Hydrologic Analysis for the Protection of Wetlands in Urban Development

by

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ABSTRACT

HYDROLOGIC ANALYSIS FOR THE PROTECTION OF WETLANDS IN URBAN DEVELOPMENT

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Wetlands depend on a dynamic hydrologic regime to support ecological function. Changes in catchment hydrologic behavior associated with urbanization affect the hydrologic regime of wetlands and impact their ability to perform ecosystem functions. Hydrologic analysis is important to demonstrate that development will not have negative impacts on wetlands. The research demonstrates the merit of thoughtful water balance analysis, hydrologic modelling, and the value of comprehensive data sets to support these efforts. Conceptual understanding of the study wetlands’ hydrology was refined through quantification of wetland water balances. This supported development of hydrologic models which were calibrated to known wetland hydroperiods. Continuous simulation predicted the impacts of development on the timing and nature of the wetland exchanges. Alternative green infrastructure systems were simulated and results provide evidence of the effectiveness of various systems to achieve identified hydroperiod targets which mitigate impacts of urbanization on the wetland.
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Chapter 1 Introduction

1.1 Research Context
Wetlands are dynamic water bodies with unique characteristics. They provide important ecosystem services such as habitat provision (Mitsch & Gosselink, 2007), carbon sequestration, water quality improvements, local climate moderation, and landscape storage which helps to attenuate floods and moderate groundwater dynamics (McLaughlin & Cohen, 2013). Wetlands not only exist because of complex hydrologic relationships but they also depend on the dynamic regimes to sustain their diverse ecological communities and to continue to provide goods and services to society. The hydroperiod of a wetland describes the seasonal water level changes and ultimately the hydrologic signature of the wetland (Mitsch & Gosselink, 2000). It depends on maintenance of water transfer mechanisms (i.e. surface water/groundwater exchanges, evapotranspiration (ET) losses). Alterations to the natural hydrologic regime are commonly responsible for wetland degradation.

It has been estimated that wetland area in Ontario has decreased by 68%, with southwestern Ontario experiencing losses as high as 90% (Snell, 1987). Recent studies have indicated that this loss and degradation in Ontario is still occurring (Ducks Unlimited, 2010). Though this loss has been historically attributed to agricultural land use, urbanization is now recognized as the largest threat to wetland health as development encroaches on these sensitive receiving features (Ducks Unlimited, 2010). Urbanization alters catchment hydrology through increasing impervious area, which results in decreased infiltration, decreased ET, increased runoff, and decreased water quality. Changes in catchment hydrology negatively impact wetland habitat, processes, and species distribution through alteration of the wetlands’ natural regime. Impacts include changes to groundwater and surface water flow pathways, changes in magnitude and frequency of inundation (Azous and Horner, 2001; Owen, 1999), increased water level fluctuations (Wright et al., 2006), increased flashiness (Wright et al., 2006), and decreased water quality (van Hengstum et al., 2007; Nakamura et al., 1997; Wright et al., 2006). Even small changes in a wetland’s natural regime can have large impacts on the wetland’s ecological integrity.

Low impact development (LID)/green infrastructure (e.g. permeable pavement, bioretention, rain water harvesting) is an important part of urban water management. The philosophy of LID includes the promotion of source control which helps to maintain watershed processes through the maintenance of natural site water balances which are ‘functionally equivalent’ to pre-development (Fletcher et al., 2014). Green infrastructure show promise to mitigate changes in catchment hydrology and the resulting impacts on hydrologic regime of adjacent wetlands. Gaps exist in the current body of knowledge regarding the ability of LID and site-scale stormwater management practices to contribute to catchment-scale responses and address wetland needs.
Wetland protection relies on obtaining a sound understanding of their hydrological and ecological functions to identify key processes and mechanisms. Wetland water balances are tools that quantify the water transfer mechanisms into and out of wetlands, defining interactions with the landscape and ultimately their hydroperiods. A wetland water balance is a key tool to confirm or refine the hydrological conceptualization of a wetland (Bradford, 2015). Water balance studies have been completed for a variety of scenarios and knowledge of water balances and techniques are in a diverse range of literature (e.g. Krasnostein & Oldham, 2004; Dietrich et al., 2007; Krause & Bronstert, 2005; Gasca & Ross, 2009; Chen & Zhou, 2011). A sound conceptual understanding of wetland hydrology can be obtained, refined, and confirmed using wetland water balances.

The impacts of urbanization on catchment hydrology are largely understood and there are a suite of simulation tools available for hydrologic modelling of catchment alterations. Hydrologic models also include tools which support the addition of LID features and their mitigation capabilities within the model framework (e.g. SWMM (US EPA, 2016)). Incorporating the wetland into the hydrologic model creates a tool where impacts are integrated and dynamic in the model, instead of part of a peripheral analysis. Using the knowledge obtained from a water balance study to inform a hydrologic model, these models can become better predictors of how catchment changes impact multiple facets of the wetlands hydrology. The capabilities of current predictive models are advancing and show promise to inform wetland management.

Bradford discusses two main challenges facing wetland management: (1) misconceptions and misunderstanding of the role of groundwater in wetlands; and (2) misunderstanding of the function of stormwater management design objectives (2015). These limitations have resulted in the mismanagement of wetland features and degradation of current wetlands. Research is needed to advance hydrologic models and analysis tools so that impacts of small hydrologic change on wetland ecology and function can be predicted (Bradford, 2015). The proposed research seeks to identify the value of a thoughtful wetland water balance to confirm conceptual understanding of wetland hydrology and direct modelling efforts. It seeks to demonstrate the use of accessible modelling tools to predict impacts of urbanization, design mitigation measures (i.e. green infrastructure), and assess their ability to mitigate impacts of urbanization on wetlands and support ecosystem objectives.

1.2 Problem Statement and Objectives

The proposed research will examine capabilities of urban water management to mitigate the impacts of urbanization on wetlands. It will determine how stormwater management systems can be better designed to protect receiving wetlands. This investigation will:

- Synthesize the existing body of research to (1) present a complete understanding of wetland hydrological processes, the characteristics which make their management difficult, and available techniques to advance the understanding and quantification of
these mechanisms; (2) summarize the impacts of urbanization on catchment and wetland hydrology and limitations of current management strategies for wetland protection; and (3) identify green infrastructure practices which show promise for mitigation of impacts, and the potential of hydrologic hydrological models to simulate the processes which are important to protecting wetland hydrological and ecological function and the effects of urbanization and mitigation on these processes.

- Conduct a wetland water balance for two study wetlands and demonstrate the value of a thoughtful wetland water balance analysis to refine and confirm the conceptual understanding of wetland hydrology.

- Using knowledge gained from wetland water balance analysis: (1) explore options for incorporating wetlands into hydrological simulation; (2) parameterize, calibrate, and validate a hydrologic model to include known wetland processes (i.e. surface, subsurface, and groundwater exchanges, ET, etc.) and characteristics (i.e. topography, storage relationships); (3) simulate a reference hydrologic regime for each of the study wetlands.

- Demonstrate the use of accessible modelling tools to predict the impacts of urbanization on catchment and wetland hydrology, design and simulate mitigation measures (i.e. green infrastructure), and assess the ability of targeted LID design to mimic key aspects of the pre-development water balance and mitigate impacts of urbanization on wetland hydrology and support ecosystem objectives.

1.3 Methodology

The methodology for the presented research was completed in three phases:

**Phase 1: Literature review.** Literature was synthesized and presented as it relates to wetland ecological and hydrological function and techniques for wetland water balances were evaluated. Effects of urbanization on catchment hydrology, the subsequent impacts on wetland hydrology, and the consequences for wetland ecological function were examined. The literature review explored the limitations of current stormwater management objectives and practices. Finally, models were evaluated in their ability to simulate catchment hydrology, wetland hydrology, surface and groundwater interactions, and LID controls.

**Phase 2: Data Analysis.** Data was provided by the Toronto and Region Conservation Authority (TRCA) for two wetland sites. A spreadsheet data analysis was conducted for the wetland water balance and results used to direct Phase 3 of the research.

**Phase 3: Modelling.** Using knowledge gained from the data analysis phase, models were selected and parameterized. Modelling was completed in PCSWMM, a software program on a
student-licence provided by Computational Hydraulics International (CHI). The simulation portion was split into two portions: (1) parameterize, calibrate, and validate the PCSWMM model to known wetland hydroperiods; and (2) use the calibrated model to evaluate the impacts of urbanization and the potential of green infrastructure to mitigate impacts on catchment and wetland hydrology.

1.4 Study Sites
These objectives are investigated using two wetland sites in the Duffins Creek Watershed. The wetlands are located less than 1 km apart, at Sideline 22 and Sideline 26, north of Taunton Road in Pickering, Ontario (Figure 1-1). Sideline 22 is an isolated wetland with no surficial inflow or outflow. Sideline 26 is a palustrine wetland with two distinct basins and perennial surficial outflow.

The contributing catchment at Sideline 22 is approximately 19 ha and Sideline 22 is 17 ha. Urban growth and expansion will result in both the wetland catchments undergoing development within the next 3-10 years. The wetlands have been monitored by the Toronto Region Conservation Authority (TRCA) since 2013. Data provided by the TRCA for the purpose of this study include: (1) continuous precipitation, temperature, groundwater and surface water levels; (2) detailed topographic surveys of the wetland basins and stage-storage relationships; and (3) results of slug tests and borehole samples. Figure 1-2 and Figure 1-3 summarize the location of the monitoring equipment and study design for both wetlands.
Figure 1-2: Sideline 22 Wetland Monitoring Study Set-up (TRCA, 2013)

Figure 1-3: Seaton Sideline 26 Wetland Monitoring Study Set-up (TRCA, 2013)
1.5 Thesis Structure
This thesis consists of six chapters, four of which (Chapters 2-5) are presented as standalone papers:

**Chapter 1 – Introduction.** Introduces the thesis topic, provides background information, identifies objectives, and presents thesis structure.

**Chapter 2 – Literature Review.** Presents a review of the impacts of urbanization on wetlands, the state of wetland water balance modelling, current approaches to mitigation of impacts of urbanization, and methods employed for modelling impacts of urbanization.

**Chapter 3 - Wetland water balances as tools confirm conceptual understanding of wetland hydrology and direct hydrologic modelling efforts to predict impacts of urbanization.** Presents an approach to wetland water balance analysis to refine conceptual understanding of wetlands and to identify gaps in understanding, additional data requirements, and necessary refinements of the wetland conceptualization.

**Chapter 4 – Wetland modelling in PCSWMM to predict impacts of urbanization:** Evaluates the capability of PCSWMM for modelling the wetland and its known water transfer interactions.

**Chapter 5 – Modelling to support design of green infrastructure systems to mitigate changes to catchment hydrology and wetland hydroperiods.** Examines the capabilities of PCSWMM to simulate impacts of urbanization on the receiving wetland and evaluates the capabilities of LID techniques to meet hydrologic targets.

**Chapter 6 – Conclusions and Recommendations.** Presents thesis conclusions and identifies areas where further research is merited.
1.6 References


Chapter 2  Literature Review: Urban water management for protection of wetlands in urban development: A synthesis of literature

2.1  Introduction

Wetlands provide tremendous value to society through ecosystem goods and services. Their ability to provide these services depends on the maintenance of their hydrologic regime. This presents a management challenge due to complex interactions which make understanding and quantifying their hydrologic processes difficult. A complete understanding of wetland hydrology is needed to identify wetlands’ roles within the landscape and the mechanisms which they rely on. Significant advances have been made in the understanding and quantification of these complex processes (i.e. groundwater exchanges, evapotranspiration, storage dynamics, etc.) making a thorough conceptualization of wetland hydrology more attainable. Wetland hydrology can be better understood through thoughtful wetland water balances.

Urbanization has been identified the leading cause of wetland loss and degradation in southwestern Ontario (Ducks Unlimited, 2010). Urbanization impacts catchment hydrology which in turn alters wetland hydrology and ecological function. Current stormwater management design objectives are insufficient to address impacts to wetland hydrology, however these limitations are not fully understood by both researchers and practitioners. Hydrological analysis for development is not rigorous and impacts of development are not being adequately mitigated. In some cases, sophisticated modelling is completed, but it is not typical practice. Better hydrologic modelling tools, approaches, and targets are needed to adequately predict impacts of development on wetlands and the performance of mitigation techniques.

The status quo for wetland management is not good enough. Successful management of wetlands in urbanization depends on a thorough understanding of wetland hydrology and interactions, a complete knowledge of how alterations to catchment hydrology directly impact wetland hydrology, acceptance and departure from the thinking that has led to misunderstood and misdirected stormwater management design objectives, and simulation and analysis tools which can reliably predict both impacts and performance of mitigation measures.

This review of literature seeks to: (1) synthesize the existing body of research to present a complete understanding of wetland hydrological processes, the characteristics which make their management difficult, and available techniques to advance the understanding and quantification of these mechanisms; (2) summarize the impacts of urbanization on catchment and wetland hydrology and limitations of current management strategies for wetland protection; and (3) identify green infrastructure practices which show promise for mitigation of impacts, and the potential of hydrologic simulation tools to predict impacts and the processes which are important to protecting wetland hydrological and ecological function.
2.2 Wetland Hydrology

Wetlands provide important ecosystem services such as habitat provision (Mitch & Gosselink, 2007), water quality improvements, and landscape storage which helps to attenuate floods and moderate groundwater dynamics (McLaughlin & Cohen, 2013). The maintenance of wetland hydrologic regime (i.e. timing, magnitude, duration, flashiness, etc.) is imperative for wetlands to continue to provide their goods and services (Poff et al., 1997). The wetland hydroperiod describes the wetland’s hydrologic regime and seasonal change in wetland water depth (Acreman & Miller, 2007). The hydroperiod is the wetland’s ‘hydrologic signature’, which is dependent on the maintenance of water transfer mechanisms into and out of the wetland (Mitsch & Gosselink, 2000). Sound management is needed to maintain and protect the hydrologic regime of wetlands so they can continue to provide these ecosystem services.

Wetlands pose a management challenge due to their unique characteristics and interactions with the landscape. Distinctive characteristics such as storage relationships, evapotranspiration losses, groundwater relationships, and soil properties are difficult to directly measure and are not always consistent across the wetland’s basin. Storage changes in wetlands are difficult to directly relate to water level changes due to spatially variable or unknown soil characteristics and lack of detailed topographic information (McLaughlin et al., 2014). Groundwater functions in wetlands are often intricate and nuanced (Winter, 1999). Evapotranspiration can be the most significant loss from a wetland; however, it is the most difficult to directly measure (Mazur et al., 2014). The intricacies of measurement and estimation of wetland properties contribute to the overall uncertainty involved in quantifying wetland exchanges, thereby causing complexities for wetland management. However, significant advances have been made in techniques for the quantification of individual mechanisms.

2.2.1 Groundwater Exchanges

Wetland-groundwater interactions act as an important hydrologic buffer by attenuating the response of the groundwater table and stabilizing aquifer dynamics (McLaughlin & Cohen, 2013). Wetlands can be both groundwater recharge and discharge locations; the direction and magnitude of groundwater exchanges vary both spatially and temporally within a single wetland (Whitely & Irwin, 1986; Gehrels & Mulamootil, 1990; Ramsar Convention on Wetlands, 2005). For example, McLaughlin and Cohen (2013) observed wetland groundwater exchanges which switched flow directions between rainfall events. Groundwater interactions are three-dimensional in nature but can be simplified using vertical and horizontal components. Groundwater exchanges have distinct chemical and thermal characteristics which make their contributions imperative (Ramsar Convention on Wetlands, 2005). For example, in the case when groundwater inflows are small, they can be a source of important chemical constituents to wetland species (Duval et al., 2011; Johansen et al., 2011). The timing and magnitude of flow can be important to prevent soil oxidation (Mitsch & Gosselink, 2000) and sustain evapotranspiration rates (Lowry & Loheide, 2010). Even in cases where groundwater flow does not affect wetland water levels,
the flushing properties can be important for maintaining water quality (Bradford, 2015). Continuous groundwater level data is needed to reveal the variation in groundwater exchanges and identify fluctuations that occur hourly, daily, or weekly.

2.2.2 Evapotranspiration

Evapotranspiration (ET) can be one of the most dominant water loss mechanisms in a wetland environment (Drexler et al., 2004; Mazur et al., 2014). It is well understood that without site-specific monitoring, estimates of wetland ET are difficult to obtain because of the unique aquatic and terrestrial characteristics and local atmospheric variability (Mazur et al., 2014). Site-specific monitoring of ET is also challenging; ET is difficult to both directly measure and to isolate from other wetland processes (Hill & Neary, 2007; Mazur et al, 2014; and others). Bowen ratio energy balance, eddy covariance, surface renewal, and LIDAR methods are examples of micrometeorological methods for estimating ET from a wetland (Drexler et al., 2004). However, these techniques are costly due to the need for multiple sensors (e.g. sonic anemometers, net radiometers, heat flux plates, etc.) and/or data processing (Drexler et al., 2004). Where onsite instrumentation is not available, empirical models including Thornthwaite, Priestley Taylor, Penman Monteith, and canopy cover methods can be used to estimate evapotranspiration (Drexler et al., 2004). Although empirical methods are less expensive with fewer limitations, there is high error associated with their broad assumptions and crude approximations (Drexler et al., 2004). Empirical methods are not site specific and cannot be universally applied across all wetland types (Drexler et al., 2004).

Evapotranspiration estimation methods such as the White method (i.e. Zhang et al., 2016; Hill & Durchholz, 2015) take advantage of ET occurring only during daylight hours and uses diurnal water level signatures to isolate ET rates. This method is applicable when no surface water exchanges are present and groundwater interactions do not vary diurnally (Hill & Durchholz, 2015; McLaughlin & Cohen, 2014; Hill & Neary, 2007). In investigations where isolated wetlands are found to violate the critical assumption for application of the approach (e.g. groundwater inputs are not constant), modifications to the White method can be used to obtain evapotranspiration rates (i.e. Hill & Neary, 2007; Mazur et al., 2014; McLaughlin & Cohen, 2014; Hill & Durchholz, 2015). For example, Mazur et al. (2014) use techniques suggested in investigations by Loheide (2008) and Gribovski et al. (2008) to perform an analysis which improves the accuracy of estimating detailed evapotranspiration rates by considering the impacts of diurnally fluctuating groundwater on ET. The significance of ET for understanding wetland hydrology, combined with the difficulty of obtaining accurate and site specific measurements, highlights why innovative methods to estimate evapotranspiration are of interest to researchers.

2.2.3 Storage Changes

Storage changes in wetlands depend on the balance of inputs and outputs. The water level-storage relationship depends on microtopography, vegetation properties (i.e. height, volume, rooting depth), and soil characteristics (i.e. porosity, specific yield). Each of these characteristics
adds to the complexity in estimating equivalent storage changes from a change in water depth. Despite increasing availability of information such as LIDAR surveys and aerial imagery, detailed topographic information is not always available and can be costly to obtain (Rayburg & Thoms, 2009). Detailed stage-storage curves account for microtopographic features such as hummocks and hollows which impact the storage relationship of wetlands (McLaughlin et al., 2014). The surface storage volume available for water can be affected by the volume of vegetation which varies with depth and seasonally with growth periods (Kadlec, 1999). The impact of vegetation volume on available surface storage and the assumption that one hundred percent of surface storage is available for water is commonly criticized in a wetland environment (Mazur et al., 2014; McLaughlin & Cohen, 2014). McLaughlin & Cohen use an open water yield of 0.95 to account for the wetland biovolume (2014). Studies recommend estimating open water available volume (or specific yield) through field observations and depth measurements to consider both the vegetation and microtopography impacts (Sumner et al., 2007).

Wetland storage changes occur beyond the open water fraction; storage changes in the soils of the banks, hummocks, and the subsurface may be important, particularly in drier periods when standing water is limited or not present. Storage changes within the subsurface necessitate estimating the specific yield of the wetland soils to translate changes in water level to equivalent change in water volume. Specific yield defines the volume of water released per unit decline in water table within an unconfined aquifer (Neuman, 1987). Estimates of this value range from 0.05 to 0.30 in soil matrices. Techniques for estimating the subsurface specific yield value have improved. For example, methods to calculate a ‘composite’ (Hill & Durchholz, 2015; Hill & Neary, 2007), ‘weighted’ (Mazur et al., 2014), or ‘ecosystem’ (McLaughlin & Cohen, 2014) specific yield which takes into account wetland specific subsurface characteristics have been presented.

Techniques for obtaining estimates of groundwater exchanges, evapotranspiration, storage changes, and specific yield have improved. Reducing the error in quantifying each independent mechanism assists in reducing the error contributing to the residual value in the water balance and helps direct refinement efforts.

2.3 Current Approaches and Tools for Wetland Conceptualization

A wetland’s hydroperiod is determined by the cumulative response of the wetland to water movement into and out of the wetland. Identifying these exchanges is necessary to develop a conceptual understanding of the mechanisms which support the wetland in its landscape. Knowledge of pre-development wetland hydrology is needed so that the hydrology can be protected—or impacts mitigated—in post-development. A wetland water balance equation takes the form: \( \text{Inputs} - \text{Outputs} = \text{Change in Storage} + \text{Residual} \). Water transfer mechanisms in wetlands include direct inputs from precipitation and catchment runoff via overland flow pathways, and evapotranspiration losses, as well as surface water and groundwater exchanges.
(Acreman & Miller, 2007). The general wetland water balance equation is displayed below (Equation 2-1) where each term is represented as equivalent depth over the wetland area.

\[ P + RO + SW_{IN} + GW_{IN} - SW_{OUT} - GW_{OUT} - ET = \Delta S + \text{Residual} \]

Equation 2-1

Where,

\( P \) = direct precipitation on the wetland area
\( RO \) = runoff from the contributing catchment, in the form of overland flow pathways
\( GW_{IN} \) = Groundwater inputs into the wetland (vertical or lateral)
\( SW_{IN} \) = surface water inputs into the wetland (in the form of channelized flow)
\( GW_{OUT} \) = Groundwater losses from the wetland basin (vertical or lateral)
\( SW_{OUT} \) = surface water losses from the wetland (via channelized or overflow pathways)
\( ET \) = evapotranspiration losses from the wetland basin
\( \Delta S \) = change in storage

A wetland water balance analysis must define the spatial boundaries and time period for the water balance. The spatial boundaries in plan-view may be the limit of inundation at a particular time or the delineated wetland boundaries. The depth of the system may be specified as the depth to a less permeable geologic layer or the depth of the rooting zone. The water balance is bounded by the time period of the monitoring data. Temporal resolution for the analysis is selected based on the type of investigation desired and can include seasonal (general patterns/behaviour), monthly (summary statistics), weekly (dry and wet periods), or daily (ET and groundwater patterns). The temporal resolution may be linked to the timescale of dominant wetland processes or known ecological requirements, and can be refined as the water balance analysis progresses.

Wetland water balances are most effective when each water transfer mechanism is independently quantified (Bradford, 2015). The residual term then accounts for the accumulation in errors associated with the quantification of each term as well as any missing components (Winter, 1981). Guidance exists regarding monitoring approaches to obtain field data and gain insight on wetland hydrology. A sound understanding of wetland hydrology combined with thoughtful selection of monitored parameters can direct wetland water balance studies. As the understanding of the wetland system develops, resources can be redirected and approaches refined to ensure the correct terms are being considered and adequately quantified.

There is a broad range of tools available to conduct water balance studies for various wetland scenarios and dominant wetland processes. Spreadsheet analysis has been successfully used for wetland water balance analysis (e.g. Whiteley & Irwin, 1986). Krasnostein and Oldham (2004) developed a process-based conceptual model to identify dominant hydrologic processes and gain a higher understanding of wetland hydrologic function. More sophisticated hydrologic and hydraulic modelling approaches have used software tools to conduct water balances for a range of specific settings such as wetlands with controlled drainage, irrigation, and water control systems (Dietrich et al., 2007, Gasca & Ross, 2009), environmental flow assessments (Chen &
Zhou, 2011), open-water wetlands and floodplains (Krasnostein & Oldham, 2004; Krause & Bronstert, 2005), complex lake-floodplain-wetland systems (Rayburg & Thoms, 2009), and grasslands, fens, and swamps within the United Kingdom (Thompson et al., 2004, Gilvear et al., 1993).

Regardless of the complexity of the approach, there are limitations and challenges. Typically, spreadsheet-type analysis provides a water balance based on each parameter acting independently and does not incorporate dynamic wetland feedback pathways. Krasnostein and Oldham’s (2004) method did not require high resolution or distributed data; however, they experienced challenges with model parameterization and emphasized the importance of obtaining detailed wetland topography. Some sophisticated approaches are critiqued on their ability to rigourously represent complex wetland processes (i.e. McKillop et al., 1999; Krasnostein & Oldham, 2004) and the data-intensive nature of the models which limits their application (i.e. Rayburg & Thoms, 2009; Thompson et al., 2004).

Water balances can aid in identifying uncertainties and additional data requirements, determining the relative magnitudes of water transfer mechanisms (Gasca & Ross, 2009), and refining the conceptual understanding of wetland hydrology (Acreman & Miller, 2007). Wetland water balances can inform hydrologic modelling and provide design criteria for measures to mitigate the effects of development.

2.4 Urban development and impacts on wetlands

2.4.1 Catchment Changes

Urbanization increases catchment imperviousness and impacts catchment hydrology by disrupting drainage patterns and altering the natural balance of infiltration, runoff, and evapotranspiration (Burns et al., 2012; Walsh et al., 2005; Fletcher et al., 2014). The increased imperviousness results in decreased vegetation area which reduces catchment surface and subsurface evapotranspiration thereby impacting catchment microclimate (Burns et al., 2012; Walsh et al., 2005). Land use change associated with urbanization increases the quantity of surface runoff, negatively impacts runoff water quality, and increases downstream erosion. Small storm hydrology is impacted as runoff is generated more frequently in post development conditions than pre-development (Pitt, 1999). Decreased water quality in urbanized catchments is a result of increased sediment, nutrient, and pollutant loading as well as thermal alterations (Wright et al., 2006).

2.4.2 Alterations to Wetland Hydrology

Development is encroaching on sensitive features such as wetlands and causing direct and indirect impacts (e.g. Wright et al., 2006). The wetland’s hydrologic regime describes the timing, magnitude, frequency, duration, and flashiness (rate of change) of water level variations (Poff et al., 1997). Urbanization in contributing drainage areas of wetland catchments impacts all facets of the hydrologic regime (Bradford, 2015). Alterations to catchment hydrology change drainage
pathways to wetlands, affecting the proportions of runoff and groundwater discharged to wetlands (Wright et al., 2006). Altered surface and subsurface pathways can negatively impact groundwater fed wetlands which are dependent on a steady source of groundwater recharge from catchment infiltration (Mitsch and Gosselink, 2007).

Rapid conveyance pathways as a result of impervious surfaces and conveyance systems impacts the timing of runoff to the wetland (Bradford, 2015). Changes in input pathways can result in increased magnitude and frequency of water level fluctuations and result in changes in the depth and duration of ponding (Wright et al., 2006; Owen, 1999). Increased volume of stormwater runoff leads to increased magnitude and duration of ponding which is exacerbated if the wetland does not have the capacity to discharge runoff (e.g. via a surface water outlet) (Wright et al., 2006). Catchment imperviousness can change microclimate conditions (e.g. increased air and water temperature, changes in humidity) which alter evapotranspiration and thermal patterns (Somers et al., 2013). Altered hydrologic regimes reduce the ability of wetlands to perform their full range of functions and services within the landscape (Krause et al., 2007; Davidson, 2014; Snell, 1987, Owen 1999). Characterizing impacts to wetlands on a range of hydrologic metrics is needed to understand and prevent alteration to wetland hydrology as a result of development (Bradford, 2015).

2.4.3 Ecological Impacts

The wetland’s hydrologic regime describes a crucial system variability which dramatically impacts the ecological make up and function of the system. Impacts to hydrology are directly translated to impacts to ecological character (e.g. vegetation and species composition). Water level fluctuations (WLF) describe the magnitude between the highest and lowest wetland water level for a period of time within a wetland (Wright et al., 2006). WLF encompass the flashiness and magnitude of the hydrologic regime. Extensive studies have been completed to understand the impacts of increased frequency and magnitude of WLF on wetland function (Wright et al., 2006). Ecological composition is affected by increases in WLF which governs vegetative species distribution (Cooke & Azous, 1997 in Wright et al., 2006) and encourages dominance of invasive species that are more tolerant to hydrologic change (Wright et al., 2006). Amphibian species presence was also found to decrease with increased water level fluctuations (Reinelt et al., 1998; Wright et al., 2006).

Wetland vegetation is dependent on hydrological input pathways for seasonal soil moisture, seasonal moist habitat, seasonal surface saturation, and access to the groundwater table (Gnangara Sustainability Strategy Taskforce, 2009). Changes to runoff volumes can dramatically impact wetlands by altering the duration and magnitude of ponding. A drying hydrologic regime can impact wetland vegetation composition when these water requirements are not being met (Froend et al., 2004). Conversely, extended inundation has negative impacts on plant species richness (Azous and Horner, 2001; Owen, 1999). Issues also arise when incorrect assumptions are made regarding the flood tolerance of plants in urban wetlands (McClean, 2000). Increases
Decreased runoff quality in post-development catchments, from the increased sediment, nutrient, chloride, and heavy metal loading, negatively impacts wetland ecological character and degrades fish and aquatic habitat. Sediment loading and deposition can alter wetland substrate properties and result in loss of habitat (van Hengstum et al., 2007) and community shifts in vegetation and aquatic invertebrate species (Nakamura et al., 1997; Wright et al., 2006). Though nutrient loading can enrich wetlands and improve productivity it ultimately favours the dominance of more tolerant invasive species (Wright et al., 2006). Higher chloride concentrations can have toxic effects. In all cases, increased pollutant loading reduces wetland biodiversity and favours more tolerant invasive species in the wetland community.

2.4.4 Stormwater Management Objectives

Stormwater management objectives for flood mitigation, water quality, erosion, and water balance were developed to address impacts of urbanization on the catchment scale. Typical flood mitigation objectives include peak flow attenuation from post-development to pre-development rates. Traditional water quality objectives target sediment removal rates, and stormwater management ponds are often designed to provide a combination of peak flow attenuation and water quality control. The “traditional” approach to stormwater management (i.e. rapidly conveys water through pipes to stormwater management ponds for end-of-pipe treatment) has been referred to as the “drainage-efficiency approach” (Burns et al., 2012). The focus on peak flow attenuation does not account for full range of consequences to receiving features (Roesner et al., 2001) which rely on hydrologic regimes influenced by a variety of factors besides peak-flow rates. More recently, volumetric control of runoff has been identified as the necessary paradigm-shift for stormwater management; the restoration of a natural catchment water balance through volume controls is recognized for its ability to reduce downstream erosion, improve water quality, maintain groundwater recharge and baseflow (Graham et al., 2004; Bradford & Gharabaghi, 2004) and contribute to flood loss avoidance (Atkins, 2015).

Jurisdictions have moved forward with volumetric retention or detention targets for stormwater runoff which aim to restore the natural catchment water balance. In general, volumetric targets aim to capture and retain (i.e. through infiltration, evapotranspiration, and/or reuse) or treat a prescribed runoff volume. However, to maintain all the characteristics of a wetland hydrologic regime, it may be important to also consider: (1) Distribution of retained volume to infiltration, evapotranspiration pathways and re-use and potential impacts of changing the proportion of infiltration; (2) Frequency of runoff / inflows to wetland (e.g. if all runoff for events up to a certain magnitude is captured and retained, then no flows are released to the downstream feature for these events) and consequence of changing this frequency from pre-development condition; (3) Timing and pathways of flows released from volume controls. Maintenance of hydrologic processes (i.e. proportions of rainfall volume distributed to ET, infiltration, and runoff) on the catchment scale is imperative to protect wetlands (Zalewski, 2000) as wetlands require surface
and subsurface flows to be delivered with appropriate timing, patterns, and volumes (Fletcher et al., 2014). To date, limitations of conventional approaches and the focus on inappropriate or misunderstood metrics has led to the inadequate protection of wetlands (Bradford, 2015).

2.4.5 Low Impact Development

Low impact development (LID) is an important part of integrated urban water management; the philosophy of LID includes the promotion of source control which helps to maintain watershed processes at the catchment scale. LID is described as a concept that aims to “maintain a natural site water balance through hydrologic landscapes which [are] ‘functionally equivalent’ to their pre-development state” (Fletcher et al., 2014). LID practices include bioretention, infiltration trenches, permeable pavement, enhanced bioswales, green roofs and rain water harvesting. Benefits of LID include improved water quality and maintenance of infiltration and runoff volumes (i.e. Hunt et al., 2012; Winston et al., 2016). LID practices can also remove water from overburdened sewers (Graham et al., 2004) and contribute to flood loss avoidance (Atkins, 2015). They are able to recreate informal drainage patterns which direct and disperse stormwater runoff through vegetated drainage pathways before reaching the receiving water feature (Burns et al., 2014). LID practices offer versatile solutions which can be implemented at a catchment-scale to address multiple objectives (Fletcher et al., 2015) and performance metrics which aim to restore elements of catchment hydrology critical to sensitive receiving features.

2.5 Hydrologic Modelling to Predict Impacts of Urbanization on Wetlands

Wetland protection in developing catchments requires a multi-level assessment approach. Water balance studies can be used to confirm conceptual understanding of wetland hydrology. However, water balances are limited in their ability to predict impacts of urbanization and evaluate mitigations measures. Knowledge gained from water balances can be used to inform hydrologic models and ensure the correct interactions are identified. Hydrologic models are valuable tools to simulate pre-development conditions, understand impacts of urbanization, aid design of mitigation measures, and demonstrate these measures are effective to meet desired stormwater management objectives.

Traditional stormwater management objectives have informed the direction of hydrologic modelling. Associated with the focus on peak-flow matching for flood mitigation objectives, stormwater management has focussed on a narrow range of flows (i.e. infrequent events) (Fletcher et al., 2014). Event-based simulation is very common to address peak flow attenuation and flood mitigation, but is unsatisfactory for volumetric targets and water quality performance which depend on cumulative responses to frequent events, with variable antecedent conditions. Continuous simulation is able to capture small storm response and antecedent conditions and their associated impacts on catchment hydrologic response. Continuous simulation can be calibrated with observation data and historical meteorological data is available to provide long term continuous simulation results.
Wetlands rely on a dynamic hydrologic regime for which it is important to understand seasonal variation and wetland response-recovery patterns. To represent the interconnectedness of the wetland-catchment relationship it is desirable for the hydrologic model to have output metrics which can assess wetland response to catchment changes. Models can provide valuable predictions of impacts of urbanization on the wetland if they are calibrated to existing conditions (i.e. observed wetland water levels). Predictive models are required to demonstrate changes in catchment and wetland hydrology from pre- to post-development. Continuous simulation can captures antecedent and seasonal conditions. To extend models to predict impacts of urbanization on sensitive receiving features, it may be necessary to include the wetland as a dynamic feature within the model to adequately represent feedback mechanisms between the catchment hydrologic changes and direct impacts on the wetland. Impacts of development on subsurface groundwater flow, evapotranspiration, infiltration, and wetland inputs are needed as simulation results. The model should provide a reasonable estimate of the wetland hydroperiod as an output so that pre-development conditions can be compared to post-development conditions. A model can also be used to “hind-cast” the wetland regime to a more naturalized or reference regime and provide insight on the extent of change that has already occurred to the wetland (i.e. from climate change) (ref). Models which can evaluate the dynamic feedbacks between the wetland and the catchment and report on appropriate hydrologic metrics to evaluate protection of wetland function will advance predictive capability of hydrologic simulation.

2.5.1 Review of Hydrologic Models
Simulation tools can take the form of surface water, groundwater, integrated, or coupled models. Surface water programs include the Soil-Water Assessment Tool (SWAT) (USDA, 2016), the Hydrological Simulation Program-FORTRAN (HSPF) (USGS, 2014b), OTTHYMO, PRMS, and SWMM (US EPA, 2015; CHI, 2015), among others. Surface water catchment modelling simulates the change in catchment runoff patterns from pre- to post-development as a result of changes to impervious area, slopes, drainage patterns, storage, etc. Surface water simulation results are analyzed to evaluate the change in precipitation-runoff response at the catchment level. Outputs include pre-and post-development hydrographs (event and/or continuous simulation) as well as changes in pre- and post-development infiltration, and evaporative losses. Surface water models alone do not directly consider the subsurface elements; however, some models have implemented groundwater modules (i.e. SWMM) to attempt to simulate subsurface behaviour. These features are generally data intensive or used as calibration tools (CHI, 2016).

Commercially available numerical models to simulate groundwater flow include MODFLOW (USGS, 2016), FEFLOW (DHI, 2016a), and MIKE SHE (DHI, 2016d). Groundwater models use either analytical or numerical methods (e.g. finite difference, finite element, finite volume) to solve groundwater flow equations. Inclusion of surface hydrological processes is generally limited to aquifer recharge and the representation of surface water interactions such as wetlands is usually limited to a constant head boundary condition which over-constrains the groundwater interactions (Levision et al., 2014). Defining surface water features as boundary conditions does
not allow dynamic interactions significant to wetland hydrology to be represented; it is important to include local features in a model atmosphere (Carol et al., 2013). In these scenarios it is also important to consider the scale of influence of groundwater on the surface water feature.

The third simulation tool available combines surface and groundwater models into integrated, coupled, or loosely-coupled models. Examples of coupled models include MIKE SHE (DHI, 2016d), GSFLOW (USGS, 2014a), and HydroGeoSphere (Aquanty Inc., 2015). MIKE-SHE uses groundwater and surface water sub-models to incorporate all aspects of hydrology such as groundwater, evapotranspiration, surface water, and recharge (DHI, 2016d). Platforms such as GSFLOW offer the ability to couple groundwater and surface water simulation platforms to provide dynamic communication between the model atmospheres and ease the implementation of integrating the models (USGS, 2014a). HydroGeoSphere is a fully integrated model which dynamically incorporates all components of the terrestrial hydrologic cycle (Aquanty Inc., 2015). Surface-groundwater models show some promise as they offer benefits such as the inclusion of surrounding surface water features like wetlands (Golden et al., 2014). However, high model complexity, intense data requirements, and sensitivity of parametrization limit their application in research and uptake (Golden et al., 2014; Gusyev & Haijema, 2011; Choi & Harvey, 2014; and others).

There is a range of available modelling tools to simulate changes in catchment hydrology. Surface water models are frequently applied but often limited in their ability to represent the groundwater system. Groundwater models have limited options for incorporating surface features and do not represent these surface processes in detail. Integrated models show promise to include both the surface and subsurface however large data requirements make their uptake and use limited. Wetland exchanges occur in the surface and subsurface and therefore models must have capabilities to include both exchanges and their dynamic interactions to simulate the entire range of impacts of urban development on the wetland hydroperiod.

2.6 Conclusions
Wetland water balances are the first step in the protection of wetlands in urban development. Challenges exist to independently quantify wetland interactions but techniques have been advanced which improve the ability to reduce errors associated with these estimates. The results of a water balance reveal dominant water transfer mechanisms such that data collection efforts can be refined. Conducting a water balance elucidates prevalent processes and informs areas where there is potential for impact from catchment urbanization. There is value in thoughtful wetland water balances to confirm conceptual understanding of wetland hydrology and direct modelling efforts. The complete conceptual understanding from the balance can identify the relative contributions of each water transfer mechanisms and catchment hydrologic processes that may impact the inputs and outputs of wetlands.
Urbanization directly impacts catchment hydrology which has consequences for receiving wetland features. Changes in catchment hydrology impact the dynamic hydrologic regime of wetlands which impacts ecologic character and function. Traditional stormwater management does not address ecologically relevant hydrologic metrics and is not adequately protecting wetlands. Low impact development shows promise to achieve catchment drainage patterns that are functionally equivalent to predevelopment rates. Knowledge gained from wetland water balances can be used to inform hydrologic models and select simulation tools. Models are needed to predict the impacts of urbanization, design mitigation measures (i.e. green infrastructure), and assess their ability to mitigate impacts of urbanization on wetlands and support ecosystem objectives.
2.7 References

Aquanty Inc. (2016). HydroGeoSphere. Waterloo, ON.


Chapter 3 Wetland water balances as tools to confirm conceptual understanding of wetland hydrology and direct hydrologic modelling efforts to predict impacts of urbanization

3.1 Introduction

Wetlands depend on dynamic hydrologic regimes to provide critical ecosystem services. The wetland hydroperiod describes the seasonal change in wetland water level and depends on maintenance of water transfer mechanisms into and out of the wetland (i.e. surface water exchanges, groundwater exchanges, evapotranspiration losses, runoff from surrounding catchments, and precipitation). Alterations to natural hydrologic regimes are often responsible for wetland degradation (Acreman & Miller, 2007).

Wetland degradation is still occurring in Ontario (Ducks Unlimited, 2010). Historically loss of wetlands has been largely due to agriculture, whereas urbanization has been identified as an important factor in recent wetland loss. Land use changes from urbanization alter catchment hydrology. Increased impervious areas result in decreased evapotranspiration, decreased infiltration, increased runoff generation, increased peak flows, and degraded runoff water quality (Burns et al., 2012; Walsh et al., 2005; Fletcher et al., 2014; Walsh et al., 2012). Changes to catchment area caused by reduced contributing area or diversion of water around wetlands can reduce inflows. Alteration of catchment hydrology negatively impacts the natural regimes of wetlands by changing the timing and the nature of the surface, subsurface, and groundwater flow (Wright et al., 2006; Owen, 1999). Altered hydrologic regimes reduce the ability of wetlands to perform their full range of functions and services within the landscape (Krause et al., 2007; Davidson, 2014; Snell, 1987, Owen 1999).

To prevent further wetland degradation due to the effects of development, more rigorous hydrologic analysis and better mitigation designs are needed. Sophisticated hydrologic modelling for development has been completed; however, it is not standard practice. In addition, there is significant resistance to intensive monitoring and modelling in southern Ontario. The small number of remaining wetlands in the Greater Toronto Area are under intense development pressure. This pressure combined with a lack of understanding of the limitations of current stormwater management practices and groundwater/surface water interactions are partially responsible for continued degradation (Bradford, 2015).

A wetland water balance equation takes the form: \[ \text{Inputs} - \text{Outputs} = \text{Change in Storage} + \text{Residual} \]. A water balance provides a test of hydrologic understanding by balancing inputs, outputs, and storage changes (Bradford, 2015). Wetland water balances are most effective when each water transfer mechanism is independently quantified (Bradford, 2015). The residual term then accounts for the accumulation in errors associated with the quantification of each term as well as any missing components (Winter, 1981). Water balances can aid in identifying
uncertainties and additional data requirements, determining the relative magnitudes of water transfer mechanisms (Gasca & Ross, 2009), and refining the conceptual understanding of wetland hydrology (Acreman & Miller, 2007). Wetland water balances can inform hydrologic modelling and provide design criteria for measures to mitigate the effects of development.

3.1.1 Objectives
The objective of this study is to demonstrate the approach to conduct a wetland water balance for two study wetlands and demonstrate the value of a thoughtful wetland water balance analysis to refine and confirm the conceptual understanding of wetland hydrology.

3.1.2 Study area and study period
Two wetlands have been monitored by the Toronto Region Conservation Authority for wetland water balance analyses. The wetlands are located at Sideline 22 and Sideline 26, north of Taunton Road in Pickering, Ontario (east of Toronto) in the Duffins Creek Watershed. Urban growth and expansion will result in both wetland catchments undergoing development within the next 5-10 years. The study sites are underlain by Halton Till. Boreholes confirmed that surficial overburden materials are predominantly silty sand to clayey silt till deposits (Sernas Associates, 2013).

Sideline 22 is classified as an isolated wetland with no surficial inflow or outflow present. The wetland is 1.38 ha with standing water present most of the year. Local surficial geology indicates that Halton till underlies the site (Gerber Geosciences Inc, 2003). Sideline 22 is a buttonbush mineral thicket /silver maple deciduous swamp and sits within the Iroquois Sand Plain (TRCA, 2013)

Sideline 26 has two discernible cells within the wetland, a basin located in the northwest which drains to the second southeastern basin. The basins together drain a catchment area of 17.0 hectares with approximately 7.0 hectares of the drainage area to the north and 10.0 hectares of the contributing area to the south. The catchment has moderate topographic relief. The wetland is classified as a palustrine wetland with no surficial inflow but seasonal surficial outflows to a small stream south of the southeastern basin. Sideline 26 is a mineral swamp with a hummock and hollow topography. It is also a buttonbush thicket /silver maple deciduous swamp and sits within the South Slope physiographic region (TRCA, 2013).

Monitoring data has been collected by the Toronto and Region Conservation Authority for the study wetlands since June 2013. The subject locations are within 1.0 kilometer of each other, therefore experiencing similar meteorological conditions. A single tipping bucket rain gauge was installed at Sideline 26 and used to record seasonal precipitation and temperature for both sites. A 3-season rain gauge, located at the Brockwest Landfill Site, approximately 3.0 kilometers to the southeast, and was updated to a heated four-season rain gauge in the fall of 2014. Precipitation and temperature data collected at the Brockwest landfill between June – November 2013 and April – November 2014 (recorded at 5.0-minute intervals) is used in this analysis.
Based on the nearest long-term climate station, the average precipitation for the area is 852.9 mm. The monitored years were preceded by a drier than average 2012 (813.7 mm) and the monitored years represent wetter than average precipitation in 2013 (875.3 mm) and drier than average conditions in 2014 (817.1 mm) (Environment Canada, 2016).

Historical spot measurements of groundwater levels and general trends were obtained from consulting reports for the surrounding area undergoing development (Sernas Associates, 2013). Water levels were available from stations established for ecohydrological studies of the same wetlands. There were two stations in Sideline 22 and four stations in Sideline 26 (two in each basin). Each station was instrumented with a surface water pressure transducer and 1-meter and 2-meter deep groundwater piezometers (Schlumberger DI501 Mini-Diver 10m range). The level loggers were mounted in stainless steel casings (30 mm diameter) and the wells were screened from 0.0 to 0.3 m above ground surface (surface water logger) and 0.7 to 1.0 m (1-meter logger) and 1.7 to 2.0 m (2-meter logger) below ground surface. A barometric logger (Schlumberger DI500 Baro-Diver) was installed at Sideline 26 to correct the pressure transducers at each station. At Sideline 22, two additional 2-m deep groundwater piezometers were installed approximately 200 meters to the east and southeast of the basin. At Sideline 26, an additional station was installed in a topographic high between the two basins. Continuous water level data is available at each monitoring location at 15-minute intervals for June – November 2013 and April – November 2014.

In Sideline 22, three shallow groundwater piezometers (Schlumberger DI501 Mini-Diver 10m Range) were installed along the hypothesized outflow path at the southwest edge of the wetland. Subsurface flow was not found to occur along this path and these piezometers were subsequently redeployed. Surface outflows at Sideline 26 were measured via surface water level logger piezometers (Schlumberger DI501 Mini-Diver 10m Range) coupled with a ramp flume (10.0 cfs maximum capacity, model number NAF10.0, Intermountain Environmental, 2013) recording data at 15-minute intervals from October 1, 2013 – November 2013 and April – November 20, 2014.

3.2 Methodology

The wetland water balance approach can be summarized with the following stages:

1) Develop a conceptual understanding of wetland hydrology and summarize in wetland water balance equations;
2) Independently estimate known inputs, outputs, and storage changes along with their corresponding uncertainties;
3) Determine the terms of the water balance associated with the greatest amount of error; and
4) Evaluate the relative contribution of water transfer mechanisms and the temporal variability of these contributions to the water balance.
Initially interactions were hypothesized based on wetland location in the landscape, site observations, and ecological indicators (TRCA, 2013). Water balance equations were developed based on the conceptualization of Sideline 22 (Figure 3-1) and Sideline 26 (Figure 3-2) each wetland and all terms are expressed as L$^3$.

Figure 3-1: Sideline 22 Conceptualization

\[
\begin{align*}
\text{Seaton Sideline 22:} & \quad P + RO + GW_{in} - ET - GW_{out} = \Delta S + \text{residual} \\
\end{align*}
\]

Figure 3-2: Sideline 26 Conceptualization

\[
\begin{align*}
\text{Seaton Sideline 26:} & \quad P + RO + GW_{in} - ET - GW_{out} - SW_{out} = \Delta S + \text{residual} \\
\end{align*}
\]
Where:
IN = sum of inputs into wetland basin
OUT = sum of outputs/losses from wetland basin
P = precipitation
RO = runoff
GW\text{in} = groundwater input (vertical and horizontal components of groundwater flow)
GW\text{out} = groundwater discharge (vertical and horizontal components of groundwater flow)
SW\text{out} = surface water discharge
ET = evapotranspiration
\Delta S = change in storage
Residual = residual error of the water balance

3.2.1 Methods used for independent estimation of terms of the water balance

Independent estimation of each term of the water balance was attempted. The volumes of each input and output are expressed as an equivalent depth over the wetland area. The area of wetland inundated in the spring of 2013 was used to define the wetland area. Precipitation data was aggregated in 15-minute intervals to match the resolution of the other monitored data.

Evapotranspiration is known to be one of the most dominant losses in a wetland (Drexler et al., 2004; Mazur et al., 2014). As a first approximation, actual evapotranspiration was assumed to equal potential evapotranspiration and the Thornthwaite method was used to estimate the potential evapotranspiration loss from each of the study wetlands. The Thornthwaite method considers hours of sunlight, distance from the equator, average monthly precipitation, and average monthly temperature (Drexler et al., 2004). The Thornthwaite approximation can be revised using diurnal water table fluctuation methods which isolate evapotranspiration from known groundwater recovery rates. Methods such as the White Method can be used when two key assumptions are in place no surface water exchanges are present, water levels fluctuate in the surface or saturated zone, and no precipitation occurs during the analysis period. Applicability of this method relies on the assumptions that ET does not occur overnight and groundwater fluxes are constant throughout the day (McLaughlin & Cohen, 2014). Groundwater recovery rates are estimated during the evening hours when no evapotranspiration occurs. The White method takes the form of:

\[ ET = (24 h \pm s) S_y \]

Where ‘h’ is the overnight groundwater recovery rate, calculated between 12:00 am and 4:00 am (Zhang et al., 2016), ‘s’ is the 24 hour decline (+) or rise (-) in the water table elevation (McLaughlin & Cohen, 2014), and ‘S_y’ is the specific yield of the storage matrix (McLaughlin & Cohen, 2014). The White method allows evapotranspiration losses to be estimated based on relating the water volume stored in the wetland and the groundwater recovery rate over the same period.
Direct measurement of catchment runoff is not feasible for catchment-scale investigations (Winter, 1981). PCSWMM, a dynamic rainfall-runoff model developed as a spatial interface for the US EPA SWMM 5.0 engine (CHI, 2015), was selected to estimate the magnitude and timing of the catchment runoff. Parameterization was based on background studies completed for each contributing catchment and land use and soil data from the TRCA (Sernas & Associates, 2013). The rainfall-runoff model considered the catchments in pre-development state with mild to moderate slopes (1-10%) and silty-loam soil. Runoff volume from the catchments was only sensitive to the imperviousness percentage in the catchment. For the study areas in the pre-development condition, hydraulically connected impervious area would be very small and have only a small range of potential values therefore there is little uncertainty associated with this component of the water balance.

Horizontal and vertical components of groundwater flows were estimated independently using Darcy’s law \( (Q = - k i A) \), where \( Q \) is the calculated flow rate in the vertical or horizontal direction, \( k \) is the hydraulic conductivity in the direction of flow, \( i \) represents the hydraulic gradient \((dh/dL)\), and \( A \) is the cross sectional flow area. The hydraulic gradient for the vertical flux is determined from the hydraulic heads in the 1m and 2m-deep piezometers. In the vertical direction, the area was taken as the wetted area of the wetland. In the horizontal direction, the area was taken as the maximum width perpendicular to the flow direction multiplied by the approximate depth of the groundwater piezometer (2m). Hydraulic conductivity estimates were based on the Hsorslev Slug Test Method to interpret on manual slug tests completed by TRCA at each monitoring station (Table 3-1). Soils at Sideline 22 had higher hydraulic conductivity values likely indicative of the proximity to the Iroquois Sand Plain. Hydraulic conductivity at Sideline 26 was measured at Basin 1 and lower values, typical of Halton Till, were found. In the absence of slug tests in Basin 2 of Sideline 26, the hydraulic conductivity was assumed to be consistent across the wetland.

<table>
<thead>
<tr>
<th>Wetland</th>
<th>Station and Depth</th>
<th>Saturated hydraulic conductivity, K (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sideline 22</td>
<td>1-10 (GW-2m)</td>
<td>6.45 E-05</td>
</tr>
<tr>
<td>Sideline 22</td>
<td>1-10 (GW-1m)</td>
<td>5.30 E-06</td>
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<td>3.20 E-07</td>
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<td>1.03 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-40 (GW-2m)</td>
<td>1.58 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-40 (GW-1m)</td>
<td>1.71 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-10 (GW-2m)</td>
<td>7.11 E-10</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-10 (GW-1m)</td>
<td>1.58 E-09</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-40 (GW-2m)</td>
<td>2.37 E-09</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-40 (GW-1m)</td>
<td>1.58 E-09</td>
</tr>
<tr>
<td>Sideline 26</td>
<td>3 (GW-2m)</td>
<td>1.04 E-04</td>
</tr>
</tbody>
</table>
The vertical hydraulic gradients \( (i_{\text{vertical}} = \frac{dh}{dL}) \) were calculated based on the measured difference in water level \( (dh) \) and the known elevation difference between the 1- and 2m groundwater logger locations \( (dL) \). In Sideline 22, vertical gradients were averaged between Station 1 and Station 2. In Sideline 26, Basin 1, the vertical groundwater flux was negligible. In Basin 2, larger gradients were observed based on the water levels measured in the 1m and 2m wells at Station 2-10 so a vertical component for the groundwater flux is reported.

Lateral groundwater gradients \( (i_{\text{lateral}} = \frac{dh}{dL}) \) were calculated based on the measured difference in water level \( (dh) \) and the known distance between the 2m deep groundwater wells. At Sideline 22, the downstream groundwater levels were consistently lower than wetland levels indicating a groundwater loss from the wetland. The lateral groundwater outflow from Sideline 22 was quantified between Station 1-10 and Station 3. In the absence of upstream piezometers, no lateral component to the north was quantified during the study period. Historical groundwater measurements indicated levels to the north and north east of the wetland basin were higher than within the wetland and may be indicative of a lateral groundwater contribution (Sernas and Associates, 2013).

At Sideline 26, there were no groundwater piezometers installed outside the wetland basins and lateral exchanges were not quantified. Historical spot measurements in wells to the northwest and southeast indicated groundwater levels surrounding the catchment which were higher than water levels observed within the wetland indicating potential lateral exchanges. Recommendations were made to the TRCA to install groundwater piezometers to confirm these exchanges though no additional piezometers have been deployed to measure these lateral exchanges. A groundwater piezometer at the surface outlet was also recommended to quantify outflow from a hypothesized lateral subsurface pathway.

Surface water losses at Sideline 26 were quantified using the relationship provided by the flume manufacturer. Unfortunately, the outflow measurements could not be used for the water balance analysis. The flume was located downstream of the wetland where there was a more distinct channel; however, the area contributing flow to this location was much larger than the wetland. There were also problems with the installation of the flume (backwater effects, bypassing of flows). It was possible to identify occurrences of surface water outflow based on the elevation of the water level in Basin 2 and the surveyed elevation of the wetland outlet.

Surveys of both wetlands were conducted between January and April of 2013. The surveys were completed using a total station (Sokkia Radian IS GPS unit and, Sokkia CX Series total station). A total of 898 surveyed points at Sideline 22, and 1732 survey points at Sideline 26 (based on sub-centimeter vertical accuracy and 6 degree UTM horizontal accuracy) were used to generate topographic maps at 0.25 m contours (TRCA, 2016). Changes in surface storage for each wetland were quantified using the stage-surface area-storage relationships derived from the
detailed topographic information. To account for storage changes in the bank and subsurface zone, the storage relationship in the wetland was extended below the base of ponding, as defined by the topographic study, to the lowest observed groundwater elevation. Specific yield is required to estimate storage relationships when the water level drops below the surface (Hill & Durchholz, 2015). Different estimates of specific yield for the bank areas and the subsurface wetland soils were selected (Gasca & Ross, 2009), and the storage relationship was extended to the banks and subsurface zones. Figure 3-3 describes the areas that were considered for each stage. Equation 3-1 to Equation 3-3 describe the total volumetric storage calculation for each stage in the wetland.

![Figure 3-3: Specific yield estimates](image)

**Scenario 1:** Water level is below base of ponding zone \( (Volume = V_{Area\ 1}) \)

**Scenario 2:** Water level is above the base of the ponding zone \( (Volume = V_{Area\ 1} + V_{Area\ 2} + V_{Area\ 3}) \)

\[
V_{Area\ 1} = A_{wetland} \times (h_{water\ surface} - h_{base\ of\ system}) \times S_{y,subsurface}
\]

\[
V_{Area\ 2} = (A_{wetland} - A_{water\ surface}) \times (h_{water\ surface} - h_{base\ of\ ponding\ zone}) \times S_{y,banks}
\]

\[
V_{Area\ 3} = Based\ on\ surveyed\ data
\]

**Equation 3-1**

**Equation 3-2**

**Equation 3-3**

### 3.2.2 Water balance approach

The terms of the wetland water balance were independently quantified using the methods described above. A monthly water balance summary was completed to evaluate the relative magnitudes of the inputs, outputs, and storage changes in each wetland as well as the residual, reflecting the cumulative error in the water balance. Water balances for dry and wet weather periods were also summarized to aid in identification of the terms with the largest errors. The
events selected varied in season, length, antecedent and total precipitation, and depth of standing water in the wetlands (Table 3-2 and Table 3-3).

Table 3-2: Dry Period Event Conditions

<table>
<thead>
<tr>
<th>Event</th>
<th>Start</th>
<th>End</th>
<th>Length (days)</th>
<th>Total Antecedent Precipitation (^1) (m)</th>
<th>Wetland Water Depth(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Summer 2013 (2)</td>
<td>8/7/2013</td>
<td>8/25/2013</td>
<td>18</td>
<td>0.035</td>
<td>-0.05</td>
</tr>
<tr>
<td>2-Fall 2013 (1)</td>
<td>9/21/2013</td>
<td>9/29/2013</td>
<td>8</td>
<td>0.023</td>
<td>-0.25</td>
</tr>
<tr>
<td>3-Fall 2013 (2)</td>
<td>10/22/2013</td>
<td>10/26/2013</td>
<td>4</td>
<td>0.015</td>
<td>-0.20</td>
</tr>
<tr>
<td>4-Summer 2014</td>
<td>8/1/2014</td>
<td>8/12/2014</td>
<td>10</td>
<td>0.011</td>
<td>0.01</td>
</tr>
<tr>
<td>5-Summer 2014 (2)</td>
<td>8/16/2014</td>
<td>9/1/2014</td>
<td>16</td>
<td>0.008</td>
<td>0.03</td>
</tr>
<tr>
<td>6-Fall 2014 (1)</td>
<td>21/09/2014</td>
<td>01/10/2014</td>
<td>7</td>
<td>0.030</td>
<td>-0.05</td>
</tr>
</tbody>
</table>

\(^1\) Total antecedent precipitation reports the total precipitation recorded for the preceding seven days

Table 3-3: Wet Period Event Conditions

<table>
<thead>
<tr>
<th>Event</th>
<th>Start</th>
<th>End</th>
<th>Length (days)</th>
<th>Total Precipitation (m)</th>
<th>Max Wetland Water Depth(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Spring 2013</td>
<td>06/06/2013</td>
<td>15/06/2013</td>
<td>9</td>
<td>0.044</td>
<td>0.27</td>
</tr>
<tr>
<td>8-Summer 2013 (2)</td>
<td>23/08/2013</td>
<td>06/09/2013</td>
<td>14</td>
<td>0.051</td>
<td>-0.04</td>
</tr>
<tr>
<td>9-Fall 2013</td>
<td>08/10/2013</td>
<td>24/10/2013</td>
<td>16</td>
<td>0.055</td>
<td>-0.18</td>
</tr>
<tr>
<td>10-Spring 2014 (1)</td>
<td>26/04/2014</td>
<td>07/05/2014</td>
<td>11</td>
<td>0.040</td>
<td>0.25</td>
</tr>
<tr>
<td>11-Summer 2014 (1)</td>
<td>24/07/2014</td>
<td>05/08/2014</td>
<td>12</td>
<td>0.020</td>
<td>0.002</td>
</tr>
<tr>
<td>12-Fall 2014 (1)</td>
<td>31/08/2014</td>
<td>19/09/2014</td>
<td>19</td>
<td>0.029</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

Dry period analysis isolates transfer mechanisms responsible for water levels fluctuations unrelated to precipitation and runoff. In the absence of precipitation the relative impact of groundwater exchanges and evapotranspiration is apparent in rates of wetland water level decline. Dry periods provided a selection of days where diurnal level fluctuations could be identified and used to refine rate of evapotranspirative loss. The wet weather periods can be used to identify differences in wetland exchanges during and subsequent to rainfall.

3.3 Results

3.3.1 General wetland trends

Examination of the data revealed different behaviour in the wetlands between the 2013 and 2014 monitoring years at Sideline 22 and Sideline 26. For example, water levels at Sideline 22 (Station 1-10 which behaved similarly to 1-40) from July-August of 2013 (Figure 3-4) and 2014 (Figure 3-5) are provided. In 2014 the vertical gradient is almost 5 times larger (average -0.006 m/m in 2013 and -0.030 m/m in 2014) indicating yearly variations in groundwater contributions. Wetland water levels in 2013 at Sideline 22 were generally lower (approximately 0.15 – 0.2m) than levels experienced in 2014. In 2012, lower than average annual precipitation occurred
whereas 2013 had higher than average annual precipitation. The lower water levels observed in 2013 are likely a result of the drier than average precipitation year in 2012, suggesting a delayed response in water table. In both monitored years, water levels drop below ground surface and into the subsurface in late July. By late August the surface water loggers were dry in 2013 but in 2014 the water levels remained at or near the surface for the entire summer monitoring period. Two, 14-day dry periods are present in the July-August time periods for both 2013 and 2014 which were used for dry period analysis.

Comparing the hydroperiod in Sideline 22 (Figure 3-5) and Sideline 26 (Figure 3-6) for the same time period in 2013 demonstrates the variability in wetland hydrology despite geographical proximity. For example, more significant increases in water level following precipitation events are apparent in Sideline 22 (Figure 3-4) than in Sideline 26 (Figure 3-6). For example, in the July 31, 2013 rainfall event, the water level increases by approximately 0.1 m (Sideline 22), 0.05 m (Sideline 26, Basin 1), and 0.2 m (Sideline 26, Basin 2). The different behaviour could be a result of different stage-storage relationships, effective drainage areas, or abstraction from interception.

At Sideline 26, water surface elevations are not the same in each wetland basin (Figure 3-6). Groundwater contributions also vary between basins (i.e. no vertical exchanges in Basin 1 vs. observed vertical losses in Basin 2) (Figure 3-6), similar to findings from Duval and Waddington who observed variation in groundwater exchanges within a wetland (2011). These observations refute the initial assumption that the Sideline 26 wetland functions as a single system and the basins were subsequently separated for the water balance analysis.

Both wetland locations in 2013 experienced decreases in the surface and groundwater levels during the two-week dry period in August 2013. Surface and groundwater levels decline at similar rates during the dry period, with the exception of Station 2-10. Diurnal fluctuations in Sideline 22 are apparent and consistent between monitored years.
Figure 3-4: Sideline 22 Station 1-10 (July - August 2013)

Figure 3-5: Sideline 22 Station 1-10 (July - August 2014)
3.3.2 Sideline 22

The water balances for Sideline 22 report vertical groundwater exchanges as an input though some time periods exist where there is a net vertical groundwater loss (negative input). Lateral groundwater losses were quantified from the wetland basin; however, data was not available to quantify lateral inputs.
### 3.3.2.1 Monthly Water Balance

The monthly water balance for Sideline 22 resulted in residual values which are both positive and negative during the analysis period (Table 3-4). For example, in July 2013 there is a large positive residual as a result of a large storage change which is not explained by the inputs and outputs calculated for that month, indicating the storage change may be overestimated. In October 2013, the residual is also large, but negative as a result of the increase in storage being larger than the inputs and outputs would predict. Comparing these two months presents conflicting interpretation with respect to over- or underestimate of the inputs and outputs, suggesting the issue may be with the quantification of storage change. In all cases, the magnitude of the residual term was proportional to the magnitude of the change in storage term. Volumetric storage change depends on the estimate of specific yield for the banks and subsurface in the wetland, indicating a need to revisit the depth dependent specific yield. The months when storage change is largest (i.e. July, October 2013; July, October 2014) the wetland water level transitions from above to below ground, indicating that the method for estimating storage change at the interface must be revisited.

**Table 3-4: Monthly water balance Sideline 22**

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>RO</th>
<th>GW\text{IN,V}</th>
<th>GW\text{OUT}</th>
<th>ET</th>
<th>IN</th>
<th>OUT</th>
<th>ΔS</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
</tr>
<tr>
<td>Jun-13</td>
<td>0.104</td>
<td>0.031</td>
<td>0.001</td>
<td>-0.043</td>
<td>-0.113</td>
<td>0.137</td>
<td>-0.156</td>
<td>0.012</td>
<td>-0.031</td>
</tr>
<tr>
<td>Jul-13</td>
<td>0.057</td>
<td>0.029</td>
<td>0.009</td>
<td>-0.053</td>
<td>-0.145</td>
<td>0.095</td>
<td>-0.197</td>
<td>-0.273</td>
<td>0.170</td>
</tr>
<tr>
<td>Aug-13</td>
<td>0.092</td>
<td>0.026</td>
<td>0.003</td>
<td>-0.052</td>
<td>-0.125</td>
<td>0.120</td>
<td>-0.177</td>
<td>-0.114</td>
<td>0.057</td>
</tr>
<tr>
<td>Sep-13</td>
<td>0.050</td>
<td>0.017</td>
<td>-0.004</td>
<td>-0.048</td>
<td>-0.079</td>
<td>0.063</td>
<td>-0.127</td>
<td>-0.115</td>
<td>0.050</td>
</tr>
<tr>
<td>Oct-13</td>
<td>0.118</td>
<td>0.039</td>
<td>-0.005</td>
<td>-0.050</td>
<td>-0.047</td>
<td>0.153</td>
<td>-0.096</td>
<td>0.259</td>
<td>-0.203</td>
</tr>
<tr>
<td>Nov-13</td>
<td>0.039</td>
<td>0.006</td>
<td>0.015</td>
<td>-0.050</td>
<td>-0.004</td>
<td>0.061</td>
<td>-0.054</td>
<td>0.010</td>
<td>-0.004</td>
</tr>
<tr>
<td>Apr-14</td>
<td>0.040</td>
<td>0.011</td>
<td>0.039</td>
<td>-0.049</td>
<td>-0.025</td>
<td>0.090</td>
<td>-0.074</td>
<td>0.000</td>
<td>0.016</td>
</tr>
<tr>
<td>May-14</td>
<td>0.051</td>
<td>0.012</td>
<td>0.023</td>
<td>-0.052</td>
<td>-0.080</td>
<td>0.085</td>
<td>-0.131</td>
<td>-0.050</td>
<td>0.004</td>
</tr>
<tr>
<td>Jun-14</td>
<td>0.090</td>
<td>0.017</td>
<td>0.030</td>
<td>-0.051</td>
<td>-0.115</td>
<td>0.137</td>
<td>-0.165</td>
<td>-0.050</td>
<td>0.022</td>
</tr>
<tr>
<td>Jul-14</td>
<td>0.047</td>
<td>0.008</td>
<td>0.011</td>
<td>-0.052</td>
<td>-0.131</td>
<td>0.067</td>
<td>-0.183</td>
<td>-0.151</td>
<td>0.034</td>
</tr>
<tr>
<td>Aug-14</td>
<td>0.047</td>
<td>0.029</td>
<td>0.014</td>
<td>-0.052</td>
<td>-0.118</td>
<td>0.090</td>
<td>-0.170</td>
<td>-0.120</td>
<td>0.040</td>
</tr>
<tr>
<td>Sep-14</td>
<td>0.103</td>
<td>0.049</td>
<td>0.007</td>
<td>-0.050</td>
<td>-0.085</td>
<td>0.160</td>
<td>-0.132</td>
<td>0.048</td>
<td>-0.020</td>
</tr>
<tr>
<td>Oct-14</td>
<td>0.108</td>
<td>0.039</td>
<td>0.017</td>
<td>-0.052</td>
<td>-0.050</td>
<td>0.163</td>
<td>-0.102</td>
<td>0.211</td>
<td>-0.150</td>
</tr>
<tr>
<td>Nov-14</td>
<td>0.045</td>
<td>0.011</td>
<td>0.022</td>
<td>-0.033</td>
<td>-0.006</td>
<td>0.079</td>
<td>-0.040</td>
<td>0.050</td>
<td>-0.011</td>
</tr>
</tbody>
</table>

### 3.3.2.2 Dry period analysis

Select dry periods were analyzed to gain insight on exchanges that occur in the wetland without the influence of precipitation and runoff (Table 3-5). Residuals are both positive and negative and range +/- 16 mm/day in magnitude. Acknowledging that storage changes are likely overestimated, the analysis focused on events with smaller storage changes to evaluate impacts of other water transfer mechanisms. For example, in Event 2, 3, and 4, there is very little (or no)
change in storage but there is a large residual value. For these events, the residual is caused by either errors associated with the other terms or a missing exchange. The balance of inputs and outputs in these events would suggest that the storage change would be much larger than observed, indicating the outputs are too large or the inputs are not large enough. During these periods the water is above the surface of the wetland therefore there is no reason to expect that potential evaporative demand is not being satisfied. It is possible that groundwater output is being over estimated or there is a lateral groundwater component missing. Historical spot measurements of the groundwater table to the north of the catchment would indicate that there is a groundwater gradient into the wetland (Sernas & Associates, 2013); however, no measurements during the study period are available to confirm.

Table 3-5: Sideline 22 Dry Period Analysis

<table>
<thead>
<tr>
<th>Event</th>
<th>GW_{IN,V} (m)</th>
<th>GW_{OUT,L} (m)</th>
<th>ET (m)</th>
<th>IN (m)</th>
<th>OUT (m)</th>
<th>ΔS (m)</th>
<th>Residual (m)</th>
<th>Residual / Day (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Summer 2013</td>
<td>0.001</td>
<td>-0.036</td>
<td>-0.044</td>
<td>0.001</td>
<td>-0.080</td>
<td>-0.128</td>
<td>0.049</td>
<td>0.005</td>
</tr>
<tr>
<td>2-Fall 2013 (A)</td>
<td>-0.020</td>
<td>-0.026</td>
<td>-0.034</td>
<td>-0.019</td>
<td>-0.060</td>
<td>-0.004</td>
<td>-0.075</td>
<td>-0.026</td>
</tr>
<tr>
<td>3-Fall 2013 (B)</td>
<td>-0.001</td>
<td>-0.013</td>
<td>-0.012</td>
<td>-0.001</td>
<td>-0.025</td>
<td>-0.011</td>
<td>-0.015</td>
<td>-0.004</td>
</tr>
<tr>
<td>4-Summer 2014 (A)</td>
<td>0.005</td>
<td>-0.034</td>
<td>-0.015</td>
<td>0.005</td>
<td>-0.049</td>
<td>0.000</td>
<td>-0.045</td>
<td>-0.004</td>
</tr>
<tr>
<td>5-Summer 2014 (B)</td>
<td>0.006</td>
<td>-0.052</td>
<td>-0.023</td>
<td>0.006</td>
<td>-0.074</td>
<td>-0.155</td>
<td>0.087</td>
<td>0.006</td>
</tr>
<tr>
<td>6-Fall 2014</td>
<td>0.010</td>
<td>-0.009</td>
<td>-0.003</td>
<td>0.010</td>
<td>-0.012</td>
<td>-0.043</td>
<td>0.041</td>
<td>0.016</td>
</tr>
</tbody>
</table>

3.3.2.3 Wet Period Analysis

The dry period analysis was able to provide some evidence of a missing groundwater inflow during dry periods. The analysis of wet weather behaviour in Sideline 22 was conducted to identify the wetland interactions when precipitation and runoff are included in the balance (Table 3-6). Event 10 and 11 have no storage change during the period of analysis and therefore the residual term is not a result of errors with the volumetric storage change. During these two events the balance of inputs and outputs would suggest that the storage should increase; therefore, the inputs are too large or the outputs are too small. Evapotranspiration is the only output reported and is not likely underestimated during a precipitation event. The uncertainty associated with estimates of precipitation and runoff is small which points to underestimation of a calculated outflow or a missing outflow. A groundwater inflow pathway was hypothesized during dry periods. If this pathway is active during wet periods, the inflows would be even larger than reported and the missing outflow would be more significant. In Events 7, 8, 9, and 12 a storage increase is reported that is larger than the balance of inputs and outputs would predict. The residual in each of these events can be explained by an inflow pathway that is not reported, or storage changes that are overestimated. Contradictory results for the wet period indicate the need to collect additional data, in addition to refining the storage change estimates.
Table 3-6: Sideline 22 Wet Period Summary

<table>
<thead>
<tr>
<th>Event</th>
<th>P (m)</th>
<th>RO (m)</th>
<th>GWv (m)</th>
<th>GW_{OUT,L} (m)</th>
<th>ET (m)</th>
<th>IN (m)</th>
<th>OUT (m)</th>
<th>ΔS (m)</th>
<th>Residual (m)</th>
<th>Residual /Day (m)</th>
<th>Max. Rainfall (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event 7</td>
<td>0.044</td>
<td>0.004</td>
<td>0.014</td>
<td>-0.031</td>
<td>-0.013</td>
<td>0.048</td>
<td>-0.029</td>
<td>0.075</td>
<td>-0.057</td>
<td>-0.007</td>
<td>19.2</td>
</tr>
<tr>
<td>Event 8</td>
<td>0.051</td>
<td>0.017</td>
<td>0.000</td>
<td>-0.014</td>
<td>-0.006</td>
<td>0.068</td>
<td>-0.020</td>
<td>0.118</td>
<td>-0.070</td>
<td>-0.017</td>
<td>57.6</td>
</tr>
<tr>
<td>Event 9</td>
<td>0.055</td>
<td>0.008</td>
<td>-0.001</td>
<td>-0.027</td>
<td>-0.012</td>
<td>0.062</td>
<td>-0.043</td>
<td>0.112</td>
<td>-0.093</td>
<td>-0.009</td>
<td>24.0</td>
</tr>
<tr>
<td>Event 10</td>
<td>0.040</td>
<td>0.040</td>
<td>0.005</td>
<td>-0.020</td>
<td>-0.009</td>
<td>0.079</td>
<td>-0.026</td>
<td>0.000</td>
<td>0.053</td>
<td>0.009</td>
<td>19.2</td>
</tr>
<tr>
<td>Event 11</td>
<td>0.020</td>
<td>0.019</td>
<td>0.000</td>
<td>-0.017</td>
<td>-0.008</td>
<td>0.039</td>
<td>-0.023</td>
<td>0.000</td>
<td>0.016</td>
<td>0.003</td>
<td>88.8</td>
</tr>
<tr>
<td>Event 12</td>
<td>0.029</td>
<td>0.027</td>
<td>-0.001</td>
<td>-0.016</td>
<td>-0.008</td>
<td>0.056</td>
<td>-0.023</td>
<td>0.029</td>
<td>0.004</td>
<td>0.001</td>
<td>31.2</td>
</tr>
</tbody>
</table>

3.3.2.4 Diurnal Analysis

Diurnal water level fluctuation analysis was conducted in Sideline 22 at an hourly resolution to attempt to isolate evapotranspiration losses from groundwater exchanges (Zhang et al., 2016; McLaughlin & Cohen, 2014). Two 14-day dry periods that occurred in July and August of 2013 and 2014 were selected to analyze diurnal fluctuations (Figure 3-4 and Figure 3-5, respectively). Daily water level fluctuations were similar for all dry periods observed and show consistent fluctuations between stations. Diurnal fluctuations for two 48-hour windows at Sideline 22 are illustrated in Figure 3-7 and Figure 3-8. The slight nighttime recovery suggests a net groundwater input via lateral and/or vertical pathways.

![Figure 3-7: Sideline 22 Station 1-10 August 20-22, 2013](image-url)
In both 2013 (Figure 3-7) and 2014 (Figure 3-8), the water level fluctuations in the 1-metre groundwater well occurred approximately 40 cm and 15 cm, respectively, below the ground surface elevation (146.28 m), therefore necessitating the use of a subsurface specific yield estimate. Using the White method with specific yield values ranging from 0.05 (Zhang et al., 2016) to 0.13 (McLaughlin & Cohen, 2014) in 2013 the evapotranspiration losses are estimated between 3.5 to 9.0 mm/day. Applying the same method and range to the 2014 dry period yields evapotranspiration estimates ranging from 6.9 mm to 13.0 mm. Estimates of evapotranspiration range were similar for both years, regardless of the observed differences in groundwater exchanges and presence of a vertical groundwater flux in 2014.

3.3.3 Sideline 26
The water balances for Sideline 26 are done separately for Basin 1 and Basin 2 because of the observed differences in surface water elevations and groundwater exchanges. In Basin 1, vertical groundwater fluxes were negligible. In Basin 1 and 2, lateral groundwater exchanges may be present; however, no instrumentation was in place to quantify these interactions. A subsurface/surface pathway is likely present from Basin 1 to Basin 2. An intermittent surface outflow path exists from Basin 2; however, measurements were not available for the analysis due to problems with the flume described in Section 3.2.1.

3.3.3.1 Monthly Water Balance
The monthly water balance for Basin 1 (Table 3-7) shows inputs are larger than the outputs in all months with the exception of July 2013, July 2014, and August 2014. For some of these months (June, August, September 2013 and May 2014) there was a measured loss of storage, suggesting that inputs are overestimated or outputs are underestimated. Unlike Sideline 22, the magnitude of the residual is not proportional to the storage change indicating errors are not due to the specific
yield estimates or issues with a depth-dependent specific yield. The residual can be explained in nearly every case by inputs being too large or outputs being too small (with the exception of June, July, and August 2014). The uncertainty associated with estimates of precipitation and runoff is small which points to underestimation of a calculated outflow or a missing outflow. These results support a hypothesis that an outflow pathway is missing from Basin 1 and without quantifying the magnitude of the output it is not possible to eliminate the possibility of a groundwater inflow pathway.

Table 3-7: Monthly water balance Sideline 26 – Basin 1

<table>
<thead>
<tr>
<th></th>
<th>P (m)</th>
<th>RO (m)</th>
<th>ET (m)</th>
<th>IN (m)</th>
<th>OUT (m)</th>
<th>ΔS (m)</th>
<th>Residual (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun-13</td>
<td>0.104</td>
<td>0.039</td>
<td>-0.113</td>
<td>0.143</td>
<td>-0.113</td>
<td>-0.009</td>
<td>0.039</td>
</tr>
<tr>
<td>Jul-13</td>
<td>0.057</td>
<td>0.075</td>
<td>-0.145</td>
<td>0.131</td>
<td>-0.145</td>
<td>-0.030</td>
<td>0.017</td>
</tr>
<tr>
<td>Aug-13</td>
<td>0.092</td>
<td>0.047</td>
<td>-0.125</td>
<td>0.139</td>
<td>-0.125</td>
<td>-0.010</td>
<td>0.024</td>
</tr>
<tr>
<td>Sep-13</td>
<td>0.050</td>
<td>0.103</td>
<td>-0.079</td>
<td>0.153</td>
<td>-0.079</td>
<td>-0.016</td>
<td>0.090</td>
</tr>
<tr>
<td>Oct-13</td>
<td>0.118</td>
<td>0.035</td>
<td>-0.047</td>
<td>0.154</td>
<td>-0.047</td>
<td>0.026</td>
<td>0.081</td>
</tr>
<tr>
<td>Nov-13</td>
<td>0.039</td>
<td>0.003</td>
<td>-0.004</td>
<td>0.042</td>
<td>-0.004</td>
<td>0.014</td>
<td>0.024</td>
</tr>
<tr>
<td>Apr-14</td>
<td>0.040</td>
<td>0.027</td>
<td>-0.025</td>
<td>0.067</td>
<td>-0.025</td>
<td>0.026</td>
<td>0.017</td>
</tr>
<tr>
<td>May-14</td>
<td>0.051</td>
<td>0.060</td>
<td>-0.080</td>
<td>0.111</td>
<td>-0.080</td>
<td>-0.015</td>
<td>0.046</td>
</tr>
<tr>
<td>Jun-14</td>
<td>0.090</td>
<td>0.025</td>
<td>-0.115</td>
<td>0.116</td>
<td>-0.115</td>
<td>0.003</td>
<td>-0.002</td>
</tr>
<tr>
<td>Jul-14</td>
<td>0.047</td>
<td>0.029</td>
<td>-0.131</td>
<td>0.076</td>
<td>-0.131</td>
<td>-0.014</td>
<td>-0.042</td>
</tr>
<tr>
<td>Aug-14</td>
<td>0.047</td>
<td>0.064</td>
<td>-0.118</td>
<td>0.111</td>
<td>-0.118</td>
<td>-0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>Sep-14</td>
<td>0.104</td>
<td>0.084</td>
<td>-0.082</td>
<td>0.187</td>
<td>-0.082</td>
<td>0.007</td>
<td>0.098</td>
</tr>
<tr>
<td>Oct-14</td>
<td>0.106</td>
<td>0.012</td>
<td>-0.050</td>
<td>0.118</td>
<td>-0.050</td>
<td>0.014</td>
<td>0.054</td>
</tr>
<tr>
<td>Nov-14</td>
<td>0.049</td>
<td>0.000</td>
<td>-0.006</td>
<td>0.049</td>
<td>-0.006</td>
<td>0.000</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Basin 2 shows similar patterns to Basin 1 (Error! Not a valid bookmark self-reference.). The storage change is not proportional to the residual value and is not consistently over- or underestimated between months. Based on the assumption that the measured storage change is in the right direction there is an issue with the inputs and outputs of the Basin 2 water balance (i.e. June, July, September, 2013; May, June, 2014). Basin 1 is upgradient of Basin 2 and there is likely a surface or subsurface inflow pathway which is not being quantified in this balance. There is also a surface outflow pathway which is active for some months of the year which is not being quantified for Basin 2. Without quantification of the relative magnitudes of the lateral surface/subsurface or groundwater inflows and outflows to this basin it is not possible to identify which term is most likely responsible for errors in the water balance.
Table 3-8: Monthly water balance Sideline 26 – Basin 2

<table>
<thead>
<tr>
<th></th>
<th>P (m)</th>
<th>RO (m)</th>
<th>GW_{out,V} (m)</th>
<th>ET (m)</th>
<th>IN (m)</th>
<th>OUT (m)</th>
<th>∆S (m)</th>
<th>Residual (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun-13</td>
<td>0.104</td>
<td>0.026</td>
<td>-0.012</td>
<td>-0.113</td>
<td>0.130</td>
<td>-0.125</td>
<td>-0.004</td>
<td>0.010</td>
</tr>
<tr>
<td>Jul-13</td>
<td>0.057</td>
<td>0.050</td>
<td>-0.015</td>
<td>-0.145</td>
<td>0.107</td>
<td>-0.160</td>
<td>-0.014</td>
<td>-0.039</td>
</tr>
<tr>
<td>Aug-13</td>
<td>0.092</td>
<td>0.032</td>
<td>-0.008</td>
<td>-0.125</td>
<td>0.124</td>
<td>-0.132</td>
<td>-0.005</td>
<td>-0.004</td>
</tr>
<tr>
<td>Sep-13</td>
<td>0.050</td>
<td>0.069</td>
<td>-0.004</td>
<td>-0.079</td>
<td>0.119</td>
<td>-0.083</td>
<td>-0.008</td>
<td>0.043</td>
</tr>
<tr>
<td>Oct-13</td>
<td>0.118</td>
<td>0.024</td>
<td>-0.003</td>
<td>-0.047</td>
<td>0.142</td>
<td>-0.050</td>
<td>0.012</td>
<td>0.080</td>
</tr>
<tr>
<td>Nov-13</td>
<td>0.039</td>
<td>0.000</td>
<td>-0.007</td>
<td>-0.004</td>
<td>0.039</td>
<td>-0.011</td>
<td>0.006</td>
<td>0.021</td>
</tr>
<tr>
<td>Apr-14</td>
<td>0.040</td>
<td>0.018</td>
<td>0.001</td>
<td>-0.025</td>
<td>0.058</td>
<td>-0.024</td>
<td>0.012</td>
<td>0.022</td>
</tr>
<tr>
<td>May-14</td>
<td>0.051</td>
<td>0.041</td>
<td>0.003</td>
<td>-0.080</td>
<td>0.091</td>
<td>-0.077</td>
<td>-0.007</td>
<td>0.022</td>
</tr>
<tr>
<td>Jun-14</td>
<td>0.090</td>
<td>0.017</td>
<td>0.003</td>
<td>-0.115</td>
<td>0.108</td>
<td>-0.112</td>
<td>0.001</td>
<td>-0.005</td>
</tr>
<tr>
<td>Jul-14</td>
<td>0.047</td>
<td>0.020</td>
<td>-0.003</td>
<td>-0.131</td>
<td>0.066</td>
<td>-0.134</td>
<td>-0.006</td>
<td>-0.061</td>
</tr>
<tr>
<td>Aug-14</td>
<td>0.047</td>
<td>0.043</td>
<td>-0.006</td>
<td>-0.118</td>
<td>0.090</td>
<td>-0.124</td>
<td>-0.003</td>
<td>-0.030</td>
</tr>
<tr>
<td>Sep-14</td>
<td>0.104</td>
<td>0.057</td>
<td>-0.006</td>
<td>-0.082</td>
<td>0.161</td>
<td>-0.088</td>
<td>0.003</td>
<td>0.070</td>
</tr>
<tr>
<td>Oct-14</td>
<td>0.106</td>
<td>0.008</td>
<td>-0.006</td>
<td>-0.050</td>
<td>0.114</td>
<td>-0.056</td>
<td>0.006</td>
<td>0.052</td>
</tr>
<tr>
<td>Nov-14</td>
<td>0.049</td>
<td>0.000</td>
<td>-0.004</td>
<td>-0.006</td>
<td>0.049</td>
<td>-0.010</td>
<td>0.000</td>
<td>0.039</td>
</tr>
</tbody>
</table>

3.3.3.2 Dry Period Analysis

More detailed analysis was done for dry periods to isolate the terms with the largest error. In Basin 1 the daily residuals were all negative and similar in magnitude, with the exception of the Fall 2013 (A) (Table 3-9). Using Event 3 and 4 as examples, a decrease in storage is expected from the balance of inputs and outputs; however, an increase in storage is experienced suggesting that an input is missing or an output is overestimated. The only output considered in this analysis is the evapotranspiration, which is not likely overestimated during dry weather since there is standing water present in the Basin 1 throughout the entire monitoring period and there is no reason to expect the potential evaporative demand is not being met. The analysis suggests a missing groundwater inflow to Basin 1. This is consistent with groundwater flow directions inferred from historical spot measurements of groundwater levels in the surrounding catchment. Unfortunately, data for the study period could not be obtained in order to quantify the groundwater exchange. Similarly in Basin 2 (Table 3-10), the analysis suggests a missing input or overestimated output. Estimated groundwater outflows are small and cannot account for the residual. Standing water is present at both stations in Basin 2 in 2014; however, in 2013 the second station dries below surface and evapotranspiration may be overestimated if the actual evapotranspiration is less than the potential evapotranspiration value reported. This is not likely the case as the water levels drop below the surveyed ground by approximately 0.35 m and the moisture in the capillary fringe is likely sufficient to satisfy PET. During Events 3 and 4, storage increases in the absence of a quantified input. It is predicted that a groundwater inflow is also missing from Basin 2; however, no data exists during the study period to support the hypothesis.
3.3.3.3 Wet Period Analysis

In Basin 1, positive residuals are the result of the storage increase being smaller than what would be expected based on the estimated inputs and outputs (Table 3-11). This suggests that inputs have been overestimated or outputs have been underestimated. There is a low uncertainty associated with the precipitation and runoff terms in the water balance. The dry period analysis suggests a missing groundwater inflow to the wetland therefore it is not likely that the inputs are being over estimated. The only outputs quantified are evapotranspirative losses, which are not likely underestimated during wet weather. The analysis suggests a missing surface and/or subsurface outflow path from Basin 1.

The same logic can be applied to Basin 2 which behaves nearly identically to Basin 1 (Table 3-12). The missing surface/subsurface outflow from Basin 1 is an equivalent missing surface/subsurface inflow to Basin 2. Field observations of a surface outflow pathway downstream of the wetland outlet is consistent with this conclusion. However, the water level is not always above the measured wetland weir crest height of 0.25 m (Table 3-3) therefore the analysis suggests a missing surface and/or subsurface outflow pathway from Basin 2.

Table 3-11: Sideline 26 Wet Period Summary (Basin 1)

<table>
<thead>
<tr>
<th>Event</th>
<th>P (m)</th>
<th>RO (m)</th>
<th>ET (m)</th>
<th>IN (m)</th>
<th>OUT (m)</th>
<th>∆S (m)</th>
<th>Residual (m)</th>
<th>Residual / Day (m)</th>
<th>Max. Rainfall (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event 7</td>
<td>0.029</td>
<td>0.040</td>
<td>-0.013</td>
<td>0.069</td>
<td>-0.013</td>
<td>0.000</td>
<td>0.056</td>
<td>0.007</td>
<td>19.2</td>
</tr>
<tr>
<td>Event 8</td>
<td>0.063</td>
<td>0.040</td>
<td>-0.006</td>
<td>0.103</td>
<td>-0.006</td>
<td>0.023</td>
<td>0.074</td>
<td>0.018</td>
<td>57.6</td>
</tr>
<tr>
<td>Event 9</td>
<td>0.032</td>
<td>0.049</td>
<td>-0.015</td>
<td>0.081</td>
<td>-0.015</td>
<td>0.019</td>
<td>0.047</td>
<td>0.005</td>
<td>24</td>
</tr>
</tbody>
</table>
Table 3-12: Sideline 26 Wet Period Summary (Basin 2)

<table>
<thead>
<tr>
<th>Event</th>
<th>P (m)</th>
<th>R0 (m)</th>
<th>GW_V_out (m)</th>
<th>ET (m)</th>
<th>IN (m)</th>
<th>OUT (m)</th>
<th>ΔS (m)</th>
<th>Residual (m)</th>
<th>Residual /Day (m)</th>
<th>Max. Rainfall (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event 7</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Event 8</td>
<td>0.051</td>
<td>0.027</td>
<td>-0.002</td>
<td>-0.006</td>
<td>0.078</td>
<td>-0.008</td>
<td>0.011</td>
<td>0.060</td>
<td>0.015</td>
<td>57.6</td>
</tr>
<tr>
<td>Event 9</td>
<td>0.055</td>
<td>0.033</td>
<td>-0.003</td>
<td>-0.015</td>
<td>0.088</td>
<td>-0.018</td>
<td>0.009</td>
<td>0.061</td>
<td>0.006</td>
<td>24</td>
</tr>
<tr>
<td>Event 10</td>
<td>0.040</td>
<td>0.016</td>
<td>0.002</td>
<td>-0.009</td>
<td>0.055</td>
<td>-0.007</td>
<td>0.000</td>
<td>0.048</td>
<td>0.008</td>
<td>19.2</td>
</tr>
<tr>
<td>Event 11</td>
<td>0.020</td>
<td>0.009</td>
<td>-0.002</td>
<td>-0.008</td>
<td>0.028</td>
<td>-0.010</td>
<td>0.004</td>
<td>0.015</td>
<td>0.003</td>
<td>88.8</td>
</tr>
<tr>
<td>Event 12</td>
<td>0.029</td>
<td>0.013</td>
<td>-0.004</td>
<td>-0.008</td>
<td>0.042</td>
<td>-0.011</td>
<td>0.003</td>
<td>0.027</td>
<td>0.005</td>
<td>31.2</td>
</tr>
</tbody>
</table>

No diurnal water level signature was present in Basin 1 or 2 therefore it was not possible to apply the White method.

3.4 Discussion
3.4.1 Water Balance Summary

Combining the knowledge gained from the dry and wet weather analyses helped to refine the conceptual understanding of wetland hydrology at Sideline 22 and Sideline 26. Independent estimation of each term of the water balance was attempted; however, it was ultimately unsuccessful due to limitations imposed by monitoring set-up and incomplete data sets. The refined water balance equations are as follows:

\[
\text{Seaton Sideline 22: } P + RO + GW_{\text{in}} - ET - GW_{\text{out, L}} = \Delta S + \text{residual}
\]

\[
\text{Seaton Sideline 26 Basin 1: } P + RO + GW_{\text{in,L}} - ET - GW/\text{SW}_{\text{out (to Basin 2)}} = \Delta S + \text{residual}
\]

\[
\text{Seaton Sideline 26 Basin 2: } P + RO + GW/\text{SW}_{\text{in(from Basin 1)}} - ET - GW_{\text{out,L}} - GW/\text{SW}_{\text{out,L}} - SW_{\text{out}} = \Delta S + \text{residual}
\]

In Sideline 22, the analysis indicated the need to refine the stage-storage relationship, particularly the specific yield near the surface-subsurface interface. Soil moisture probes were installed in 2015 to support refined estimates of soil specific yield values, measure moisture content within the zone of fluctuation at the lower water level, and quantify storage changes occurring in the unsaturated zone. Historical groundwater levels suggest groundwater inflow likely occurs to this wetland and dry and wet weather analysis supported this finding for some events. However, overall findings were contradictory and inconclusive. The relative magnitude of groundwater inflows and outflows are uncertain for the wetland basin. Additional monitoring
equipment was deployed in Fall 2015 to record groundwater elevation northwest of the wetland basin and quantify groundwater inflow to the wetland.

The refined conceptual understanding of Sideline 26 included two separate wetland cells, which allowed for representation of the variability between basins. At Sideline 26, no groundwater loggers were installed in the surrounding catchment area which inhibited quantification of lateral groundwater interactions. In Basin 1, the detailed analysis supported the hypothesis that a groundwater inflow pathway was present, at least during dry periods. During wet weather, an outflow pathway from Basin 1 was not quantified though analysis supports its presence. The overall analysis suggests a net groundwater inflow in Basin 1. The detailed analysis of Basin 2 indicated that an inflow was missing during dry periods in the form of groundwater from the surrounding catchment. Instrumentation problems restricted the ability to quantify surface water outflow from Sideline 26. The wet weather analysis of this Basin indicated that outflow pathways, in the form of surface and/or subsurface losses, were missing. An additional groundwater piezometer was deployed at outflow of Basin 2 in Fall 2015 and recommendations were made to deploy two additional monitors in the basins’ surrounding catchments. The flume installation was altered in the summer of 2015, and the combination of the flume and the groundwater logger can be used to quantify outflows from the basins for future years.

In the case of both study locations net groundwater fluxes were hypothesized over the course of the study period. In both wetlands, historical groundwater measurements in the surrounding catchments were used to support hypothesized groundwater exchanges, though lack of coinciding monitoring data did not support independent estimation of this component. Therefore the groundwater inflow and outflow were not independently quantified and the relative magnitude of each component is not known.

Bradford (2015) discusses the importance of independently quantifying the magnitude of groundwater inflow and outflow in a wetland environment to identify the role of groundwater in wetland function. For example, in the case when groundwater inflows are small, they can be a source of important chemical constituents to wetland species (Duval et al., 2011; Johansen et al., 2011). The timing and magnitude of flow can be important to prevent soil oxidation (Mitsch & Gosselink, 2000) and sustain evapotranspiration rates (Lowry & Loheide, 2010). Even in cases where groundwater flow does not affect wetland water levels, the flushing properties can be important for maintaining water quality (Bradford, 2015). Therefore, additional monitoring recommendations for the wetlands were directed at instrumentation to provide data on the groundwater interactions and quantify both inflow and outflow pathways.

3.4.2 Advantages of Proposed Wetland Water Balance Approach
The wetlands at Sideline 22 and Sideline 26 were used as case studies to test an approach to conducting a thoughtful wetland water balance analysis. The methodology attempted to independently estimate each water transfer mechanism acting in the wetlands and to confirm or refine the conceptual understanding of wetland hydrology. The analysis was refined as it
progressed, with more sophisticated approaches applied when the analysis indicated a need. The water balance analysis used accessible monitoring tools, analysis techniques and principles to process the monitoring data and develop reasonable estimates of each term in the water balance. The resulting water balance can effectively inform hydrologic modelling and direct future monitoring efforts. Though the analysis presented uses two specific wetlands, the process is not site-specific and can be transferred to other wetland studies. Key findings from the study are summarized as follows:

1. **Value of a continuous data set:** Groundwater and surface water levels were collected at an hourly resolution for the two study years. The resulting data set was instrumental in conducting the water balance. General trends, similarities, and differences were apparent from the yearly plots of the wetland hydroperiods, directing the analysis and identifying the terms and locations which would be used for the water balance. The approach presented relies on a range of meteorological conditions to gain a thorough understanding of wetland hydrology (i.e. dry and wet periods). Accurate water level fluctuations are needed to perform diurnal water level fluctuation analysis methods to independently quantify evapotranspiration rates (McLaughin & Cohen, 2011). A continuous data set captures diurnal water level fluctuations over the course of the year so that variations in evapotranspiration losses can be identified.

2. **Importance of multiple years of data:** A single year of monitoring is insufficient to evaluate the impacts of dry and wet years on wetland hydrology. The two years monitored for the study wetlands represented both a drier than average (2014) and wetter than average year (2013) indicating the importance of multiple years of data to elucidate seasonal variation in precipitation and water levels. However, both wetlands experienced lower water levels in 2013 compared to 2014, indicating the seasonally dry year in 2012 may have had delayed impacts on wetland water levels. The multiple years of data also influenced the interpretation of wetland hydrology as the wetlands demonstrate different behaviour with seasonally varied precipitation; considering only the drier year (2013) unveiled groundwater interactions in Sideline 22 which would not have been identified had only a single year of monitoring occurred (the same is true for an independent analysis of 2014).

3. **Value of hierarchy of analysis periods:** The continuous water level data was first presented in a monthly summary. The monthly summaries saw residual terms which were both positive and negative and large in magnitude and the analysis produced contradictory findings for each of the wetlands studied. In some cases the monthly water balance could be used to identify potential issues, but they were generally insufficient to refine or confirm the conceptual understanding. Analysis of periods with different conditions (i.e. dry vs. wet periods, sunlight vs. overnight hours) was performed, using the same data sets as the monthly summaries, to gain additional knowledge about missing or uncertain water transfer mechanisms. Isolating dry periods provided an opportunity to assess the residual in the absence of precipitation and runoff impacts. Dry periods identified groundwater inflow pathways in Sideline 22 and Sideline 26 which were not apparent in the monthly analysis. Increasing the resolution of analysis to look at diurnal
fluctuations confirmed the evapotranspiration estimates were reasonable for the wetlands. Knowledge gained from the dry periods was transferred to the wet weather analysis and additional impacts of wet weather on wetland hydrology was assessed. For example, in both basins of Sideline 26, surface and surface outflow pathways were identified during the wet periods that were not active during dry periods.

4. Importance of iterative approach and the value of using better methods when feasible to localize errors: The methodology for the wetland water balance is an iterative process. It is not reasonable to accept one calculated value of a term without considering the magnitude of error associated with the estimate. Refining estimates in the wetland water balance was desirable to minimize errors where feasible (Acreman & Miller, 2007). For example, results of the water balance often pointed to an over or underestimation in the storage changes. Since a detailed topographic survey was available, uncertainties related to wetland microtopography were minimized and focus shifted to narrowing down impacts of specific yield, storage within the zone of fluctuation at lower water levels. In Sideline 22, analysis ruled out surface outflow and the groundwater piezometers were redeployed to other areas where more information was needed. For example, net groundwater exchanges were identified in both wetlands and analysis informed the best locations to redeploy loggers. The water balance analysis successfully identified where to direct additional monitoring efforts.

3.5 Conclusions
The case studies presented demonstrate the value of a thoughtful wetland water balance to refine and confirm the conceptual understanding of wetland hydrology for two study wetlands. The continuous data set provided information on general trends and behaviour. It allowed for efforts to be focused on the locations and time period which were used in more detailed stages of the water balance. In some cases it identified seasonally varied behaviour, the need to reassess the water balance control volume (i.e. splitting the basins in Sideline 26). The hierarchal approach which was used to analyzing variation in wetland hydrology under a range of conditions (dry, wet, overnight, etc.) would not have been possible without the continuous data as it required a range of time periods from within the greater data set. Multiple years of data is essential for a water balance as it identified variations in wetland hydrologic interactions and seasonal variations.

To reduce error in the independent estimation of terms, a number of factors are imperative. Detailed topographic information reduced the uncertainty in the stage-storage relationship above ground. Further analysis and site specific information could reduce the error associated with the specific yield estimates below ground. Evapotranspiration estimates are possible with reliable diurnal fluctuations. To accomplish this, careful attention to installation of barologgers and pressure transducers are needed. The water balance analysis directed additional monitoring to refine the conceptual understanding of the wetland hydrology, such as the removal and
redeployment of surface level loggers at outlet Sideline 22 and additional locations at Sideline 26.

Knowledge gained from the water balance study can be used to select and parameterize hydrologic models and provide confidence that the correct interactions are considered in the simulation. The wetland water levels for the monitored years can provide a calibration and validation data set for the hydrologic model. The water balance analysis provides a check on the modelling to ensure the correct hydrological processes and interactions are included in the simulation. Long term meteorological records can be applied to get a reference regime for the study wetlands. Better informed hydrologic models have the potential to be excellent tools to predict impacts of development on the wetland features and evaluate effectiveness of mitigation measures.
3.6 References


Gerber Geosciences Inc. (2003) Duffins Creek watershed hydrogeology and assessment of land use change on the groundwater flow system. For TRCA: Toronto, ON.


Chapter 4 Wetland modelling in PCSWMM to predict impacts of urbanization

4.1 Introduction
Wetlands are sensitive ecosystems under significant pressure from land use changes and land and water management practices. In southern Ontario, they are being negatively impacted by urban development, which increases surface runoff volumes and alters surface and groundwater drainage patterns (Davidson, 2014; Snell, 1987). Many existing strategies are not sufficiently addressing the impacts of urbanisation on wetlands; human activities and conventional stormwater management are altering the natural regimes of these systems with undesirable ecological responses (Elliot et al., 2010; Burns et al., 2012; Wagner and Breil, 2013; and others). The ability of wetlands to continue to provide critical ecosystem services in urbanizing areas largely depends on our ability to protect their hydrologic regimes. Hydrologic modelling is an important tool for predicting changes in the hydrologic response in an urbanizing catchment and the capacity of proposed stormwater management systems to mitigate hydrologic alterations.

The wetland hydroperiod describes the seasonal change in wetland water depth or its ‘hydrologic signature’, which is dependent on the maintenance of water transfer mechanisms into and out of the wetland (Mitsch & Gosselink 2000). Water transfer mechanisms in wetlands include surface water exchanges, groundwater exchanges, evapotranspiration losses, and inputs include precipitation and runoff from the surrounding areas (i.e., in the form of overland flow pathways) (Acreman & Miller, 2007). Each of these local wetland interactions and mechanisms must be represented in the model to determine the impacts of urbanization and how they cumulatively affect the wetland’s hydroperiod (Carol et al., 2013). The model must be able to provide a reasonable estimate of the wetland hydroperiod as a model output so that pre-development conditions can be compared to post-development conditions, allowing impacts to the wetland’s regime to be quantified (Gasca & Ross, 2009) and ultimately mitigated. Wetlands have unique attributes and incorporating them into the model often requires simplification; however, care must be taken to avoid oversimplification which may misrepresent crucial interactions and limit the ability to predict alterations to the hydrologic regime.

PCSWMM is a program developed by CHI to act as spatial decision support for EPA SWMM’s dynamic, 1D/2D, stormwater and watershed hydraulic-hydrologic model (CHI, 2015). PCSWMM is primarily a surface water model however the inclusion of a groundwater/aquifer layer allows for the infiltrated catchment water to reach and move within the subsurface.

4.2 Purpose/Objective
The purpose of this investigation is to use knowledge gained from wetland water balance analysis to: (1) explore options for incorporating wetlands into hydrological simulation; (2) parameterize, calibrate, and validate a hydrologic model to include known wetland processes (i.e.
surface., subsurface, and groundwater exchanges, ET, etc.) and characteristics (i.e. topography, storage relationships); (3) simulate a reference hydrologic regime for each of the study wetlands.

4.3 Methods

4.3.1 Description of Study Sites

The study sites for this investigation are two wetlands in the Duffins Creek Watershed. The wetlands are located at Sideline 22 and Sideline 26, north of Taunton Road in Pickering, Ontario. Urban growth and expansion will result in both the wetland catchments undergoing development within the next 3-10 years.

The study sites are underlain by Halton Till; boreholes in the catchment areas encountered silty sand to clayey silt till deposits near surface (Sernas Associates, 2013). Sideline 22 is classified as an isolated wetland with no surficial inflow or outflow. The wetland is 1.38 ha with surface water present most of the year. Sideline 22 is a mineral swamp and sits within the Iroquois Sand Plain (TRCA, 2013; Gerber Geosciences Inc, 2003). Sideline 26 has two discernible cells within the wetland, a basin located in the northwest which drains to the second southeastern basin. The basins together drain a catchment area of 17.0 hectares. The catchment has moderate topographic relief. The wetland is a palustrine wetland with no surficial inflow but seasonal surficial outflows to a small stream south of the southeastern basin. Sideline 26 is a mineral swamp with hummocks and hollows. It sits within the South Slope physiographic region (TRCA, 2013).

4.3.2 Available Data

Monitoring data has been collected by the Toronto and Region Conservation Authority for the study wetlands since June 2013. A single tipping bucket was installed a nearby wetland location which was also being studied as part of this investigation. The subject locations are within 1.0 kilometer of each other, therefore experiencing similar meteorological conditions. A single tipping bucket rain gauge was installed at Sideline 26 and used to record seasonal precipitation and temperature for both sites. A 3-season rain gauge is located at the Brockwest Landfill Site, approximately 3 kilometers to the southeast, and was updated to a heated four-season rain gauge in the fall of 2014. Precipitation and temperature data collected at the Brockwest landfill between June – November 2013 and April – November 2014 is used in this analysis. Long term meteorological data was obtained from the nearest weather station (Buttonville Airport) for the years 1986-2012 (Environment Canada, 2016).

Historical spot measurements of groundwater levels and general trends were obtained from consulting reports for the surrounding area undergoing development (Sernas Associates, 2013). Water levels were available from stations established for ecohydrological studies of the same wetlands. There were two stations in Sideline 22 and each station was instrumented with a surface water level logger as well as two groundwater piezometers (1-meter and 2-meter-deep. Two additional 2-m deep groundwater piezometers were installed approximately 200 meters to
the east and southeast of the basin. Continuous water level data is available at each monitoring location at 15-minute intervals for June – November 2013 and April – November 2014.

The TRCA provided detailed survey data for the two wetlands. The surveying was completed over 2 days in January 2013 at Sideline 22 and over 9 days in February and April 2013 at Sideline 26. Hydraulic conductivity estimates were based on slug tests completed by TRCA at each monitoring station location (Table 4-1).

Table 4-1: Slug test results (performed by TRCA on June 15, 2016)

<table>
<thead>
<tr>
<th>Wetland</th>
<th>Station and Depth</th>
<th>Saturated hydraulic conductivity, K (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sideline 22</td>
<td>1-10 (GW-2m)</td>
<td>5.97 E-06</td>
</tr>
<tr>
<td>Sideline 22</td>
<td>1-10 (GW-1m)</td>
<td>5.27 E-05</td>
</tr>
<tr>
<td>Sideline 22</td>
<td>1-40 (GW-2m)</td>
<td>4.05 E-05</td>
</tr>
<tr>
<td>Sideline 22</td>
<td>1-40 (GW-1m)</td>
<td>2.13 E-07</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-10 (GW-2m)</td>
<td>3.20 E-07</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-10 (GW-1m)</td>
<td>1.03 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-40 (GW-2m)</td>
<td>1.58 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-40 (GW-1m)</td>
<td>1.71 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-10 (GW-2m)</td>
<td>7.11 E-10</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-10 (GW-1m)</td>
<td>1.58 E-09</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-40 (GW-2m)</td>
<td>2.37 E-09</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-40 (GW-1m)</td>
<td>1.58 E-09</td>
</tr>
<tr>
<td>Sideline 26</td>
<td>3 (GW-2m)</td>
<td>1.04 E-04</td>
</tr>
</tbody>
</table>

4.3.3 Conceptual Understanding of Wetland Hydrology

Initial interactions were hypothesized based on the location of the wetland within the landscape, site observations, and ecological indicators (TRCA, 2013). Monitoring data was analyzed in a detailed water balance study which refined the conceptualization and informed the modelling efforts. The conceptual understanding of wetland hydrology is summarized in the following sections.

4.3.3.1 Sideline 22

A single isolated basin is present at Sideline 22. In addition to direct precipitation, the wetland receives runoff from the upstream catchment. There is likely very little actual surface runoff, but the conceptual model includes lateral flow to the wetland in the shallow subsurface. Water balance analysis quantifies total lateral groundwater outflow, vertical groundwater inflow, and a missing component of groundwater inflow, likely from the lateral direction to the northwest. Groundwater inflow is hypothesized based on historical spot elevations of the water table to the west and losses to the southeast were quantified in the water balance study. Vertical gradients of 0.001m/m were consistently measured at Station 1-40, driving water into the wetland. Water also leaves the wetland through evapotranspiration. The water balance equation can be written as follows:
Seaton Sideline 22:  \[ P + RO + GW_{in} - ET - GW_{out,L} = \Delta S + \text{residual} \]

4.3.3.2 Sideline 26
Two distinct wetland basins exist at Sideline 26. Inputs to the system include direct precipitation on each basin and inflow from the catchments, primarily along shallow subsurface flow paths. The low hydraulic conductivity of wetland deposits limit vertical groundwater exchanges in Basin 1; however, in Basin 2 a vertical groundwater flux is measured during some of the monitoring time period, driving water out of the wetland. Preliminary analysis of the wetland basins indicate the surface water elevations are different and the basins were analyzed separately for the water balance. Groundwater inflows into Basin 1 and Basin 2 were hypothesized based on historical spot-measured elevations of the water table to the northeast and southwest; however, these were not quantified during the monitoring period. Water from the northwest basin (Basin 1) spills into the southeast basin (Basin 2) when the water level is higher than the connecting crest elevation. Water balance analysis indicated missing inflow pathways to Basin 2; however, the distinction between surface water and groundwater from Basin 1 was not made. Water exits the system via evapotranspiration losses and an intermittent surface-subsurface outflow at the southern end of Basin 2. The water balance equations for each basin can be written as follows:

Seaton Sideline 26 Basin 1:  \[ P + RO + GW_{in,L} - ET - GW/SW_{out} = \Delta S + \text{residual} \]

Seaton Sideline 26 Basin 2:  \[ P + RO + GW_{in,L} - ET - GW_{out,V} - GW_{out,L} - SW_{out} = \Delta S + \text{residual} \]

4.3.4 Model Set-up and Parameterization

4.3.4.1 Model Approach
PCSWMM was used to model the wetlands and their catchments. The approach was to begin with a simple catchment system and increase the level of complexity necessary to define all the known interactions in the wetland and achieve calibration. The 2013 data set was used for calibration and the 2014 data set used for validation.

4.3.4.2 Model Set-up
Climatology and Simulation Options. The PCSWMM model was run at a 1-hour dry-weather time step, a 5-minute wet-weather time step, and a 30-second routing time step for the calibration and validation periods. The model was run continuously for the calibration period from June – November 2013, and from April – November 2014 for the validation period. An external climate file specified precipitation data at a 5-minute time interval based on the nearest rain gauge and ambient temperature data at daily minimum and maximum values. Evapotranspiration was calculated based on Hargreaves’s method.

Catchment and Aquifer Parameterization. The wetland subcatchments incorporated into the PCSWMM model were delineated based on topographic information from GIS maps provided
by the Toronto and Region Conservation Authority (TRCA, 2013). The GIS information helped to identify slopes and land use types. Soil properties were obtained through borehole information from wetland and catchment (Sernas Associates, 2013). At Sideline 22, two upstream catchments were defined, a 6.7 ha catchment to the north and a 13.0 ha catchment to the west. For Sideline 26, a 7.0 ha catchment to the northwest and a 10.0 ha catchment to the southeast were defined. The catchment delineation was based on topographic maps of the study areas and confirmed by site observations. Subcatchment parameterization for Sideline 22 and 26 is summarized in Table 4-2.

Table 4-2: Subcatchment properties

<table>
<thead>
<tr>
<th></th>
<th>Sideline 22 SC1</th>
<th>Sideline 22 SC2</th>
<th>Sideline 26 SC1</th>
<th>Sideline 26 SC1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use</td>
<td>Agricultural</td>
<td>Agricultural</td>
<td>Agricultural</td>
<td>Agricultural</td>
</tr>
<tr>
<td>Area (ha)</td>
<td>13.03</td>
<td>6.73</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Width (m)</td>
<td>857</td>
<td>442</td>
<td>658</td>
<td>461</td>
</tr>
<tr>
<td>Flow length (m)</td>
<td>152</td>
<td>152</td>
<td>152</td>
<td>152</td>
</tr>
<tr>
<td>Slope (%)</td>
<td>10</td>
<td>3</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Percent impervious (%)</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Manning’s n – impervious (-)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Manning’s n – pervious</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Depression storage – impervious (mm)</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Depression storage – pervious (mm)</td>
<td>6.85</td>
<td>6.85</td>
<td>6.85</td>
<td>6.85</td>
</tr>
<tr>
<td>Infiltration method</td>
<td>Green &amp; Ampt</td>
<td>Green &amp; Ampt</td>
<td>Green &amp; Ampt</td>
<td>Green &amp; Ampt</td>
</tr>
<tr>
<td>Soils</td>
<td>Loam</td>
<td>Loam</td>
<td>Loam</td>
<td>Loam</td>
</tr>
<tr>
<td>Soil capillary suction head (mm)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity (mm/hr)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Initial soil moisture deficit (-)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Stage-Storage Relationships. Adding the wetland required defining a feature which could adequately include storage relationships, and surface and groundwater interactions. Ultimately, the wetland was incorporated as a storage unit because of the capacity in PCSWMM to define a stage-storage relationship and its ability to interact with the groundwater system. The soils underlying the wetlands were found to have low hydraulic conductivity in the field and the seepage parameters selected for the wetland storage unit was representative of these characteristics.

Detailed wetland topography is required to quantify the relationship between the water level change and the resulting change in storage. To account for storage changes in the bank and subsurface zone, the storage relationship in the wetland was extended below the base of ponding as defined by the topographic study to the lowest observed groundwater elevation. Specific yield must be defined to estimate storage relationships (Hill & Durchholz, 2015). Different estimates
of specific yield for the bank areas and the subsurface wetland soils were selected (Gasca & Ross, 2009) to extend the storage relationship to the subsurface zone. Chapter 3 describes the method used to generate new storage relationships for each wetland.

**Groundwater Interaction.** PC SWMM handles groundwater interaction using aquifer modules. The user-defined subcatchments can be associated with an “aquifer” unit by defining “groundwater” parameters, which determine the behaviour of the groundwater as it travels through the aquifer. The introduction of the aquifer layer, defines the subsurface zones in the catchment which introduces the element of ‘evapotranspiration’ from the aquifer. At Sideline 22, a single aquifer was used, and at Sideline 26 one aquifer for each catchment was used to accommodate distinct water table elevations in the contributing catchments. The underlying soils in the area informed the choice of parameters for the aquifer. Table 4-3 summarizes the aquifer parameters. The wetland storage unit was assigned as the receiving feature for each subcatchment. The model was sensitive to the initial groundwater elevation and it was used as calibration parameter.

In Sideline 22, groundwater interaction parameters for each subcatchment (A1, B1, A2, B2) were used as calibration parameters to achieve hydroperiod matching. In Sideline 26, the relative magnitude of groundwater and surface water exchanges into and out of the catchment were largely unknown. Therefore, using results from the dry period water balance analysis, groundwater inflow rate was estimated and incorporated into the model by altering the groundwater parameters in the subcatchment editor (A1, B1, A2, B2) to achieve the groundwater input rate identified in the water balance analysis.

**Table 4-3: Aquifer properties**

<table>
<thead>
<tr>
<th>Aquifer Property</th>
<th>Sideline 22</th>
<th>Sideline 26 – North (Basin 1 Catchment)</th>
<th>Sideline 26 – South (Basin 2 Catchment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Silt loam (mid-range)</td>
<td>Silt loam (low-range)</td>
<td>Silt loam (low range)</td>
</tr>
<tr>
<td>Porosity (-)</td>
<td>0.58</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>Wilting point (-)</td>
<td>0.17</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Field capacity (-)</td>
<td>0.34</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Conductivity (mm/hr)</td>
<td>7.62</td>
<td>3.30</td>
<td>3.30</td>
</tr>
<tr>
<td>Conductivity slope (-)</td>
<td>8.00</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>Tension slope (-)</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Upper evap. Fraction (-)</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Lower evap. Depth (m)</td>
<td>6.20</td>
<td>2.70</td>
<td>2.70</td>
</tr>
<tr>
<td>Lower GW loss fraction (-)</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Bottom elevation (m)</td>
<td>140.00</td>
<td>177.00</td>
<td>173.00</td>
</tr>
<tr>
<td>Water table elevation (m)</td>
<td>154.00</td>
<td>192.5</td>
<td>191.5</td>
</tr>
<tr>
<td>Unsaturated zone moisture (-)</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
</tbody>
</table>
**Losses from the wetlands.** PCSWMM can simulate the loss of water from storage units via seepage, based on user-defined Green and Ampt parameters. This mechanism for water loss was not suitable to represent the actual subsurface outflows from the wetlands and each basin was modelled with an impermeable base to avoid misrepresentation of exchanges. In Sideline 22, groundwater outputs quantified for the study period were incorporated into the model. Two options for simulating groundwater outflow were explored: (1) PCSWMM defined groundwater interactions with a downstream aquifer unit and (2) outflow from the storage unit via an orifice. The first option involved adding another catchment to the model and associating an aquifer with this catchment. Groundwater outflow from the storage unit to the aquifer was simulated by entering negative groundwater coefficients. The second option involved adding a circular orifice at the base of the wetland system. User input parameters are the orifice coefficient and area. Details of the calibration and selection of these options are discussed in the Sideline 22 calibration section.

In Sideline 26, water was observed to exit the southeast wetland basin via a surface pathway to an intermittent stream, equipped with monitoring equipment over the study period. Surface outflow is known to occur from Basin 1 into an intermittent stream when water levels reach the wetland outfall crest elevation. Channels were used in PCSWMM to simulate the surface pathways between basins and to the surface outfall. When the level in the wetland is below the elevation of the observed outfall, the wetland water balance study hypothesized additional surface and/or subsurface pathways acting in Sideline 26, both from Basin 1 to Basin 2 as well as additional losses from Basin 2 to the outlet. To represent subsurface losses from Basin 1 to Basin 2 and out of Basin 2, orifices were included to restrict the flow to rates indicative of subsurface exchanges. The model was calibrated to the orifice coefficient and area, as detailed in the calibration section.

4.3.5 Calibration

4.3.5.1 Calibration approach and general processes

Pre-development models for Sideline 22 and Sideline 26 were calibrated to known surface and groundwater elevations. During periods with surface ponding in 2013, the surface water level loggers were coincident with the groundwater loggers and the 1m deep groundwater wells were representative of surface conditions. Therefore, the average groundwater elevation between the wetland basins were used as calibration targets. The 2013 data set was used for sensitivity analysis and calibration. Calibration proceeded in different stages for Sideline 22 and Sideline 26 (Figure 4-1 and Figure 4-2). Critical elements in the calibration were magnitude and timing of response to precipitation and the rate of drawdown or drying in the wetland during dry periods.
Figure 4-1: Calibration process for Sideline 22

1. Parameterize catchment and perform sensitivity
   ↓
2. Incorporate wetland and stage-storage curve
   ↓
3. Compare to observed surface water levels
   ↓
4. Refine stage-storage curve to include subsurface
   ↓
5. Compare to observed 1m groundwater levels
   ↓
6. Incorporate groundwater inflow
   ↓
7. Compare to observed 1m groundwater levels
   ↓
8. Investigate options to include groundwater outflow
   ↓
   9a. Option (1): Orifice loss
   10a. Calibrate and validate
   ↓
   9b. Option (2): DS catchment
   ↓
   10b. Calibrate and validate

Figure 4-2: Calibration process for Sideline 26

1. Parameterize catchment and perform sensitivity
   ↓
2. Incorporate two wetland basins and stage-storage curve
   ↓
3. Compare to observed surface water levels
   ↓
4. Refine stage-storage curve to include subsurface
   ↓
5. Compare to observed 1m groundwater levels
   ↓
6. Incorporate estimated groundwater inflow
   ↓
7. Compare to observed 1m groundwater levels
   ↓
8. Add spillover connections from Basin 1 to Basin 2
   ↓
9. Compare to observed groundwater levels
   ↓
10. Add subsurface outflow pathway from Basin 1 and 2
    ↓
11. Calibrate and validate
Parameterization of the catchments were completed based upon known catchment characteristics and land use. The sensitivity analysis of the catchment parameters revealed that the volume of runoff from the catchment to the wetland was most sensitive to depth of depression storage, flow length and Manning’s ‘n’ for impervious surface. The wetland conceptualization developed from the water balance did not find runoff to be a significant contribution to the wetland water level in either wetland. The sensitivity analysis demonstrated that even the most sensitive catchment parameters for generating runoff volume (when varied within reasonable values) contributed to only approximately +/- 0.07 m of water depth across the wetland for the entire simulation period.

The storage curve for the wetland was defined from the detailed topographic survey. The model was run for the 2013 period and compared to known surface water levels in the wetland. The wetland dries below the surface water level during summer months, and calibrating to observed surface water levels was insufficient to represent this drying. The storage curve was refined to include the subsurface using the method described above. The simulation was compared to the monitored groundwater levels to evaluate model performance. Matching of wetland hydroperiod was unsuccessful with the extended storage curve so additional detail was incorporated.

Based on knowledge of groundwater exchanges from the water balance analysis the wetlands were defined as receiving nodes for groundwater exchanges with the subcatchment aquifer layer. Sensitivity was performed on the aquifer parameters and groundwater coefficients. Sensitive aquifer parameters were the initial water table elevation and soil type. In Sideline 22, the groundwater inflow was calibrated using the A1, A2, B1, and B2 parameters to achieve matching in the rates and timing of wetland water level changes. The magnitudes of increases and decreases in wetland water levels were not well matched. In Sideline 22, it was hypothesized that this was due to a missing loss mechanism from the wetland. In Sideline 26, groundwater inflow was specified during model set-up. Hypothesized exchanges between basins and flow through the wetland was not being represented in sufficient detail and was used as the calibration parameter for the time period.

4.3.5.2 Losses from Sideline 22

In the absence of a surface outlet, losses from the wetland only occurred through seepage in the model, controlled by the specified Green and Ampt parameters: saturated hydraulic conductivity, suction head, and initial deficit. This “seepage” did not adequately represent the groundwater outflows from the wetland which are dependent on depth of water in the wetland and gradient between wetland and downgradient groundwater system. Alternative methods for representing groundwater loss from the wetland were explored: (1) a downstream orifice with a controlled flow loss dependent on area of flow and head above the orifice; (2) a downstream catchment with negative groundwater coefficients. Each option was investigated for its ability to meet the timing and magnitude of drawdown of levels at specific times within the wetland’s hydroperiod. Option (1) was calibrated by modifying orifice area and discharge coefficient; Option (2) was calibrated by modifying groundwater coefficients. Parameterization of the downstream catchment was completed using the same soils as the upstream catchment, known surface
topography, and the monitored groundwater level in the downstream wells. The model for both options were calibrated to the observed water level in the 1m groundwater wells.

In Option 1, the downstream orifice was successful in matching decreasing groundwater levels in the spring and summer but could not represent the drying which occurred in the summer. Calibration was performed by selecting an orifice area and calibrating the discharge coefficient.

In Option 2, the downstream groundwater catchment was calibrated by setting $B_1 = 2$ and determining the $A_1$ value. The model was very sensitive to the value of $A_1$ to achieve general matching of the overall water levels and model convergence, therefore the $A_1$ value was evaluated based on fixed $B_1$ to determine overall behaviour and convergence. The $B_1$ coefficient was used to fine tune the calibration. Option (2) successfully met the timing and drawdown for the beginning of the year. However, the groundwater outflow would not converge in the later months of the simulation. The calibrated parameterization for each option is presented in Table 4-4.

Table 4-4: Sideline 22 Calibrated Model Parameter Summary

<table>
<thead>
<tr>
<th>Option 1: Orifice</th>
<th>Option 2: Downstream Catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>0.045</td>
</tr>
<tr>
<td>Width (m)</td>
<td>0.045</td>
</tr>
<tr>
<td>Inlet offset (m)</td>
<td>0.0</td>
</tr>
<tr>
<td>Discharge coefficient</td>
<td>0.055</td>
</tr>
<tr>
<td>Surface elevation (m)</td>
<td>150</td>
</tr>
<tr>
<td>$A_1$ Coefficient</td>
<td>$-2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B_1$ Coefficient</td>
<td>2.07</td>
</tr>
<tr>
<td>$A_2$ Coefficient</td>
<td>0.0</td>
</tr>
<tr>
<td>$B_2$ Coefficient</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 4-3 displays the results of the calibration for each option. Option 1 displayed good performance in 2013. Option 2 also displayed good performance in early 2013; however, after the November rain event (approximately 144 days into simulation), hydroperiod matching is limited and the model performance statistics are poor.
4.3.5.3 *Sideline 22 Model Performance*

The two options were evaluated based on the statistical outputs from PCSWMM. In the early portion of 2013 (first 110 days) the downstream catchment performed very well. However, in the latter part of the year the groundwater elevations are very close to the surface and this impacts the stability of the simulation causing it to not successfully predict the hydroperiod. Calibration of the simulated orifice is more successful than the downstream catchment. In 2013, the results are summarized for the first 110 days compared to the entire simulation period. It is valuable to use several different evaluation functions to assess model performance (James, 2005): The Nash-Sutcliffe efficiency is a good measure of the predictive power of hydrologic models; model performance for Option 1 and Option 2 is very good for the first 144 days with a NSE of 0.862 and 0.694, respectively. For this time period, additional model performance parameters have been summarized and are presented in Table 4-5.

Table 4-5: Model performance for 2013 calibration and 2014

<table>
<thead>
<tr>
<th>Evaluation Functions</th>
<th>Value of Perfect Measure</th>
<th>Option 1: Orifice</th>
<th>Option 2: Downstream Catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2013 (189 days)</td>
<td>2013 (144 days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013 (189 days)</td>
<td>2013 (110 days)</td>
</tr>
<tr>
<td>Nash-Sutcliffe efficiency (NSE)</td>
<td>1</td>
<td>-0.037</td>
<td>0.908</td>
</tr>
<tr>
<td>Coefficient of determination</td>
<td>1</td>
<td>0.306</td>
<td>0.104</td>
</tr>
<tr>
<td>Standard error of estimate (SEE)</td>
<td>0</td>
<td>0.215</td>
<td>0.127</td>
</tr>
</tbody>
</table>
Using the calibrated models from each of the options described above, the model was validated against the 2014 data set. Figure 4-4 compares the 2014 simulations for each of the options used to represent outflow.

![Figure 4-4: Validation results for 2014 data at Sideline 22](image)

The wetland conditions in 2014 were not the same as 2013 as the wetland in general experienced high water levels throughout 2014. In the absence of winter precipitation data, the validation run was completed independently of the calibration run. All parameters remained unchanged with the exception of the initial water elevations in the wetland and in the downstream aquifer unit for simulation of Option 2. Table 4-5 presents the model performance for the validation period. Option 2 performs better in 2014 than Option 1. The difference in performance suggests that the factors governing orifice flow may be more sensitive to the water level in the wetland and the larger depths in the wetland in 2014 result in larger flows. Therefore, the calibrated parameters for Option 1 at Sideline 22 are not appropriate and the use of a downstream aquifer catchment is more appropriate to represent wetland lateral groundwater losses. Utilizing a downstream catchment in Option 2, the model performs better indicating less sensitivity to small changes in the wetland water level.
4.3.5.4 Losses from Sideline 26

The wetland water balance analysis indicated the presence of surface/subsurface losses from Basin 1 to Basin 2. Site observations indicated the presence of surface losses from Basin 2 to the downstream system and the water balance analysis suggested the presence of subsurface losses from Basin 2 as well. Detailed topographic information was used to parameterize the surface outflow pathways from Basin 1 to 2 and from Basin 2 to the outlet; however, it did not sufficiently to represent the additional subsurface exchanges hypothesized. Surface flow exchanges occur when the wetland water level crests the ‘connecting elevation’ and it was not adequate to simply lower that elevation to represent subsurface groundwater losses.

Alternative methods for representing the subsurface exchanges were investigated. The options investigated for Sideline 22 were less applicable for Sideline 26 as groundwater flow did not just leave the basins but was transferred from one to the other. An orifice was added to the connection between Basin 1 and Basin 2 and at the outfall of Basin 2 to mimic the ‘subsurface/lateral’ groundwater flow pathway that is hypothesized at each location. The orifices were to restrict flow to reasonable lateral groundwater exchange rate. The model was calibrated by modifying orifice area and discharge coefficient to match the observed wetland water levels in Basin 1 and Basin 2.

Table 4-6: Sideline 26 Calibrated Parameter Summary – Basin 1 Outlets

<table>
<thead>
<tr>
<th>Basin 1 Subsurface Outlet</th>
<th>Basin 1 Surface Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape</strong></td>
<td>Circular (orifice)</td>
</tr>
<tr>
<td><strong>Height (m)</strong></td>
<td>0.007</td>
</tr>
<tr>
<td><strong>Width (m)</strong></td>
<td>0.007</td>
</tr>
<tr>
<td><strong>Inlet offset (m)</strong></td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Discharge coefficient</strong></td>
<td>0.065</td>
</tr>
</tbody>
</table>

Table 4-7: Sideline 26 Calibrated Parameter Summary – Basin 2 Outlets

<table>
<thead>
<tr>
<th>Basin 2 Subsurface Outlet (orifice loss)</th>
<th>Basin 2 Subsurface Orifice Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape</strong></td>
<td>Circular (orifice)</td>
</tr>
<tr>
<td><strong>Height (m)</strong></td>
<td>0.012</td>
</tr>
<tr>
<td><strong>Width (m)</strong></td>
<td>0.012</td>
</tr>
<tr>
<td><strong>Inlet offset (m)</strong></td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Discharge coefficient</strong></td>
<td>0.064</td>
</tr>
</tbody>
</table>
4.3.5.5 Sideline 26 Model Performance

Figure 4-5 displays the results of the calibration for Basins 1 and 2, respectively. Both calibrations display good matching (Table 4-8). However, issues with water level response to precipitation are apparent in both Basin 1 and Basin 2. Precipitation data is recorded at 5-minute intervals and

[Figure 4-5: Calibration results for 2013 data at Sideline 26]

Table 4-8: Model performance for 2013 calibration and 2014 Evaluation

<table>
<thead>
<tr>
<th>Evaluation Functions</th>
<th>Value of Perfect Measure</th>
<th>Basin 1</th>
<th>Basin 2</th>
<th>Basin 1</th>
<th>Basin 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2013</td>
<td>2014</td>
<td>2013</td>
<td>2014</td>
</tr>
<tr>
<td>Nash-Sutcliffe efficiency (NSE)</td>
<td>1</td>
<td>0.502</td>
<td>-82.3</td>
<td>-11.2</td>
<td>-3.79</td>
</tr>
<tr>
<td>Coefficient of determination (R2)</td>
<td>1</td>
<td>0.12</td>
<td>0.01</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Standard error of estimate (SEE)</td>
<td>0</td>
<td>0.362</td>
<td>0.921</td>
<td>0.312</td>
<td>0.231</td>
</tr>
<tr>
<td>Simple least squares (LSE)</td>
<td>0</td>
<td>538</td>
<td>461</td>
<td>398</td>
<td>291</td>
</tr>
<tr>
<td>Root mean square error (RMSE)</td>
<td>1</td>
<td>12.7</td>
<td>10.5</td>
<td>10.1</td>
<td>10</td>
</tr>
</tbody>
</table>

In the absence of winter precipitation data, the validation run was completed independently of the calibration run (Figure 4-6). All parameters remained unchanged with the exception of the initial water elevations in the wetland. Table 4-8 presents the model performance for the validation period.

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Overall, the calibrated and validated models did not display good performance using a simplified approach to represent subsurface/lateral groundwater exchanges between the basins. Similar to Sideline 22, the rate of loss through the orifice is more sensitive to the water level in the wetland and the larger depths in the wetland in 2014 result in more rapid water level decline. The orifice representation of the subsurface catchment is not ideal to represent the factors governing the exchanges between basins. PCSWMM has limitations in regards to groundwater ‘flow through’ as you cannot specify groundwater tables below storage units and therefore it does not allow groundwater to flow through a storage unit.

4.4 Conclusions
This study presents the calibration and validation procedure and results for two wetlands with different hydrologic interactions. In Sideline 22, two options for incorporating subsurface outflow from the wetland in the PCSWMM hydrologic model framework were investigated. Including the subsurface zone in the catchment aquifer allows for the groundwater inflows to be simulated. Losses can be simulated using either a downstream catchment or an orifice loss. The orifice loss had better calibration results but validation was unsuccessful and model performance using the downstream catchment was used to define a reference hydrologic regime for the Sideline 22 wetland. Storage units can be used in PCSWMM to represent a wetland and define detailed topographic information. Groundwater from the catchment subsurface can discharge to the wetland feature. In Sideline 22, with the absence of a known surface water outflow path, it was desirable to model the groundwater losses from the wetland basin. The seepage parameters for the storage units are insufficient to represent complex wetland groundwater losses, which occur both vertically and laterally. Workarounds must be applied to define groundwater flows.
out of a surface storage unit and into a downstream catchment. This option displayed good calibrated and validated performance for Sideline 22 and further software extensions and capabilities in PCSWMM may ease the ability to represent these types of wetland processes.

In Sideline 26, two wetland basins were incorporated to be consistent with the findings of the water balance study. These basins receive groundwater from the surrounding catchments and lose groundwater through surface and subsurface pathways. Results of calibration and validation indicate good performance for hydroperiod matching in the selected years, though some limitations due to the governing orifice equations (as identified in Sideline 22) limited the performance of the model for the validated year. In Sideline 26, it was not possible to represent groundwater flow from one basin to the other using the same techniques as Sideline 22. Limitations with the PCSWMM aquifer capabilities result in the inability to diligently represent the groundwater exchange pathways. However, using the orifice technique to mimic lateral groundwater exchanges was a somewhat crude representation of actual processes, though in the absence of other options provided reasonable hydroperiod matching.

4.5 Next Steps
Next steps include to use the calibrated and validated models to incorporate development on the wetland catchments and predict the impacts of development. A hypothetical development scenario with residential development of 50% impervious area has been applied to the contributing catchment areas at both Sideline 22 and Sideline 26. The main hydrologic alterations experienced from the surface system were those typical from development (i.e. increased runoff, decreased evapotranspiration, and decreased infiltration). These alterations are seen in the subsurface groundwater layer (evapotranspiration and infiltration) and a decrease in groundwater output from the catchment into the wetland.

The wetland hydroperiod is being impacted by the catchment development through alterations to the surface and subsurface processes. The next step in the modelling is to separate and quantify the impacts on the wetland hydroperiod due to changes in the surface and subsurface. Low impact development practices will be incorporated in the model. Design of low impact development measures using the models for Sideline 22 and Sideline 26 will be completed and compared to designs for event simulation. LID design will target mitigation of the catchment hydrology to restore the wetland hydroperiod.
4.6 References


Gerber Geosciences Inc. (2003) Duffins Creek watershed hydrogeology and assessment of land use change on the groundwater flow system. For TRCA: Toronto, ON.


Toronto and Region Conservation Authority (2014) February_23_2012_Seaton_Data GIS Database. Toronto, ON.


Chapter 5  LID Modelling

5 Modelling to support design of green infrastructure systems to mitigate changes to catchment hydrology and wetland hydopериods

5.1 Introduction

Development is encroaching on sensitive features such as wetlands and causing direct and indirect impacts (e.g. Wright et al., 2006). Increased catchment imperviousness disrupts drainage patterns and alters the natural balance of infiltration, runoff, and evapotranspiration (Burns et al., 2012; Walsh et al., 2005). Alterations to catchment hydrology change drainage pathways to wetlands, affecting the proportions of runoff and groundwater discharged to wetlands (Wright et al., 2006). Altered subsurface pathways and rapid conveyance pathways as a result of impervious surfaces and conveyance systems impacts the timing of runoff to the wetland (Bradford, 2015). Increased proportion of runoff can result in increased magnitude and frequency of water level fluctuations and result in changes in the depth and duration of ponding (Wright et al., 2006; Owen, 1999). Increased volume of stormwater runoff leads to increased magnitude and duration of ponding which is exacerbated if the wetland does not have the capacity to discharge runoff (e.g. via a surface water outlet) (Wright et al., 2006). Catchment imperviousness and decreased vegetation area can change microclimate conditions (e.g. increased air and water temperature, changes in humidity) which alter evapotranspiration and thermal patterns (Somers et al., 2013; Burns et al., 2012; Walsh et al., 2005). Altered hydrologic regimes reduce the ability of wetlands to perform their full range of functions and services within the landscape (Krause et al., 2007; Davidson, 2014; Snell, 1987, Owen 1999). Characterizing impacts to wetlands using a range of hydrologic metrics is needed to understand and prevent alteration to wetland hydrology as a result of development (Bradford, 2015).

Low impact development (LID) is an important part of integrated urban water management; the philosophy of LID includes the promotion of source control which helps to maintain watershed processes at the catchment scale. LID is described as a concept that aims to “maintain a natural site water balance through hydrologic landscapes which [are] ‘functionally equivalent’ to their pre-development state” (Fletcher et al., 2014). LID practices include bioretention, infiltration trenches, permeable pavement, enhanced bioswales, green roofs and rain water harvesting. Benefits of LID include improved water quality and maintenance of infiltration and runoff volumes (i.e. Hunt et al., 2012; Winston et al., 2016). LID practices can also remove water from overburdened sewers (Graham et al., 2014) and contribute to flood loss avoidance (Atkins, 2015). They are able to recreate informal drainage patterns which direct and disperse stormwater runoff through vegetated drainage pathways before reaching the receiving water feature (Burns et al., 2014). LID practices offer versatile solutions which can be implemented at a catchment-scale to address multiple objectives (Fletcher et al., 2015) and performance metrics which aim to restore elements of catchment hydrology critical to sensitive receiving features.
Hydrologic models are valuable tools to simulate pre-development conditions, understand impacts of urbanization, aid design of mitigation measures, and demonstrate these measures are effective to meet desired stormwater management objectives. PCSWMM is a program developed by CHI to act as spatial decision support for EPA SWMM’s dynamic, hydrology-hydraulic, stormwater model (CHI, 2015). In addition to simulation of surface hydrology, SWMM has a groundwater component capable of representing some unsaturated and saturated zone processes. SWMM allows the user to define a continuous rainfall pattern and has capabilities which include interception of rainfall into depression storage, infiltration into unsaturated soil layers, percolation into groundwater layers, and retention and detention of runoff by LID controls (US EPA, 2015). Detailed representation of a range of LID controls (e.g. permeable pavement, rain gardens (bioretention), infiltration trenches, street planters, green roofs, rain barrels, and vegetative swales) and support for their hydraulic modeling is provided in PCSWMM. PCSWMM has well defined storage processes, making the LID controls useful from a simulation perspective (Jayasooriya and Ng, 2014). PCSWMM can also be used to analyse multiple LIDs, evaluate long term performance including clogging and reduction of infiltration capacity, compare scenarios for continuous hydrologic analysis, and perform sensitivity analysis and calibration (CHI, 2015).

5.1.1 Purpose/Objective
The purpose of this investigation is to explore the ability of PCSWMM to predict impacts of urbanization on catchment hydrology and the resulting alterations to wetland hydrology. It will examine the use of PCSWMM as a tool to simulate and advance design of LID practices. Targeted LID design will be explored to assess its ability to mimic key aspects of the pre-development water balance and mitigate impacts of urbanization on the wetland.

5.1.2 Description of Study Sites
The study site for this investigation was the Sideline 22 wetland in the Duffins Creek Watershed, located north of Taunton Road in Pickering, Ontario. Residential development in the wetland’s catchment is planned. Sideline 22 is classified as an isolated wetland with no surficial inflow or outflow. The wetland is a 1.38 ha mineral swamp with surface water present most of the year. Local geology indicates that the presence of Halton till underlying Iroquois Sand Plain deposits (Gerber Geosciences Inc, 2003).

5.1.3 Available Data
Monitoring data has been collected by the Toronto and Region Conservation Authority for the study wetland since June 2013. A tipping bucket was installed at another wetland located less than 1 km away. A 3-season rain gauge is located at the Brockwest Landfill Site, approximately 3 kilometers to the southeast. Precipitation and temperature data collected at the Brockwest landfill between June – November 2013 and April – November 2014 is used in this analysis. Long term meteorological data was obtained from the nearest weather station (Buttonville Airport) for the years 1986-2007 (Environment Canada, 2016).
Historical spot measurements of groundwater levels and general trends were obtained from consulting reports for the surrounding area undergoing development (Sernas Associates, 2013). Water levels were logged at three depths (surface ponding and groundwater at 1-m and 2-m) in two locations within the wetland. Two additional 2-m deep groundwater piezometers were installed approximately 200 meters to the east and southeast. Continuous water level data is available at each monitoring location at 15-minute intervals for June – November 2013 and April – November 2014.

The TRCA provided detailed survey data for the wetland. The surveying was completed over 2 days in January 2013. Hydraulic conductivity estimates were based on slug tests completed by TRCA at each monitoring station location (Table 5-1).

<table>
<thead>
<tr>
<th>Wetland</th>
<th>Station and Depth</th>
<th>Saturated hydraulic conductivity, K (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sideline 22</td>
<td>1-10 (GW-2m)</td>
<td>6.45 E-05</td>
</tr>
<tr>
<td>Sideline 22</td>
<td>1-10 (GW-1m)</td>
<td>5.30 E-06</td>
</tr>
<tr>
<td>Sideline 22</td>
<td>1-40 (GW-2m)</td>
<td>2.70 E-06</td>
</tr>
<tr>
<td>Sideline 22</td>
<td>1-40 (GW-1m)</td>
<td>1.60 E-05</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-10 (GW-2m)</td>
<td>3.20 E-07</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-10 (GW-1m)</td>
<td>1.03 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-40 (GW-2m)</td>
<td>1.58 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 1</td>
<td>1-40 (GW-1m)</td>
<td>1.71 E-08</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-10 (GW-2m)</td>
<td>7.11 E-10</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-10 (GW-1m)</td>
<td>1.58 E-09</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-40 (GW-2m)</td>
<td>2.37 E-09</td>
</tr>
<tr>
<td>Sideline 26 Basin 2</td>
<td>2-40 (GW-1m)</td>
<td>1.58 E-09</td>
</tr>
<tr>
<td>Sideline 26</td>
<td>3 (GW-2m)</td>
<td>1.04 E-04</td>
</tr>
</tbody>
</table>

5.1.4 Conceptual Understanding of Wetland Hydrology
An initial conceptual hydrologic model was based on wetland location in the landscape, site observations, and ecological indicators. It was refined based on a detailed water balance analysis. A single isolated basin is present at Sideline 22. In addition to direct precipitation, the wetland receives runoff from the upstream catchment. There is likely very little actual surface runoff, but the conceptual model includes lateral flow to the wetland in the shallow subsurface. Groundwater inflow occurs based on historical spot elevations of the water table to the northwest. Vertical gradients of 0.001m/m, indicating groundwater inflow, were consistently measured at one monitoring location. The relative importance of input pathways (i.e shallow vs. deep) is not clear. Water leaves the wetland through evapotranspiration and lateral groundwater flow to the southeast. The understanding of wetland hydrology informed the representation of the wetland in PCSWMM and the model calibration and validation.
5.1.5 Pre-development model parameterization, calibration, and validation

**Climatology and Simulation Options.** The PCSWMM model was run at a 1-hour dry-weather time step, a 5-minute wet-weather time step, and a 30-second routing time step for the calibration (June – November 2013) and validation (April – November 2014) periods. Evapotranspiration was calculated based on Hargreaves’s method. Daily precipitation totals, and minimum and maximum temperatures were provided in the inputs files.

**Wetland Parameterization.** The model included the wetland as a dynamic feature of the simulation. Detailed stage-storage information was defined for the wetland unit. The storage curve accounted for open water, bank storage, and subsurface storage volumes in the wetland. Detailed representation of stage storage was important as water level response to precipitation events was a focus of calibration.

**Catchment and Aquifer Parameterization.** Two upstream catchments were defined: a 6.7 ha catchment to the north and a 13.0 ha catchment to the west. The catchment delineation was based on topographic maps of the study areas and confirmed by site observations. Parameters for Sideline 22 were selected to represent agricultural land use with mild to moderate slopes and low hydraulic conductivity. To allow for the simulation of evapotranspiration from subsurface soils and to represent the shallow subsurface flow system, a single aquifer unit was associated with the catchments. Geological information for the study area was used to determine appropriate subsurface parameters.

**Groundwater Interaction.** Groundwater exchanges into and out of the wetland were required in the model. The aquifer component of the catchment identified the wetland as the receiving node for groundwater inputs from the catchment. Losses to groundwater were simulated by incorporating a downstream catchment and aquifer to simulate outflow (‘negative’ inflow) from the wetland.

**Sensitivity, Calibration, and Validation.** A model sensitivity analysis was completed. The model was calibrated to the subcatchment’s groundwater interaction parameters. Successful calibration was based on visual matching of the wetland hydroperiod, including precipitation response and dry down rates. Statistical parameters (i.e. Nash-Sutcliffe Efficiency) indicated good performance for 2013. A validation run in 2014 also displayed good visual and statistical performance.

5.1.6 Post-development model parameterization

**Development on the Catchment.** The area is zoned for residential development with some small commercial lots. Preliminary draft subdivision plans and lot layout configurations were consulted to determine development extent and layout. A hypothetical development scenario was based on the proposed conditions. Post-development conditions were represented by altering the percent impervious to 50% and maximum flow path to 30 m.
**Low Impact Development Control Parameterization.** LID controls are incorporated as subcatchment properties with a user-defined percentage of runoff from impervious areas diverted to the LID practice. The investigation focused on implementing bioretention cells as they are versatile in their ability to achieve infiltration, evapotranspiration, and detention. Bioretention cells include three layers (surface vegetated area, engineered soil, and storage layer) with the option to include an underdrain (Table 5-2). Underdrains were not used in this study. The cells were sized to capture the water quality volume, which was obtained using a 1-hour, 25mm event. A sensitivity analysis was performed to examine the effects of altering berm height, vegetation volume, layer thickness, and soil media conductivity. For the mitigation scenarios, the subsurface profile of the bioretention cells was kept the same throughout the development. The area of the cells varied depending on lot proportion and available installation area and mitigation scenario.

<table>
<thead>
<tr>
<th>Surface Layer</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berm height (mm)</td>
<td>300</td>
</tr>
<tr>
<td>Vegetative volume (fraction)</td>
<td>0.10</td>
</tr>
<tr>
<td>Surface roughness (-)</td>
<td>0.0</td>
</tr>
<tr>
<td>Surface slope (%)</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Layer</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>200</td>
</tr>
<tr>
<td>Porosity (-)</td>
<td>0.40</td>
</tr>
<tr>
<td>Field capacity (-)</td>
<td>0.105</td>
</tr>
<tr>
<td>Wilting point (-)</td>
<td>0.047</td>
</tr>
<tr>
<td>Conductivity (mm/hr)</td>
<td>60</td>
</tr>
<tr>
<td>Conductivity slope (%)</td>
<td>5.0</td>
</tr>
<tr>
<td>Suction head (mm)</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage Layer</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>200</td>
</tr>
<tr>
<td>Void ratio (voids/solids)</td>
<td>0.7</td>
</tr>
<tr>
<td>Seepage rate (mm/hr)</td>
<td>5.5</td>
</tr>
<tr>
<td>Clogging factor</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Sensitivity Analysis of Bioretention Design Parameters.** Sensitivity analysis was completed for the 2013 study year to assess the impacts of altering the characteristics of the bioretention cell on the system’s performance. The sensitivity of total catchment infiltration, evaporation, and runoff volume to the design parameters (soil depth, storage layer thickness, vegetation volume, berm height, cell area, soil hydraulic conductivity) were assessed. Infiltration volume was not sensitive to increased berm height (150 mm to 300 mm). This was not surprising as the bioretention cells did not experience surface ponding greater than 150mm for the 2013 simulation period and therefore the increase in berm height would not change the capture volume. Total infiltration volume from the bioretention cell was not sensitive to an increase or decrease in soil depth (200 mm to 1200 mm). Infiltration volume is dependent on how much...
water gets into the bioretention cell and the soil matrix, and with no overflow occurring from the cells, more storage for the runoff water is of no benefit.

The vegetation volume did not impact the evaporation volumes simulated by SWMM, however an increase in vegetation resulted in a slightly increased runoff and decrease in infiltration volume due to less available storage in the surface area of the cell. The increase in vegetation volume increased the instances of overflow of the bioretention cells. Increasing the hydraulic conductivity of the bioretention soils by a factor of 2.0 (from 30 mm/hr to 60 mm/hr) had a minimal impact on the total infiltration as the surface storage never filled and there were no need to more rapidly move the runoff through the soil matrix. Increasing the bioretention cell area by 1.5 times increased the infiltration volume by approximately 10%, this was to be expected as the total volume of infiltration depends on the available area for infiltration (i.e. additional bioretention area).

Based on these results, the bioretention cells were implemented with the characteristics summarized in Table 5-2. Further analysis of the impact of altering the bioretention cell area and treatment area (i.e. proportion of impervious area treated) is provided in the results and discussion. The results and discussion present the implications of the sizing on the performance of the bioretention cells as well as factors beyond cell parameterization which need to be considered.

5.2 Results and Discussion
5.2.1 Impacts of Development
The hypothetical development in the catchment impacted the catchment hydrology (surface and subsurface) and the receiving wetland feature. The results presented are for the 2013 monitoring year.

5.2.1.1 Catchment Hydrology
Catchment Surface Water Balance. The surface water balance in PCSWMM describes the distribution of rainfall between infiltration, evaporation, and runoff (Figure 5-1, Equation 5-1).
Evaporation from the subcatchment is lost from water ponded in the pervious and impervious depression storage. Infiltration volume is a function of subcatchment soil properties and slopes. Development impacts the surface water balance by substantially decreasing the pervious area available for infiltration thereby significantly increasing the runoff volume.

In event simulation, comparing pre-development to post-development surface water balance provides an event-based change in the distribution of the precipitation on the catchment. Continuous simulation over a longer time period is needed to account for antecedent moisture conditions and inter-event periods which affect the total values of catchment evaporation and infiltration. In continuous simulation the post-development surface water balance shows decreases in infiltration and increases in runoff. Evaporation increases as a result of increased ponding in the catchment impervious areas which contribute to more surface water available for evaporation. Evapotranspiration is not a part of the surface water balance.

**Catchment Subsurface Water Balance.** To adequately represent the catchment water balance, it is necessary to consider how the infiltrated water is distributed, which requires including evapotranspiration losses.

“Aquifers” are included in PCSWMM to account for sub-surface soil layers that are necessary to simulate evapotranspiration and vertical groundwater exchanges. The aquifer layer includes both the saturated and unsaturated zone and is defined in the subcatchment properties by specifying...
soil parameter and water table/saturation parameters (CHI, 2010). Water enters the aquifer via infiltration from the surface layer and then evapotranspires or enters the groundwater transport system (CHI, 2010) depending on the aquifer properties. The subsurface water balance in PCSWMM therefore describes the distribution of infiltrated surface water between ET and the groundwater system.

\[
\text{Groundwater recharge (GWR)} = \text{Infiltration (I)} - \text{Evapotranspiration (ET)} \quad \text{Equation 5-2}
\]

In pre-development the evapotranspiration makes up a large portion of the subsurface water balance (approximately 50% of total rainfall and 55% of total infiltration). In post-development the groundwater recharge portion decreases and makes up approximately 25% of the total rainfall and 33% of the total infiltration.

**Complete Catchment Water Balance in PCSWMM.** Combining the surface and subsurface behaviour in PCSWMM provides a more complete representation of the catchment water balance (Figure 5-3, Equation 5-3).
Rainfall from the catchment is distributed into surface evaporation, subsurface evapotranspiration, groundwater recharge, and runoff. Evapotranspiration occurs from the saturated and unsaturated zones and is calculated using on Hargreaves’s equation.

**Impacts of Development on the Complete Catchment Water Balance.** Table 5-3 summarizes the alterations from pre-to post-development in the surface, subsurface and catchment water balance.

**Table 5-3: Alterations to the catchment water balance pre- to post development**

<table>
<thead>
<tr>
<th>Sideline 22 Subcatchment 1</th>
<th>Pre-development</th>
<th>Post-Development (No Mitigation)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent Impervious</td>
<td>3.5%</td>
<td>50%</td>
</tr>
<tr>
<td>Area (ha)</td>
<td>13.03</td>
<td>13.03</td>
</tr>
<tr>
<td>Surface Evaporation, E (mm)</td>
<td>2.5</td>
<td>40.8</td>
</tr>
<tr>
<td>Infiltration, I (mm)</td>
<td>420.1</td>
<td>204.6</td>
</tr>
<tr>
<td>Runoff, RO (mm)</td>
<td>12.9</td>
<td>187.0</td>
</tr>
<tr>
<td><strong>Subsurface</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evapotranspiration, ET (mm)</td>
<td>227.2</td>
<td>103.8</td>
</tr>
<tr>
<td>Groundwater Outflow, GW (mm)</td>
<td>11.5</td>
<td>9.0</td>
</tr>
<tr>
<td>Catchment Water Balance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Rainfall (mm)</td>
<td>435.4</td>
<td>435.4</td>
</tr>
<tr>
<td>Groundwater recharge, GWR (mm)</td>
<td>192.9</td>
<td>100.8</td>
</tr>
<tr>
<td>Groundwater Outflow, GW (mm)</td>
<td>11.5</td>
<td>9.54</td>
</tr>
<tr>
<td>Total Evapotranspiration, E + ET (mm)</td>
<td>229.7</td>
<td>144.62</td>
</tr>
<tr>
<td>Runoff, RO (mm)</td>
<td>12.9</td>
<td>187.0</td>
</tr>
</tbody>
</table>

Increased impervious area in the post-development scenario has typical responses with increased runoff and decreased infiltration and total evapotranspiration. The water balance shows that in pre-development, over half of the infiltration volume is released as ET. In post-development, ET and infiltration both decline, however even though infiltration has decreased by 215 mm, the portion of infiltration reaching the groundwater system has decreased by 90 mm, not 215 mm, which is only apparent when including the subsurface.

The groundwater outflow volume reported by SWM is not directly related to the values of catchment infiltration. In Table 5-3, the total groundwater outflow only decreases by 3.5mm for the entire simulation period even though the infiltration volumes decrease by significantly more. The groundwater outflow parameter represents the portion of the groundwater recharge that goes to the wetland and is based on the water table elevation in the wetland and in the catchment.

**Importance of the inclusion of the subsurface in the catchment.** The aquifer component of the subcatchments is important to include when simulating and evaluating impacts on catchment hydrology. Even in the situations that do not require simulation of groundwater flows, it is necessary to incorporate the groundwater/aquifer layer to ensure pre-development ET processes and the associated impacts of urbanization are represented. The subsurface catchment water balance accounts for the path of infiltrated water into ET and groundwater recharge. It elucidates the distribution of precipitation between runoff, groundwater recharge, evaporation, evapotranspiration, runoff, and groundwater outflow. It identifies an infiltration target for post development which considers the substantial decrease in ET.

### 5.2.1.2 Wetland Hydrology

The wetland hydroperiod is impacted in post development. Surface and subsurface pathways from the catchment to the wetland are altered and the proportions and timing of groundwater and runoff inflows change. Runoff to the wetland drastically increases (from approximately 100 mm over the wetland to 4.8 m total) in proportion to the increased impervious area and the resulting wetland water levels are significantly higher in post-development with no mitigation. Changes to wetland evapotranspiration in post-development were not simulated. A limitation in PCSWMM is the inability to simulate microclimate changes as a result of development, which can impact the ET losses experienced by the wetland (Somers et al., 2013).
5.2.2 Performance of Low Impact Development Measures

5.2.2.1 Replication of Catchment Hydrology

Low impact development practices were assessed for their ability to meet pre-development hydrology. Pre-development and post-development (unmitigated) were compared to four additional scenarios which were assessed based on their ability to meet the complete catchment water balance:

- Scenario 1: Pre-development
- Scenario 2: Post-development
- Scenario 3: Bioretention cells sized to treat roof and driveway runoff (55% impervious area)
- Scenario 4: Bioretention cells with increased footprint to treat runoff from driveway, roof, and portion of right-of-way (88% impervious area)
- Scenario 5: Scenario 4 with engineered media hydraulic conductivity doubled (60 mm/hr)
- Scenario 6: Scenario 5 with 40% of roof area directed to rain barrels
- Scenario 7: Scenario 6 with 95% impervious area treated by bioretention cells

Figure 5-4 and Figure 5-5 summarize the water balance for each scenario. The results demonstrate the importance of considering the surface and the subsurface water balance when evaluating the effectiveness of the mitigation techniques. Scenario 3 – 5 all have various extents of bioretention installations and treatment areas; however the surface water balance suggests that not enough water is being infiltrated. This is not in fact the case, since the subsurface ET deceases in post-development. The groundwater recharge that occurred pre-development is much smaller and analysis of the subsurface water balance (Figure 5-5) indicates that the pre-development value is being exceeded in each of the bioretention scenarios (Scenario 3-5).
Figure 5-4: Comparison of catchment surface water balance

Figure 5-5: Comparison of catchment subsurface water balance

Scenario 6, disconnects a portion of the roof-top from the bioretention cell and directs it to a rainwater harvesting system (a “rain barrel” in PCSWMM). Scenario 6 incorporates the maximum extent of bioretention (or infiltration practices) without exceeding the pre-
development groundwater recharge. Bioretention cells do increase evapotranspiration relative to the grassed areas they replace, however pre-development ET is not matched, and the excess runoff generated is not mitigated. Therefore, additional stormwater LIDs are needed which are capable of removing the surplus from the stormwater management system. Retention of the surplus runoff volume in the form of rainwater harvesting (for indoor reuse) or green roofs is needed to meet the pre-development water balance. In some cases, “enhanced” recharge or recharge in excess of pre-development levels may be desirable (Scenario 7). This should only be considered in the context of integrated urban water management where the enhanced recharge is needed to mitigate effects of external factors such as water-takings which impact water table levels. Scenario 7 was developed to demonstrate the results of a groundwater recharge scenario.

Table 5-4 summarizes the comparison of pre-development and post-development mitigated catchment water balance for the scenarios.

Table 5-4: Results of bioretention installation

<table>
<thead>
<tr>
<th>Sideline 22 Subcatchment 1</th>
<th>Pre-development</th>
<th>Scenario 6</th>
<th>Scenario 7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent Impervious</td>
<td>3.5%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Area (ha)</td>
<td>13.03</td>
<td>13.03</td>
<td>13.03</td>
</tr>
<tr>
<td>Surface Evaporation, E (mm)</td>
<td>2.5</td>
<td>47.09</td>
<td>48.00</td>
</tr>
<tr>
<td>Surface Infiltration, I (mm)</td>
<td>420.1</td>
<td>328.0</td>
<td>365.0</td>
</tr>
<tr>
<td>Runoff, RO (mm)</td>
<td>12.9</td>
<td>65.5</td>
<td>65.5</td>
</tr>
<tr>
<td><strong>Subsurface</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subsurface Evaporation, ET (mm)</td>
<td>227.2</td>
<td>119.48</td>
<td>119.0</td>
</tr>
<tr>
<td>Groundwater Outflow, GW (mm)</td>
<td>11.5</td>
<td>10.0</td>
<td>11.6</td>
</tr>
<tr>
<td><strong>Catchment Water Balance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall (mm)</td>
<td>435.4</td>
<td>435.4</td>
<td>435.4</td>
</tr>
<tr>
<td>Groundwater Recharge, GWR (mm)</td>
<td>192.9</td>
<td>198.8</td>
<td>241.2</td>
</tr>
<tr>
<td>Total Evaporation, E + ET (mm)</td>
<td>229.7</td>
<td>166.6</td>
<td>167.0</td>
</tr>
<tr>
<td>Groundwater Outflow, GW (mm)</td>
<td>11.5</td>
<td>10.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Runoff, RO (mm)</td>
<td>12.9</td>
<td>65.5</td>
<td>31.5</td>
</tr>
</tbody>
</table>

Using PCSWMM to Optimize Bioretention Design. In Section 5.1.6 the sensitivity of elements of the catchment water balance to each of the sizing parameters was discussed. Upon thorough evaluation of the characteristics of the catchment and subcatchment water balances, the ultimate scenario for bioretention installation (contributing drainage area) and extent (total surface area) was balanced to meet pre-development catchment hydrology, including an upper limit on infiltration (Scenario 6). The bioretention sizing parameters which most impact the catchment water balance are the parameters which change the frequency of overflow of the bioretention system (i.e. vegetation volume, ponding depth). The other bioretention sizing parameters (i.e soil and storage media depth) do not significantly impact the ability of bioretention cells when to meet catchment hydrology (when varied within reasonable design
values) and these parameters can be selected based on other consideration (i.e. rooting depth, vegetation requirements).

Optimizing bioretention design for wetland protection requires recognition of characteristics it is desirable to mimic. It is important to recognize that meeting catchment hydrology is not necessarily sufficient to maintain wetland hydrology. Matching pre-development catchment water balance (i.e. proportion of ET, groundwater recharge, and runoff) is a significant component of mitigating impacts of urbanization. Wetlands rely on water from the catchment in the form of overland flow and lateral groundwater pathways. These pathways must also be matched in post-development, particularly where the timing of water delivery to the wetland is important to ecological function. Also, the excess runoff (after meeting pre-development recharge and runoff) from the proposed design will need to be directed elsewhere. In some cases, it may be directed to a downstream receiving feature, bypassing the wetland. Alternatively, some or all of the excess may be captured by rainwater harvesting for indoor use and removal from the catchment water balance.

In Scenario 6, maximum bioretention installation is achieved by directing a portion of the rooftops away from the bioretention cells and to rainwater harvesting (RWH) practices to avoid ‘over-infiltrating’. Installation of RWH to collect the remaining rooftop runoff and remove it from the system was explored to reduce the volume of runoff draining to the wetland. Modelling the rain barrels within PCSWMM determined a maximum installation of rain barrels for the development based on the number of lots and the treated impervious area. In Scenario 7, pre-development groundwater recharge is exceeded however groundwater outflow is matched (Table 5-4). Additional groundwater and/or coupled groundwater-surface water modelling is merited in cases where it is necessary to more fully understand the effects of multiple human activities and mitigation practices.

**Evapotranspiration from bioretention cells.** LID processes are surface/storage processes in PCSWMM. When LIDs are implemented on the catchment, they replace either paved or landscaped surfaces. They can only send water to the groundwater system via their infiltration processes but cannot receive groundwater or dynamically interact with the groundwater system. This limits the ability of PCSWMM to adequately represent the important subsurface processes (i.e. ET) that bioretention cells can mitigate in post-development. PCSWMM calculates the surface evaporation from the available volume of ponded water in bioretention cell. However, the model does not simulate the evapotranspiration from moisture in the subsurface layers of bioretention cells. The mechanisms determining ET from the catchment are not the same as those controlling ET from the bioretention cells, which is a limitation in comprehensively representing that process.

One of the multiple benefits provided by bioretention cells is the “retention” of runoff via ET and it is desirable to understand how this mechanism impacts the performance of various mitigation scenarios. When considering the complete catchment water balance in pre-development, it is
possible to recognize that too much infiltration could be occurring post development if the
distribution of water into the groundwater recharge and evapotranspiration components is not
incorporated. However, the reverse is also true: if evapotranspiration from bioretention cells has
been found to count for anywhere from 50% to 75% of the direct rainfall (Wadzuk, et al., 2014)
then the infiltrated volume being report by SWMM does not reflect the volume which is lost to
ET from the bioretention cell and infiltration may be underestimated. Understanding the impact
of this limitation was a goal of this investigation.

Subsurface ET from catchment areas are simulated when an underlying aquifer unit is included.
A separate unit-bioretention catchment was created with an aquifer to replicate the subsurface
zone of a bioretention cell. A subcatchment was parameterized to represent a unit bioretention
cell and the subsurface “aquifer” layer was parameterized to represent the zones of the
bioretention cell. When the cell receives input in the form of only direct precipitation, the cell
loses approximately 70% of the precipitation to evapotranspiration, consistent with the
experimental findings of Wadzuk et al. (2014). This accounts for an annual depth of
approximately 12 mm ET in addition to the SWMM evaporation output as a result of changing
the grassed area to a bioretention cells. However, when the unit bioretention cell receives runoff
from contributing impervious drainage area in addition to direct precipitation, the
evapotranspiration goes down to approximately 6% of the total rainfall and evaporation increases
to 40% of the total run-off from the catchment. This change is a result of the ponded water in the
bioretention cell from the increased drainage area. The unit bioretention cell analysis indicates
that the total evaporation and evapotranspiration losses expected from the bioretention cells is
equivalent to an annual depth of 29 mm. The PCSWMM output which uses the bioretention cells
as LID controls indicates that from post-development ‘unmitigated’ to post-development ‘with
LID’, the total evaporation (E+ET) increases on the subcatchment by approximately 23 mm.
Therefore the processes which the LID control bioretention cells are losing water to E and ET in
PCSWMM is more reasonable and representative of the actual processes.

Additional accuracy and stringency with the groundwater routine in LID cells could overcome
the remaining discrepancy in actual ET from bioretention cells by representing bioretention units
as individual groundwater aquifers, where ‘groundwater evapotranspiration’ is reported as a
model output. This would extend the design to match catchment water balance (i.e.
evapotranspiration, infiltration, groundwater recharge, etc.) and have ET sufficiently considered
from the bioretention cells on a long term basis in the same way it is calculated in the catchment.

**LID Interaction with Groundwater.** Infiltration from the bioretention units is added on to the
subcatchment infiltration component and passed on to the groundwater routine. However it is not
possible to specify a surface elevation or a water table elevation in the bioretention cells. In some
cases, where groundwater tables are low and mounding is not an issue this may not be
problematic. In cases where bioretention mitigation measures are being applied where the water
table is close to the surface, it is important to consider this interaction and model its impacts.
There is no option in SWMM to evaluate the impact on bioretention cell performance in the case
that the water table elevation reaches close enough to surface to encroach into the bioretention cells. This is a limitation for modeling bioretention cells that are installed with their base very close to the observed range of seasonally variable water table elevation.

**Event performance of bioretention cells.** The ability of the LID installation to meet key elements of the catchment water balance and the pathways and volumes to the wetland were evaluated using the continuous data set. The bioretention cell design was also analyzed during design storms. The bioretention cells capture the 5-year storm event with no overflow. The soil and storage zone layers are both at capacity but the surface storage does not exceed the storage volume available. This was not expected as the bioretention cells were only designed to capture the 1-hour 25-mm event without overflowing. However, the design storms used to compare were typical, 4-hour Chicago distribution storms using the IDF curve parameters for the study area. This calls into question the appropriateness of a 1-hour duration water quality storm.

Event simulation does not consider two details imperative to bioretention design: (1) there is no inter-event period for evapotranspiration; and (2) range of antecedent moisture conditions. Table 5-5 compares the event performance of the 2-year storm (run for 12 hours) with the continuous output for 2013 for Scenario 6. The percentage of each component in relation to the total precipitation is included in parentheses. Analysis of these results in isolation would indicate very different performance and treatment capacity of the proposed bioretention design. For example potential mitigation abilities of the bioretention is not being reported in the event simulation which does not run long enough to appreciate those effects. In addition, the proportion of runoff, infiltration, and groundwater recharge is inconsistent between each scenario (Table 5-5) indicating how it is inadequate to only consider design storm performance.

| Table 5-5: Results of bioretention installation for continuous vs. event simulation |
|-----------------------------------|-----------------|-----------------|-----------------|
| **Sideline 22 Subcatchment 1**    | Pre-development| Scenario 6      | 2-Year Design Storm |
| **Surface**                       |                 |                 |                 |
| Percent Impervious                | 3.5%            | 50%             | 50%             |
| Area (ha)                         | 13.03           | 13.03           | 13.03           |
| Surface Evaporation, E (mm)       | 2.5 (0.6%)      | 47.09 (11%)     | 0.47 (1.4%)     |
| Surface Infiltration, I (mm)      | 420.1 (97%)     | 328.0 (75%)     | 19.13 (59%)     |
| Runoff, RO (mm)                   | 12.9 (3.0%)     | 65.5 (15%)      | 5.0 (15%)       |
| **Subsurface**                    |                 |                 |                 |
| Subsurface Evaporation, ET (mm)   | 227.2 (52%)     | 119.48 (27%)    | 0.0 (0.0%)      |
| Groundwater Outflow, GW (mm)      | 11.5 (2.6%)     | 10.0 (2.3%)     | 0.01 (0.03%)    |
| **Catchment Water Balance**       |                 |                 |                 |
| Rainfall (mm)                     | 435.4           | 435.4           | 32.27           |
| Groundwater Recharge, GWR (mm)    | 192.9 (44%)     | 198.8 (46%)     | 18.65 (58%)     |
| Total Evaporation, E + ET (mm)    | 229.7 (52%)     | 166.6 (38%)     | 0.47 (15%)      |
| Groundwater Outflow, GW (mm)      | 11.5 (2.6%)     | 10.0 (2.3%)     | 0.01 (0.03%)    |
| Runoff, RO (mm)                   | 12.9 (3.0%)     | 65.5 (15%)      | 5.0 (15%)       |
5.2.2.2 Mitigation of Impacts on Wetland Hydrology

A complete representation of changes in catchment hydrology better informs the targets for post-development. The final bioretention scenario (Scenario 6) incorporated the maximum extent of bioretention as an infiltration-type practice without exceeding pre-development recharge.

Final Design. There are two mitigation scenarios to match study wetland’s hydroperiod. The first option is described by providing a maximum installation for the bioretention as to not exceed total ‘groundwater recharge’ (Scenario 6). In this scenario, the total groundwater volume to the wetland is not met and the volume to the wetland is maintained by a runoff making up for the decrease in groundwater discharge. In the second case (Scenario 7), the bioretention cells can be sized to receive runoff from a larger contributing drainage area (by increasing the percent of impervious area treated).

In both cases, it is possible to meet the total volume of water to the wetland via the combination of surface and subsurface pathways, however the bioretention installations do not meet the frequency or magnitude of runoff behaviour in pre-development. That is, when comparing the pre-development inflow hydroperiod to the mitigated inflow hydroperiod. Runoff occurs from the catchment less frequently and when it does occur, the peaks are larger (by 150-300%) than pre-development. This does not impact the wetland hydroperiod in post-development (Figure 5-4, Figure 5-5). Figure 5-6 and Figure 5-7 depict the performance of LID design for the Sideline 22 wetland in 2013 and 2014, respectively.

![Figure 5-6: Comparison of Observed, Pre-development, Scenario 6, and Scenario 7 wetland hydroperiod (2013)](image-url)
There is potential in PCSWMM to evaluate the performance of a mitigation strategy and aid understanding LID design parameters. In the absence of simulation results regarding catchment evapotranspiration, the combination of bioretention and RWH show the promise of an infiltration and capture system whereby the maximum infiltration volume is achieved in post-development by infiltration-type LID systems (i.e. bioretention) and the excess volume captured in RWH systems.

5.3 Conclusions

Urbanization on a small catchment was simulated in PCSWMM. Using a calibrated and validated model for a 19 ha contributing catchment area, the impacts of urbanization on the wetland hydroperiod were evaluated. Development impacts all aspects of the catchment water balance, including the surface and subsurface zones. Including a subsurface groundwater layer provides a more detailed distribution of rainfall to evaporation, evapotranspiration, and groundwater recharge which is important to determine how the wetland will be impacted. However, the model does not simulate alterations in microclimate and there are limitations in evaluating impacts on wetland ET as a result of development on the catchment.

The maximum installation of bioretention design can be determined based on the groundwater recharge values calculated for the catchment. However, there is still an increase in runoff volume which cannot be fully mitigated by the bioretention design. It is therefore necessary to introduce mitigation strategies on the catchment which are able to capture and retain (either via rainwater reuse or evapotranspiration) the additional runoff. Limitations exist in PCSWMM which complicate the analysis of impacts of bioretention cells on ET performance. These include the inability to define an aquifer layer in the cell to represent the same process governing ET loss as
the catchment subsurface and the inability to simulate microclimate changes and their impacts on evapotranspiration.

This study highlights the importance of continuous simulation and the inclusion of the subsurface soils in PCSWMM to (1) predict changes in catchment hydrology; (2) develop designs to mitigate changes in subsurface infiltration and evapotranspiration; (3) assess and optimize performance and design of bioretention practices to mitigate changes to catchment subsurface water balance; and (4) identify additional LID measures required to ensure protection of wetland hydroperiods in development.

5.4 Next Steps
Next steps in this research include the analysis of these systems for a long-term simulation. The simulation would look at how the mitigation strategies perform under varying climatic conditions which were not represented in the 2013 and 2014 data sets. In addition suitable target hydrologic performance metrics for the wetland hydroperiod must be identified and quantified for the historic data. Analysis of the ability of the LID installation to meet these targets would be included in their performance evaluation.
5.5 References


Gerber Geosciences Inc. (2003) Duffins Creek watershed hydrogeology and assessment of land use change on the groundwater flow system. For TRCA: Toronto, ON.


Chapter 6  Conclusions & Recommendations

6.1  Conclusions

The following discussion examines the main conclusions from the investigation as they relate to each research objective:

6.1.1  Urban water management for the protection of wetlands in urban development: A synthesis of literature

The research synthesis and review of the current body of knowledge provided the following key insights and gaps in knowledge:

- Challenges exist to independently quantify wetland interactions but techniques have been advanced which improve the ability to reduce errors associated with these estimates. There is value in conducting a water balance to elucidate important hydrologic processes, inform areas where there is potential for impact from catchment urbanization, confirm conceptual understanding of wetland hydrology, and direct modelling efforts.

- Changes in catchment hydrology impact the dynamic hydrologic regime of wetlands which impacts ecologic character and function. Traditional stormwater management has limitations to address ecologically relevant hydrologic metrics which is resulting in wetland degradation.

- Low impact development shows promise to achieve catchment drainage patterns that are functionally equivalent to predevelopment rates. Gaps exist in modelling software and practice to predict the impacts of urbanization, design mitigation measures (i.e. green infrastructure), and assess their ability to mitigate impacts of urbanization on wetlands to support ecosystem objectives.

6.1.2  Wetland water balances as tools to confirm conceptual understanding of wetland hydrology and direct hydrologic modelling efforts to predict impacts of urbanization

An approach for conducting a thoughtful wetland water balance analysis has been presented. Using accessible monitoring data the conceptual understanding of wetland hydrology was refined for the two study wetlands. The water balance was successful in isolating important wetland processes, directing further monitoring efforts, and identifying the components of the water balance which required further refinement. The following conclusions can be made about the wetland water balance analysis approach:

- Conducting a wetland water balance to refine and confirm hydrology is possible with an accessible data set (i.e. ground and surface water levels data). The continuous data sets are imperative to provide information on general trends and behaviour, identify seasonally varied behaviour, provide a range of time periods for more in-depth analysis,
and inform a hierarchal approach to analyze variation in wetland hydrology under a range of conditions (dry, wet, overnight, etc.).

- A single season of monitoring is insufficient to obtain a complete conceptual understanding of wetland hydrology. Multiple years of data are essential for a water balance as they identify variations in wetland hydrologic interactions and seasonal behaviour.

- Detailed topographic information can reduce the uncertainty in the stage-storage relationship above ground. Site specific information is needed reduce the error associated with the specific yield estimates below ground.

- Evapotranspiration estimates are possible with reliable diurnal fluctuations. To accomplish this, careful attention to installation of barologgers and pressure transducers is needed.

- Knowledge gained from the water balance study can be used to select and parameterize hydrologic models and provide confidence that the correct interactions are considered in the simulation.

6.1.3 Wetland modelling in PCSWMM to predict impacts of urbanization
The water balance was used to inform the parameterization of a hydrologic simulation tool of the wetlands and their catchments. A hydrologic model was calibrated and validated to known wetland hydroperiods. Using knowledge acquired from the wetland water balance analysis it was possible to incorporate known wetland processes (i.e. surface, subsurface, and groundwater exchanges, ET, etc.) and characteristics (i.e. topography, storage relationships) into the model. The tool was then used to simulate a reference hydrologic regime for each of the study wetlands. The following conclusions can be made about the application of PCSWMM to simulate wetlands and their catchments:

- Storage units can be used in PCSWMM to represent wetlands. This allows for storage relationships to be defined based on detailed topographic information and for the discharge of groundwater from the catchment subsurface to the wetland feature.

- Hydrologic simulations can be best calibrated to wetland hydroperiods by considering trends, rate of water level change (decline to drying or rise from inflow), and outflow pathways.

- There are challenges with representing outflow pathways which are a combination of surface and subsurface pathways as the governing orifice equations do not adequately represent these relationships.
Groundwater interaction was defined in PCSWMM for inflow and outflow was successfully represented using a new approach to define groundwater loss to a downstream aquifer from the storage unit. Limitations with the PCSWMM aquifer capabilities result in the inability to diligently represent the groundwater exchange pathways. Additional software extensions and capabilities in PCSWMM may ease the ability to represent these types of wetland processes.

6.1.4 Modelling to support design of green infrastructure systems to mitigate changes to catchment hydrology and wetland hydroperiods

With a calibrated and validated hydrologic model, impacts of urbanization on catchment and wetland hydrology could be predicted. Systems of green infrastructure practices were designed and simulated to determine the design extent and targets for matching key aspects of predevelopment catchment hydrology to mitigate impacts of urbanization on the wetland. It was found that:

- Including a subsurface groundwater layer in PCSWMM provides a more detailed distribution of rainfall to evaporation, evapotranspiration, and groundwater recharge which is important to determine how the wetland will be impacted. There are limitations in evaluating impacts of urbanization on wetland ET as the model does not simulate alterations in microclimate as a result of development on the catchment.

- The maximum installation of bioretention design can be determined based on groundwater recharge in the catchment. However, there is still an increase in runoff volume which cannot be fully mitigated by the bioretention design. It is therefore necessary to introduce mitigation strategies on the catchment which are able to capture and retain (either via rainwater reuse or evapotranspiration) the additional runoff.

- Limitations exist in PCSWMM which complicate the analysis of impacts of bioretention cells on ET performance. These include the inability to define an aquifer layer in the cell to represent the same process governing ET loss as the catchment subsurface and the inability to simulate microclimate changes and their impacts on ET.

- Continuous simulation and the inclusion of the subsurface soils in PCSWMM is needed to (1) predict changes in catchment hydrology; (2) develop designs to mitigate changes in subsurface infiltration and evapotranspiration; (3) assess and optimize performance and design of bioretention practices to mitigate changes to catchment subsurface water balance; and (4) identify additional LID measures required to ensure protection of wetland hydroperiods in development.
6.1.5 Key Research Findings

A powerful management tool has taken form by combining the state of the knowledge of (1) wetland water balances to advance understanding of wetland hydrologic processes; (2) the capacity to obtain a complete representation of the impacts of urbanization on wetland hydrology; and (3) the ability to develop predictive simulation tools to model impacts of urbanization, how these impacts manifest on the wetland, and the design and performance of mitigation techniques. There is a valuable opportunity to use what we have learned to inform responsible development and ensure better protection of wetlands.

6.2 Recommendations

Results of the investigation indicate that wetland water balances have value to refine conceptual understanding of wetland hydrology and inform hydrologic models. It is possible to calibrate and validate these models to known wetland hydroperiods and develop predictive tools to assess impacts of urbanization and performance of low impact development practices. The following recommendations are presented based on the findings of the study:

- Data limitation and issues with monitoring set-up affected the ability to independently quantify all water transfer mechanisms. It is therefore recommended to complete the water balance analysis for the 2016 monitoring year and increase the scope to include data provided from the additional monitors.

- When modelling in PCSWMM, it is imperative to consider the impacts of the subsurface layers to evaluate changes in catchment and wetland hydrology. It is recommended that the subsurface be included in future modelling studies to ensure important aspects of predevelopment hydrology are included in hydrologic simulation.

- Low impact development practices in PCSWMM show some promise to mimic key aspects of pre-development hydrology. However, limitations exist in their inability to interact with the groundwater table and to simulate evapotranspiration losses through the LID cells. Additional software capabilities in PCSWMM which allow for LID controls to undergo the same processes as the catchment subsurface may improve the ability to fully represent these exchanges.

- Research is needed to extend the analysis of the models for long-term simulation to (1) evaluate behaviour under varying climatic conditions; (2) identify suitable target hydrologic metrics for the wetland hydroperiod under pre-development conditions; and (3) analyze the ability of mitigation strategies to meet the hydrologic targets.