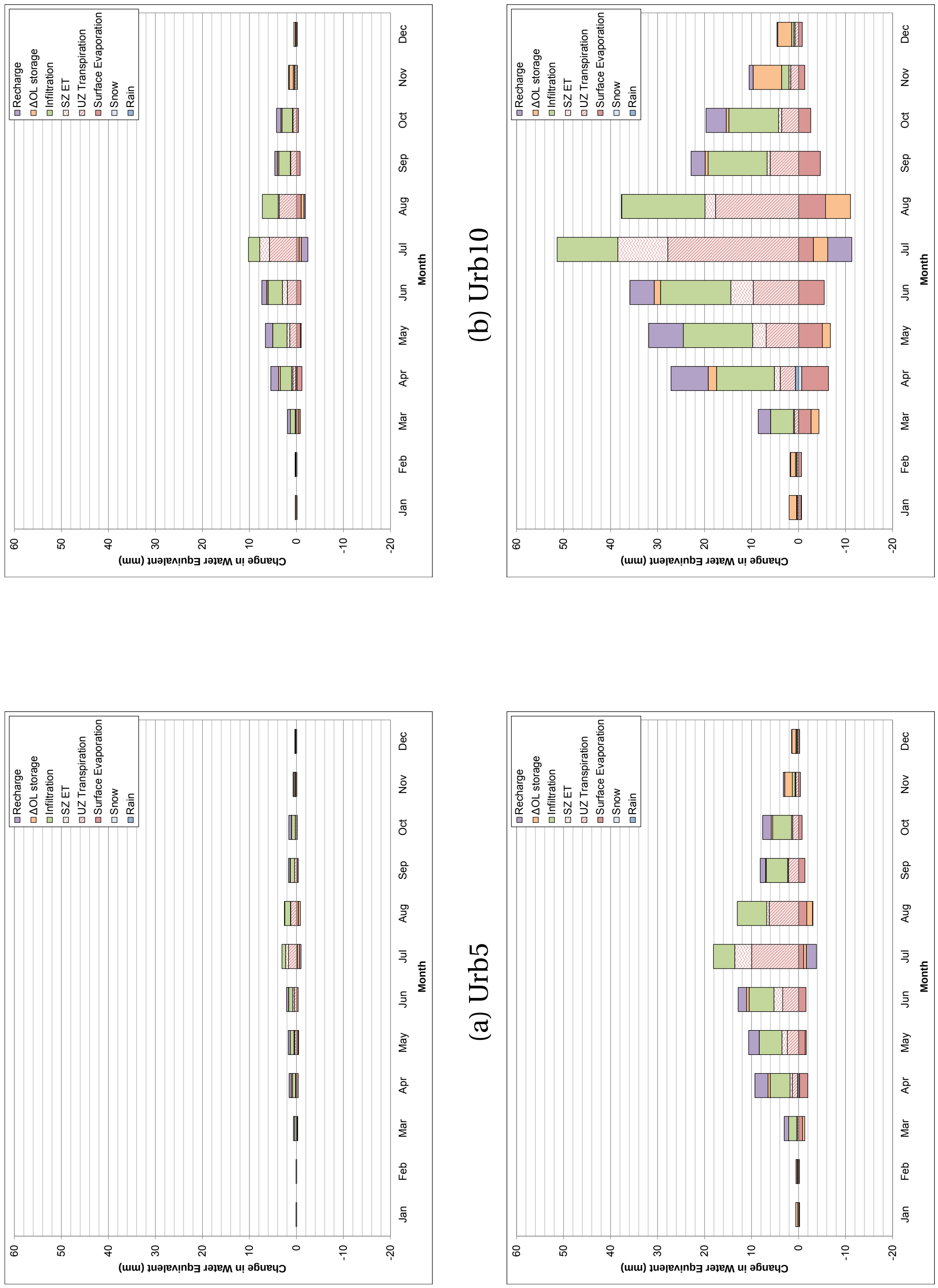
5.5 Land Use Change Results

Each of the land use change scenarios described in Section 4.6 are intended to illustrate the potential hydrological response to these changes. As stated previously, while land use change scenarios were simulated explicitly within the MIKE SHE model, all results are presented on a relative basis, comparing land use change results to those of the baseline (current) scenario. Note that the previously described sign convention used for water balance results applies to the relative values as well. The following sections describe the potential hydrological impacts of the urbanization, row crop, and naturalization scenarios within the DMW.

5.5.1 Urbanization

The urbanization land use change scenario aims to identify the hydrological impacts of a hypothetical urban expansion of the city of Portage la Prairie. As described in Subsection 4.6.1, this land use change scenario is built into the MIKE SHE model mainly through a gradual expansion of the impervious land use class. The four urbanization sub-scenarios, denoted Urb5, Urb10, Urb15, and Urb39 represent increasing percentages of the impervious land use class within the DMW. After executing a MIKE SHE model for each of the four sub-scenarios, water balance results were exported and compared against corresponding water balance results from the baseline model. Figure 5.10 presents the same water balance components shown previously, but with plotted values representing the *change* in each water balance term relative to the baseline results.

Results indicate that any potential urban expansion within the DMW would impact the water balance characteristics in the area proportionate to the degree of the expansion. In the Urb5 scenario, there is very little change in water balance components relative to baseline conditions. However, there is a slight positive change in infiltration and transpiration indicating that these negative water balance components are *decreasing*. A



(a) Urb5

(b) Urb10

(c) Urb15

(d) Urb39

FIGURE 5.10: Relative water balance results - Urbanization scenarios

decrease in infiltration would be expected upon changing a portion of the watershed to a mostly impervious urban land use, as paved surfaces would not allow passage of water into the ground. Decreased transpiration would similarly be expected as paved areas replace vegetation that would otherwise take up water through their roots. As the degree of urban expansion increases, infiltration and transpiration depths correspondingly decrease. Negative water balance changes also become more prominent with increasing urbanization; evaporation depths increase with increasing urbanization (represented by negative relative depths). As mentioned in Subsection 4.6.1, no land drainage features were added to accompany the urbanization land use changes. In reality, land drainage infrastructure would be added to control water that ponds on paved surfaces such as roads and parking lots. In the MIKE SHE model, that water has nowhere to go but sit on the impervious surface and become available for additional evaporation.

Potential changes in overland storage as a result of urbanization are more clearly shown through an analysis of relative marsh inflows, or the degree to which runoff from the DMW into the marsh changes as a result of the land use change.

5.5.2 Row crop

The row crop land use change scenario represents potential changes in agricultural practices within the DMW. While crop rotation is common among agricultural producers, some indication of increasing row crop prevalence has been observed within the DMW (see Figure 4.17). The purpose of simulating a row crop land use change as part of this study is to examine the potential hydrological impacts that may be associated. Four row crop sub-scenarios were created to represent increasing percentages of the DMW's agricultural areas seeded with row crops; Subsection 4.6.2 explains the row crop sub-scenarios in more detail. As with the urbanization scenario, Figure 5.11 displays relative water balance depths associated with the four row crop sub-scenarios.

Generally speaking, and especially when compared to those of the urbanization scenario, model results show minimal impact on DMW water balance due to increasing row crop coverage. A slight increase in evaporation can be seen in the RC100 sub-scenario results; annual average change in surface evaporation is less than 1 mm over the watershed. As described in Subsection 4.6.2, the row crop land use change was implemented in MIKE SHE by simply increasing the surface roughness parameter for the cropland land use class. Increased surface roughness decreases the rate of overland runoff, resulting in increased surface ponding and therefore slightly higher evaporation from the ponded water. Conversely, summer infiltration and transpiration decrease slightly under the row crop scenario. Again, changes in water depth are very slight, even under the RC100 sub-scenario, but it is expected that the small increase in evaporation "uses up" the water that would normally be available for infiltration and then taken up by plants as transpiration.

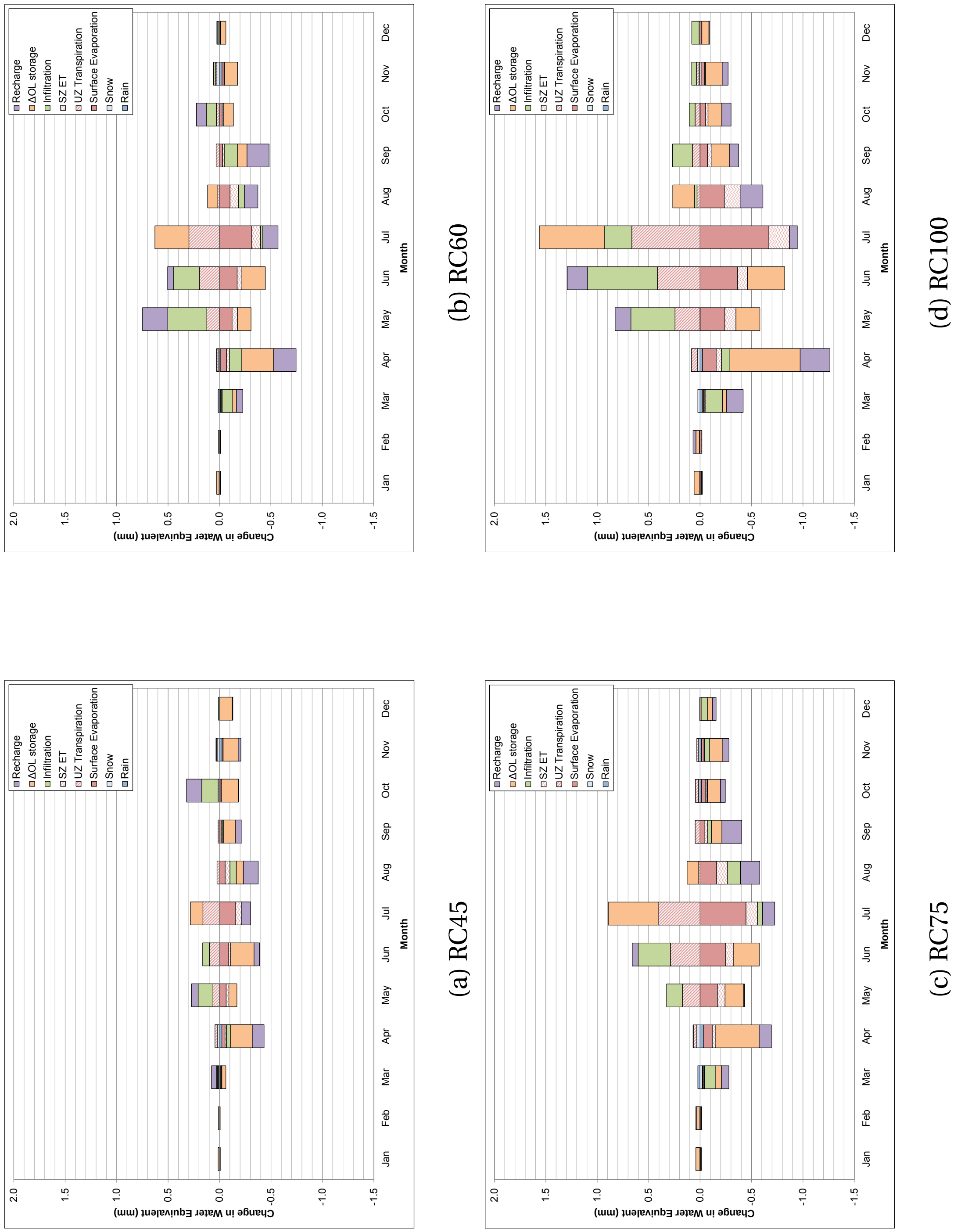


FIGURE 5.11: Relative water balance results - Row crop scenarios

5.5.3 Naturalization

The final scenario considered in this project was the naturalization scenario, representing a land use transition from agricultural predominance to a more natural and uncultivated state. As explained in Subsection 4.6.3, the naturalization land use change scenario is somewhat unlikely but may present insight into hydrological conditions of the DMW prior to its agricultural development. To implement this scenario, all cropland regions of the DMW were changed to the shrub/grass class, with vegetation and surface roughness parameters changed accordingly. Figure 5.12 illustrates relative water balance depths for the naturalization scenario.

Model results for the naturalization scenario depict a slight increase of both infiltration and transpiration, particularly over the summer months. The rougher ground surface associated with shrub/grass lands, as opposed to cultivated croplands, leads to increased ponding of water on the surface. Research has shown that wetting depths increase beneath surface vegetation (Ludwig et al., 2005), implying that greater steady-state infiltration rates can be achieved beneath thicker vegetation coverage. Increased surface ponding combines with higher infiltration potential to result in greater infiltration under the naturalization scenario versus the baseline. Transpiration rates increase due to the more consistent nature of natural shrubs and grasses. In the DMW, agricultural plants are typically seeded in the spring, grow over the summer months, and are

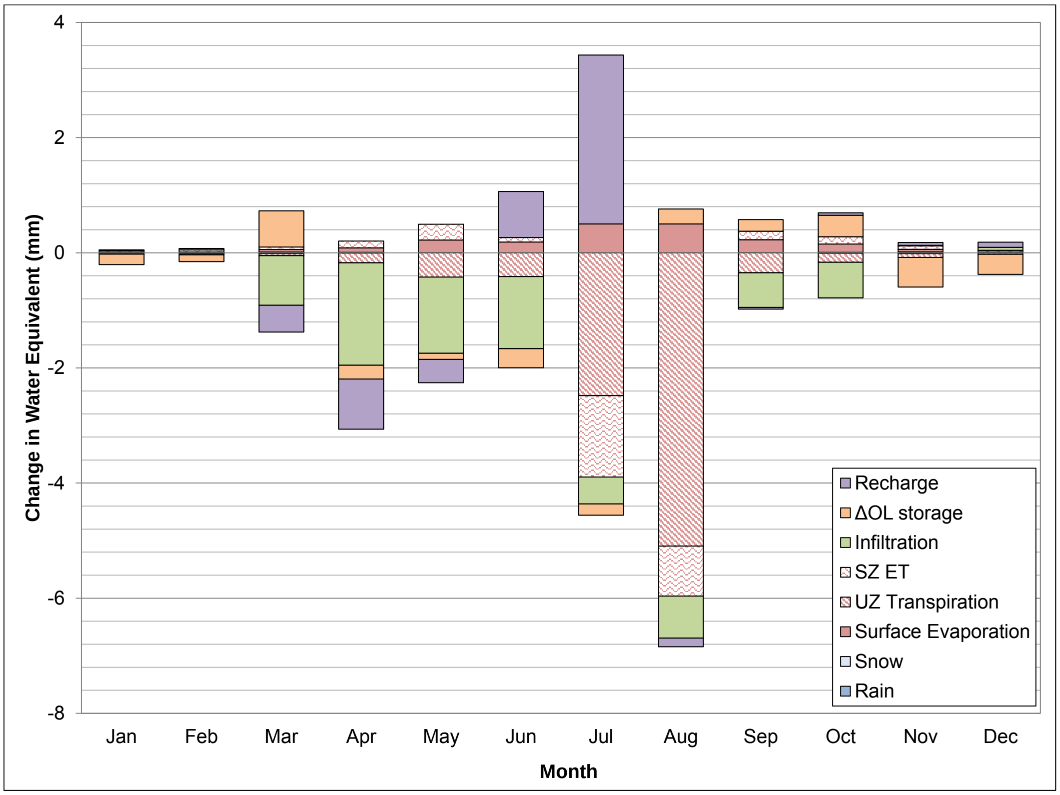


FIGURE 5.12: Relative water balance results - Naturalization scenario

harvested in the fall. Simulated vegetation parameters reflect these growing conditions (see Subsection 4.3.5). Shrubs and grasses, however, are not normally cultivated and are therefore in a state of maturity for more of the year, explaining the slight increase in transpiration for the naturalization scenario. Finally, slight decreases in recharge are demonstrated for the naturalization scenario, particularly in the month of July, on average. This change in recharge depth is nearly identical to the increase in UZ transpiration, suggesting that recharge decreases because water that would be available for passage from the UZ into the SZ under baseline conditions simply transpires before it can travel downwards.

5.5.4 Relative marsh inflows

As with the baseline results, annual average overland flow across each pre-established flow line was extracted for each land use change scenario model. Similarly, Portage Creek hydrograph results were also generated for each scenario for the entire simulation period. Twelve-year average annual hydrographs were created for each flow line and Portage Creek; these results were then summed to yield total annual average hydrographs for each land use change scenario. Comparing these total hydrographs to the baseline results yields *relative* hydrographs that represent the change in total annual average inflow across all flow lines and through Portage Creek for each scenario. A positive change in discharge indicates *more* water entering the marsh under a given scenario than for the baseline; the converse applies for a negative change. Relative annual average hydrographs are shown in Figure 5.13, and a summary of changes in total annual marsh inflow volumes is shown in Table 5.5.

As expected from the water balance analyses, urbanization in the DMW yields increasingly higher marsh inflows, relative to baseline conditions. As water lands on the hypothetically paved surface, it runs off overland, unable to infiltrate into the impervious

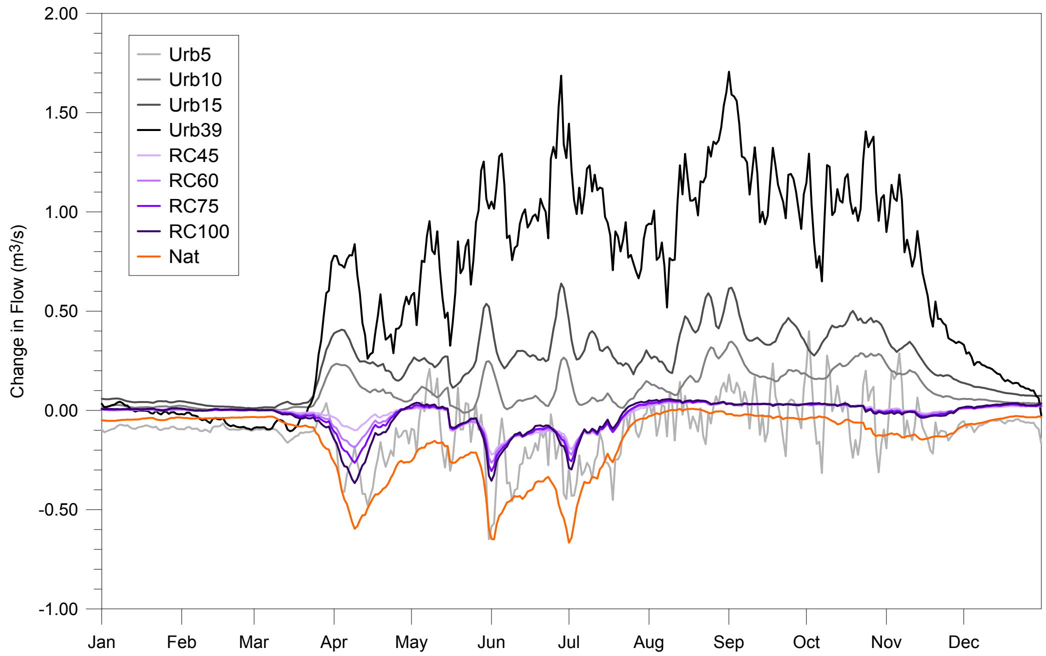


FIGURE 5.13: Change in annual average marsh inflow hydrographs

TABLE 5.5: Change in average annual marsh inflow volumes

	Volume (1000 m^3)	Percent Change
Urb5	-3,150	-8.0%
Urb10	3,190	8.1%
Urb15	7,480	19%
Urb39	19,950	51%
RC45	-540	-1.4%
RC60	-640	-1.6%
RC75	-740	-1.9%
RC100	-880	-2.2%
Nat	-4,710	-12%

ground. The greater the degree of urban expansion, the larger the increase in streamflow to the marsh; the Urb39 scenario results in an average of 51% more water volume entering the marsh than under current conditions. It can also be noted that the relative annual average hydrographs for the urbanization scenarios are significantly “peakier” than are those of the other scenarios. This is typical rainfall/snowmelt-runoff behavior for impervious land uses; since very little water infiltrates into the ground, it all runs off in general proportion to the rate at which it falls (rain) or melts (snow). With less infiltration, surface roughness, or other sources of runoff attenuation, “spikes” in discharge occur after each snowmelt or rainfall event.

Generally lower marsh inflows are observed for both the row crop and naturalization scenarios; indeed, the naturalization relative hydrograph follows a similar shape to those of the row crop sub-scenarios, but with greater magnitudes. As would be expected after the water balance analyses, a transition to greater row crop coverage, and a rougher overall agricultural land surface, increases surface ponding allowing for more evaporation and infiltration. This behavior can be observed in the small decreases in marsh inflows during the spring melt and over two separate summertime events. As has been demonstrated, marsh inflows are a function of the losses that occur in the upland watershed; an overall basin water balance is maintained such that increases in water balance losses such as infiltration or ET are mirrored by decreases in overland runoff. Similar to the row crop scenario, marsh inflows decrease in the spring under the naturalization scenario. Again, a rougher land surface increases ponding and hinders overland runoff. The relative decrease in marsh inflows are slightly greater for the naturalization scenario than for the row crop because, in addition to a rougher land surface, vegetation parameters are modified in the naturalization scenario. Referring to Figure 4.7, note that the shrub/grass class has a slightly lower LAI and greater rooting depth, as compared to the cropland class of the baseline condition. These vegetation changes combine to result in a greater relative change in transpiration for the naturalization scenario versus the row crop.

Chapter 6

Conclusions and Recommendations

A numerical modelling study was conducted for the Delta Marsh Watershed to better understand and quantify its hydrological processes. The first step in digitally representing the DMW was delineating the watershed itself by identifying the physical limits within which all surface water flows towards the Delta Marsh. Field monitoring activities provided first-hand insight into watershed conditions as well as ground-truthing information for the watershed delineation. Additionally, limited streamflow data were collected for calibration and validation of the hydrological model. Building the hydrological model involved many physiographic and meteorologic data inputs, all combining to form a complete digital representation of the DMW's near-surface hydrological cycle. Once calibrated and validated, simulated water balance results were extracted to define current hydrological conditions within the DMW.

After analysis of baseline conditions, the model was modified to represent potential land use changes within the DMW. Scenarios representing urbanization, row crop, and naturalization land use changes were developed and analyzed. The degree to which these land use changes alter baseline hydrological conditions was estimated through comparisons of scenario results to baseline results.

6.1 Conclusions

Field and digital data were collected and assimilated for the creation of a comprehensive hydrological model of the DMW using the MIKE SHE modelling platform. Topographic and hydrographic information were used to identify the watershed extents and form the physical domain of the hydrological model; watershed delineation showed the DMW covers approximately 558 km^2. Results from over 12 simulation years provide a description of the typical DMW water balance. As is characteristic of prairie watersheds, wintertime hydrological activity in the DMW is limited to inputs of snowfall; frozen conditions restrict overland flow, infiltration, and ET. In the spring time, infiltration increases as frozen soils melt. Snow pore-water and ponded surface water begin to evaporate and transpiration rates increase as plants begin to grow and uptake more water. However, these abstractions are exceeded by the amount of water contained within the accumulated snowpack, and some meltwater runs over the surface towards the Delta Marsh as overland flow. Through the summer months, ET and infiltration depths exceed incoming precipitation. As an agriculturally-dominated watershed, transpiration comprises over 50% of total ET during the peak growing months of July and August in the DMW. Moving into the fall, infiltration and ET depths begin to decrease and precipitation transitions from rainfall to snow.

Model results show that approximately 40 million m^3 of water enters the Delta Marsh from the DMW surface in an average year. Portage Creek is shown to be the most significant single inflow to the marsh, contributing 12 million m^3/yr, on average; the remainder of the East Marsh receives relatively little overland runoff. The West Marsh, however, receives significant runoff averaging 15 million m^3/yr. Analysis of inflow timing show that significant volumes of water generated within the DMW arrive at the marsh throughout the year, and not just during the spring melt. It is expected that the hydraulic connection between the DMW and the marsh has an impact on timing of marsh inflows.

The hydrological model of the DMW was applied to represent three land use change scenarios: urbanization, row crop, and naturalization. Results of the land use change analyses show that annual overland runoff would increase by up to 51% as a result of urban expansion in the watershed, depending on the degree of expansion. A paved land surface would limit infiltration and increase evaporation of the ponded water. Conversely, a transition from mixed croplands to row crop predominance as well as a change from cropland to natural shrubs and grasses would result in decreased runoff within the basin. Changing all of the DMW's agricultural area to row crops would result in a 2.2% decrease in average annual runoff, while converting all cropland to natural shrubs and grasses would decrease runoff by 12%. Changes in surface roughness would result in increased surface ponding and therefore more infiltration. Additionally, shrubs and grasses would exhibit different vegetative processes and growing season than would cultivated cropland, also impacting the overall water balance of the DMW.

6.2 Limitations

The DMW hydrological model and associated results are subject to a number of limitations. Firstly, certain aspects of the DMW water system were not represented by the model. Drainage infrastructure such as culverts were not included in the model due to limited information on their locations and the difficulties in using a hydrological model to describe these hydraulic features. Culverts connect ditches and maintain hydraulic continuity within the flat, agricultural watershed. Since simulated overland runoff is defined by surface topography but does not include culvert connections, it can be expected that overland flow paths are restricted in some instances. Simulated overland flow may become stagnant in the low-lying areas that, in reality, are connected by culverts. Similarly, agricultural water infrastructure such as irrigation and tile drainage was also not represented in the model. It can be expected that artificial precipitation applied by irrigation and artificial infiltration/unsaturated zone drainage facilitated by tile drains impact the DMW water balance.

The MIKE SHE model also does not represent the hydraulic connections between the DMW and the Delta Marsh itself. Marsh bathymetry is included as part of the inputted DMW topography layer, so overland runoff that reaches the marsh simply ponds within the low elevations of the marsh. Hydraulic processes such as wind effects or inter-marsh mixing are not calculated on the water that becomes retained in this marsh representation. Therefore, any hydraulic factors impacting runoff into the marsh are not encapsulated by the model.

Finally, the absence of a detailed uncertainty analysis limits the dependability of modeled results. The ability of any model to fully represent a complex series of real-world hydrological processes, even if perfectly calibrated, is inherently limited. Calibration and validation results for the MIKE SHE model indicate that DMW hydrology is subject to a number of uncertainties. However, without a detailed uncertainty analysis, it is impossible to define the limits of the model and its results. Therefore, the results presented in this thesis should not be considered “predictions” or be used for design of engineering works without further examination of model uncertainty.

6.3 Significance of Findings

This study provides important information about the hydrological conditions of the DMW both currently and under potential future land use changes. Model results show that there is a significant inflow contribution from the DMW to the Delta Marsh on the order of nearly 40 million m^3 in an average year, which exceeds the total contribution from the Portage Diversion. This confirms that any marsh rehabilitation or land management strategy should consider the large volume of water that enters from the upland watershed. The volume of water entering the marsh via the DMW should not be ignored: upland inflows form a key part of the balance struck by the vegetation and wildlife of the Delta Marsh. Furthermore, water management and usage within the DMW should be carefully considered since changes in inflow contribution from the land may directly impact marsh water levels, which are demonstrated by Aminian (2015) as a key factor in marsh functionality and overall health.

Results of this study highlight areas of the DMW that are especially active in terms of runoff production. Portage Creek and areas upland of the West Marsh, in particular, carry significant runoff volumes into the marsh. These results may provide DUC and other stakeholders information on prioritizing areas for management of nutrient runoff or other environmental factors that may impact the health of the Delta Marsh. Model results also show that marsh inflows from the DMW are not limited to the spring melt season; inflows during the summer months are also significant. Land owners, agricultural producers, and other watershed users should be aware of the important year-round connection between the watershed and the marsh.

Finally, this study has shown that changes to land use within the DMW will impact the overall water balance as well as inflows to the marsh. Despite being hypothetical in nature, the scenarios analyzed during this project provide insight into what the hydrological manifestations of these changes may be. These results can be used to inform land use management within the DMW into the future.

6.4 Recommendations for Future Work

Additional field data would help to improve model calibration results and could be used to verify the model-estimated marsh inflows and water balance characterization. Collection of streamflow data throughout the spring, summer, and fall is recommended because model results have shown that inflows to the marsh are not limited to the spring melt period. Streamflow measurements closer to the marsh are also recommended to capture runoff from all portions of a given inflow sub-basin. Marsh inflow and sub-basin water balance results can be used to prioritize flow monitoring locations: it is recommended that, at a minimum, Portage Creek as well as channels flowing into the West Marsh be monitored throughout the unfrozen seasons. These regions have been shown to comprise approximately two-thirds of the total annual marsh inflow from the watershed, on average.

Connections between this study and other components of the greater marsh-watershed system would further demonstrate the significance of DMW hydrology. Firstly, it is recommended that the results of this study be paired with those of Aminian (2015). While the original intent of these two projects was to link the DMW hydrological model and Delta Marsh hydraulic model, differences in student timelines made this unachievable. Adding the marsh inflow results produced by the MIKE SHE model as inputs to the MIKE 21 hydraulic model would complete the integrated system. Relative land use change marsh inflow results could also be input to the MIKE 21 model and would provide an estimate of land use change impacts on marsh water levels and flows. Given the large inflow volumes from the DMW, an impact on marsh water levels would be expected, even under baseline conditions. The degree of this impact could be estimated by linking the two models and would provide additional insight on marsh function and the role of DMW hydrology in the overall marsh water system. A comparison of impacts on marsh water levels and discharges by Lake Manitoba water levels, wind effects, Portage Diversion inflows, and finally DMW inflows would be of interest to DUC and other stakeholders. A total-system water quantity analysis would provide additional insight on possible factors in declining Delta Marsh health.

Recommendations specific to future use of the hydrological model include:

1. Integrate hydrological model results with hydraulic model results of Aminian (2015)
   - Add simulated hydrographs from each *FlowThroughLine* and MIKE 11 outlet (baseline model results) as point flow inputs to the MIKE 21 marsh model; analyze marsh response (water levels, hydraulic mixing, etc.)
   - Once hydrological inputs are incorporated, compare hydraulic model results to measured marsh water levels, velocities, etc. and determine if calibration of either MIKE 21 or MIKE SHE model should be revisited
   - Add simulated hydrographs from each *FlowThroughLine* and MIKE 11 outlet (from each land use change scenario) as point flow inputs to the MIKE 21 marsh model; analyze marsh response (water levels, hydraulic mixing, etc.) relative to that of the baseline conditions
2. Perform a quantitative uncertainty analysis to corroborate the dependability of simulated results, especially if the MIKE SHE model is to be used for detailed land management decision-making

3. Determine locations of tile drains within the DMW (access Provincial Government information or perform field assessments) and consider incorporation of tile drainage in the model

4. Incorporate more detailed information on culverts and overland hydraulic connectivity within the watershed (access Provincial Government information or perform field assessments to identify locations)

5. Identify other potential land use change scenarios, or refine those outlined in this project, and simulate hydrological response

    - Examine partial conversion from cropland to natural shrub/grass (as opposed to complete conversion, as analyzed here)
    - Examine partial conversion from natural shrub/grass to cropland, particularly in the northeast region of the watershed
    - Examine increased prevalence of tile drainage throughout cropland land use class

The third Civil Engineering component of the *Delta Marsh - Restoring the Tradition* project involves collection and analysis of stable water isotope data (Glavonić, in progress). Isotopic analyses can be used to improve the hydrological model calibration and to corroborate the water balance results through application of mass balance models for source-separation of marsh inflows. Connections between the DMW hydrology results shown here, the hydraulic modelling results of Aminian (2015), and the stable water isotope results of Glavonić (in progress) would result in a more comprehensive understanding of the lake-marsh-watershed system.

Finally, the recently completed study by Stanley (2017) analyzed nutrient loading to the marsh as a function of DMW land use, and recommended that additional information on DMW water yield would help to inform landscape management decisions. Therefore, the DMW water balance and marsh inflow results shown in this thesis would complement the results presented by Stanley. Pairing the water quantity results presented here and the water quality results shown by Stanley would help to further characterize the impacts that land use in the DMW has on marsh function and overall health.

Appendix A

Supplementary Model Information

TABLE A.1: Land use classes by sub-basin

	W1	W3	E2	E3	E4	E6	E7	E8
Land Use Class	**Area (km^2)**							
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Impervious	1.1	0.6	1.9	0.4	3.8	0.2	0.4	6.1
Shrub/Grass	1.3	0.6	3.3	0.2	7.2	0.4	0.8	4.7
Cropland	23.0	7.7	34.7	7.4	44.9	5.5	14.9	33.7
Deciduous Forest	0.0	0.0	0.3	0.0	0.3	0.1	0.2	0.1
TOTAL AREA	**25.4**	**8.8**	**40.2**	**8.1**	**56.2**	**6.2**	**16.3**	**44.6**

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