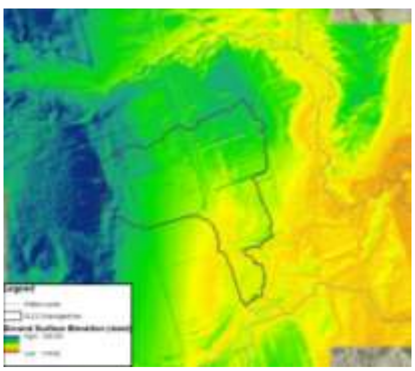
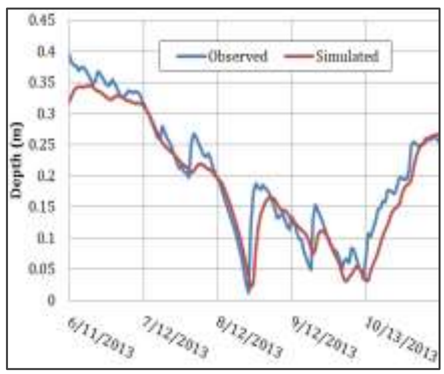
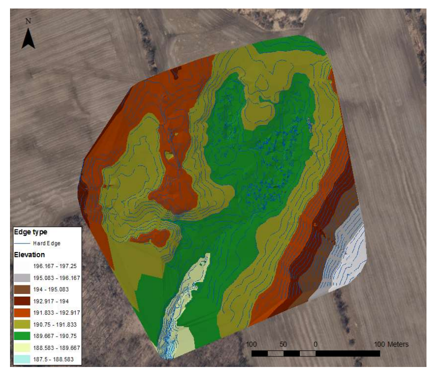
Wetland Water Balance Modelling Case Studies

(Appendix to TRCA Wetland Water Balance Modelling Guidance Document)

July 2018







Toronto and Region Conservation Authority

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1.0 Introduction

1.1 Purpose and Scope

Continuous hydrological models are a key tool for predicting the impact of land development and infrastructure construction on the hydrology of wetlands and other natural features. Models can also be used in the design of stormwater management facilities to offset such impacts, where mitigation is deemed necessary. Determining the appropriate model to simulate wetland hydrology can be challenging, as there are many factors to consider: the hydrological processes operating at a particular wetland, the representation of these processes in the model as they relate to wetland storage dynamics, the representation of stormwater management and low impact development (LID) facilities, and the personal preferences and abilities of the modeler in question, to name just a few. This appendix is intended to be a resource for modelers to help them make more informed decisions in modelling wetland water balance scenarios.

This appendix provides a series of case studies illustrating the set-up, calibration, and validation process for five commonly used continuous hydrology models (HEC-HMS, HSPF, MIKE SHE, Visual Otthymo, and SWMM). The calibrated and validated models are then used to explore the effects of different development scenarios to predict the change in wetland storage relative to the baseline condition, both with and without hypothetical mitigation measures. The modelling case studies shown here were produced by TRCA staff and external contributors from the University of Guelph and Civica Infrastructure. All the examples shown are based on two wetland sites located in central Pickering Township, where monitoring data was collected by TRCA starting in 2013 in anticipation of eventual development of the catchment areas. Additional data on the wetland catchment and basin were compiled for these two sites to inform the modelling exercise. The development scenarios and proposed mitigation measures were hypothetical, as plans for the development of areas surrounding the two wetlands were not sufficiently advanced at the time of writing, but the scenarios are based on realistic assumptions about development form and layout that draw on the experience of professional water resource engineers.

This appendix is intended to be used as a resource for modelers to consult for applications requiring a wetland water balance. It is not intended to definitively outline best practices for modelling, but rather to provide examples of considerations for the application of the five continuous hydrology models shown here, including data requirements, model complexity or simplicity, calibration and validation procedures, representation of different hydrological processes, and so on.

2.0 Common Data Sources

2.1 Aerial Photography

Recent aerial photographs can provide useful information about the land use context in the vicinity of the wetland and can be used to help classify different land cover types for the purposes of subdividing and/or parameterizing the wetland catchment. Some municipalities may be able to provide data free of charge, whereas others may not. TRCA cannot provide aerial photography data to proponents at present. Data can also be purchased from other sources (e.g. First Base Solutions).

2.2 Topography & Bathymetry

Topography data is essential in the delineation of wetland catchments and in understanding how water is stored in and released from the wetland. A minimum vertical resolution of 25 cm is recommended for the area contributing drainage to the wetland. Within the wetland pool itself, a higher vertical resolution is required because wetlands often occur in broad, flat areas, where there can be dramatic differences in the area of ponded water with relatively small changes in stage. Similarly, where surficial outflow channels are poorly defined, the stage-discharge curves must be very precise in order to define the elevation at which a wetland begins to discharge. For these reasons, a vertical resolution of 5 cm is recommended for the area of the wetland that might contain standing water at any point during the year. Where there is standing water at the time of topographic data collection, it may be necessary to collect bathymetry data to better constrain wetland storage volumes. High resolution (e.g. LiDAR-derived) topographic data exists for the entire TRCA jurisdiction and can be purchased from private vendors.

2.3 Wetland Pool Rating Curves

For the reasons cited above, realistic and accurate simulation of wetland storage dynamics requires precise topography and bathymetry data within the wetland pool. The elevation at which wetland pools begin to discharge is a key variable to inform development of wetland pool rating curves. As these rating curves can change dramatically over a small elevation range where outlets are less well defined, a vertical resolution of 5 cm is recommended. Some hydrodynamic models (e.g. MIKE-11) also have hydrodynamic routines to determine inflow and outflow condition dynamics and the inundation process of the wetland; these may be accepted in lieu of rating curves where model capabilities allow.

Some wetlands may consist of multiple pool areas that may be connected by overland flow or channelized flow, particularly for larger wetlands. Representation of these wetlands as a single storage unit with one associated rating curve or as separate units is a decision that will depend on expert opinion and the capabilities of the model(s) under consideration.

2.4 Catchment Delineation

Delineation of the wetland catchment should be completed using the highest resolution digital elevation model available. In most cases, software packages (e.g. ArcHydro) will offer the highest degree of precision in delineating the wetland catchment. However, it may be appropriate in some cases to manually correct delineated catchments to reflect the influence of subsurface or concealed drainage features (e.g. culverts, tile drains) on the wetland's contributing drainage area.

2.5 Land Use

Land use data is important for catchment parameterization, and is available from a variety of sources. Land Information Ontario offers a wide variety of classified land use layers for purchase. Municipalities and conservation authorities may also offer land use datasets free of charge or for a nominal data service fee. Aerial photographs may also be used to manually classify land use.

2.6 Soils

The surficial soils within the catchment, in combination with the topography, control to a large extent the catchment's hydrological response, and are often used in combination with land use data to determine catchment parameters and/or delineate hydrologic response units. As regional-scale datasets (e.g. Ontario Ministry of Agriculture and Rural Affairs soil atlas) generally offer little detail at the site scale, local geotechnical investigations or the finest resolution surficial sediment mapping data available are always preferred.

2.7 Monitored Well Data

Monitoring well data can be used to estimate the potential degree of groundwater interaction at the wetland in question. Some models require groundwater timeseries data to calibrate an aquifer component or the groundwater component of an integrated groundwater-surface water model. The Ontario Ministry of the Environment collects data through the Provincial Groundwater Monitoring Network. The Oak Ridges Moraine Groundwater Program (https://oakridgeswater.ca/) provides groundwater data on a subscription basis, with data coverage across south central Ontario. Municipalities and conservation authorities often have groundwater monitoring networks and may be able to provide data.

2.8 Meteorological Data

Environment Canada maintains a data portal with current and historical meteorological records varying in temporal resolution from daily to 5-minute intervals. Conservation authorities and municipalities may also have precipitation gauges and meteorological stations. It is always preferable to use multiple meteorological stations to interpolate precipitation and other forcing variables between stations, rather than simply using the closest station available, to increase model accuracy.

3.0 Continuous Hydrologic Models

3.1 Hydrologic Modelling System (HEC-HMS)

3.1.1 HEC-HMS: Background

The US Army Corps of Engineers (USACE) Hydrologic Engineering Centre Hydrologic Modelling System (HEC-HMS) model is designed to simulate the complete hydrologic processes of watershed systems. HEC-HMS is comprised of a graphical user interface, integrated hydrologic analysis components, data storage and management capabilities, and graphics and reporting facilities. HEC-HMS is flexible in that there are many different methods available to calculate the losses, runoff transform, baseflow, routing, and reservoirs, each of which can be selected separately. The soil moisture accounting (SMA) loss method in conjunction with potential evapotranspiration data and snowmelt routines is ideal for conducting continuous simulations. The SMA model is patterned after Leavesley's Precipitation-Runoff Modelling System (1983) and is described in detail in Bennett (1998). **Figure 1** presents a conceptual model schematic for the continuous soil moisture accounting algorithm.

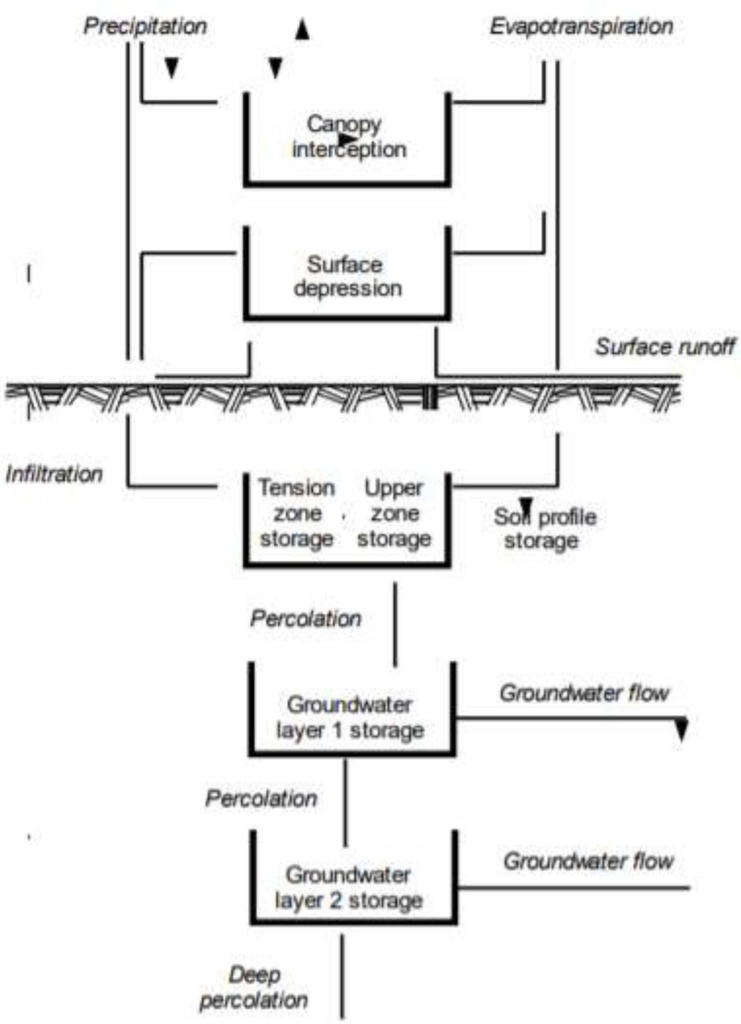


Figure 1: Conceptual schematic of the continuous soil moisture accounting algorithm (Bennett, 1998)

3.1.2 HEC-HMS: Model Setup, Existing Conditions

The case study area used for evaluation is a wetland at Seaton Sideline 26, which is located in the City of Pickering within the Duffins Creek Watershed. **Figure 2** shows the wetland and drainage areas, which were delineated using a 1m by 1m bare earth grid that was generated using LiDAR data from 2014. The wetland is divided into two pools. 2.05 hectares drain to the west pool of the wetland. The west pool drains overland to the east pool. The east pool receives runoff from an additional 7.31 hectares of land, for a total drainage area of 9.36 hectares.

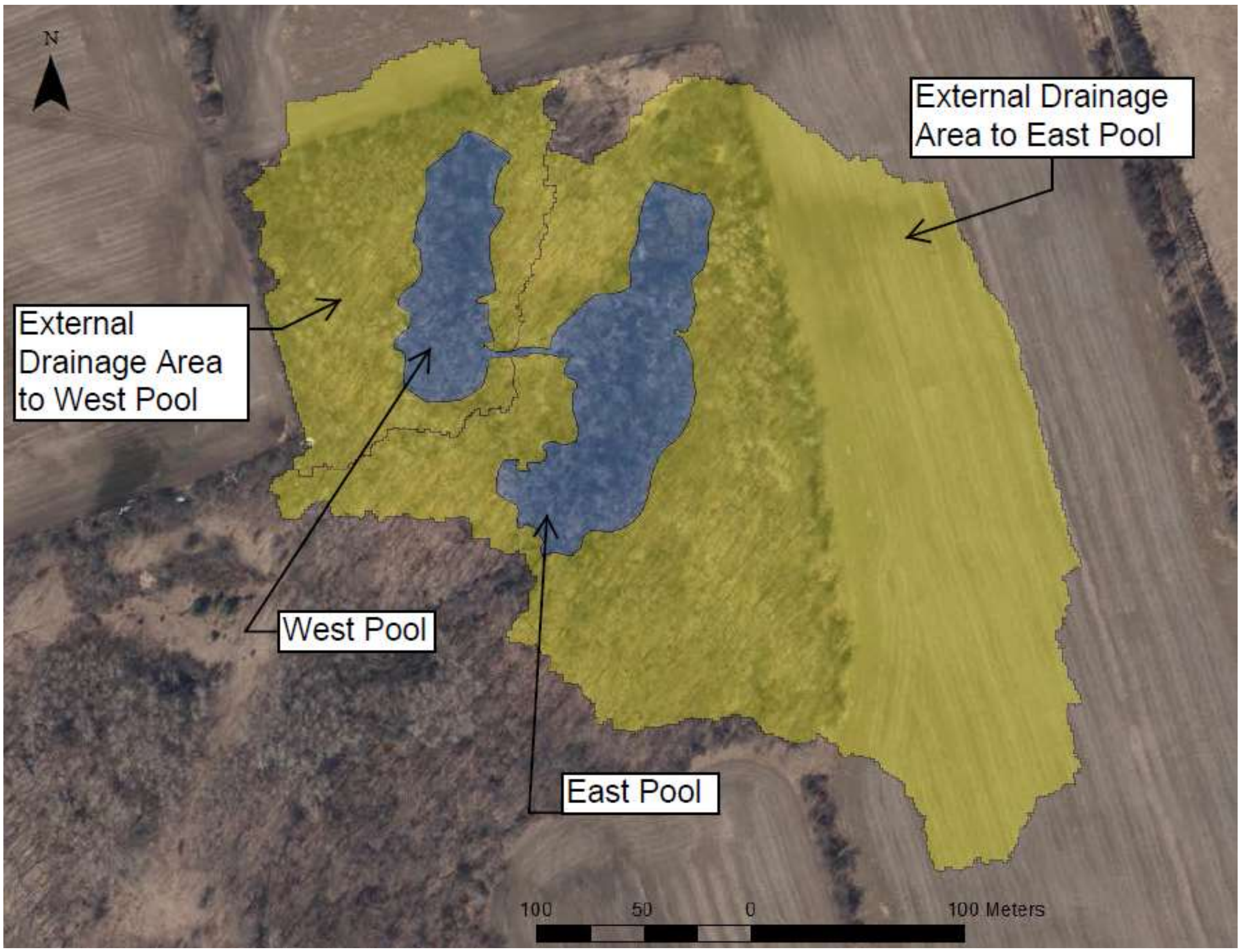


Figure 2: Sideline 26 Wetland Drainage Areas

Figure 3 shows the land use within the wetland drainage area, which includes farmland, forest, successional, and wetland. The parameters for each subbasin were lumped based on the area-weighted parameters of each of the four land use categories.

Figure 3: Sideline 26 Wetland Land Use

The soil classification for the entire drainage area to the wetland is a Gleyed Gray Brown Luvisol. A soil description from Agriculture and Agri-Food Canada was used to generate initial parameters for the maximum infiltration, soil storage, tension storage, soil percolation, groundwater percolation, and groundwater storage parameters.

Figure 4 shows the topography and bathymetry of the wetland, which was generated from a site survey. The elevation information was used to create detailed stage-storage relationships for each of the two major wetland pools. In order to estimate the discharge at each stage, the wetland was modeled in HEC-RAS as two storage areas connected by a broad-crested weir, and discharging over a second broad-crested weir to the downstream channel. Cross-sections were cut at the outlet of each pool using the elevation information, and the cross-section information was used for the weir geometry. An unsteady simulation was performed, with flow rates gradually ramped up from a low flow to a high flow, in order to ensure that the results would have a good spread of stage-discharge information. Equations were fit to the resulting rating curves, so that discharge values could be calculated at each known elevation and storage for each pool. The resulting stage-storage-discharge information was used in two separate reservoir commands which represent the surface storage at the west pool and the east pool of the wetland. The exact elevation at which each pool begins to discharge, as well as the discharge estimates closest to these elevations were treated as a calibration parameters. The outflow structures reservoir method was used in order to account for percolation from the wetland. A depth-surface area relationship for each pool was also required in order to account for the monthly evaporation from the wetland.

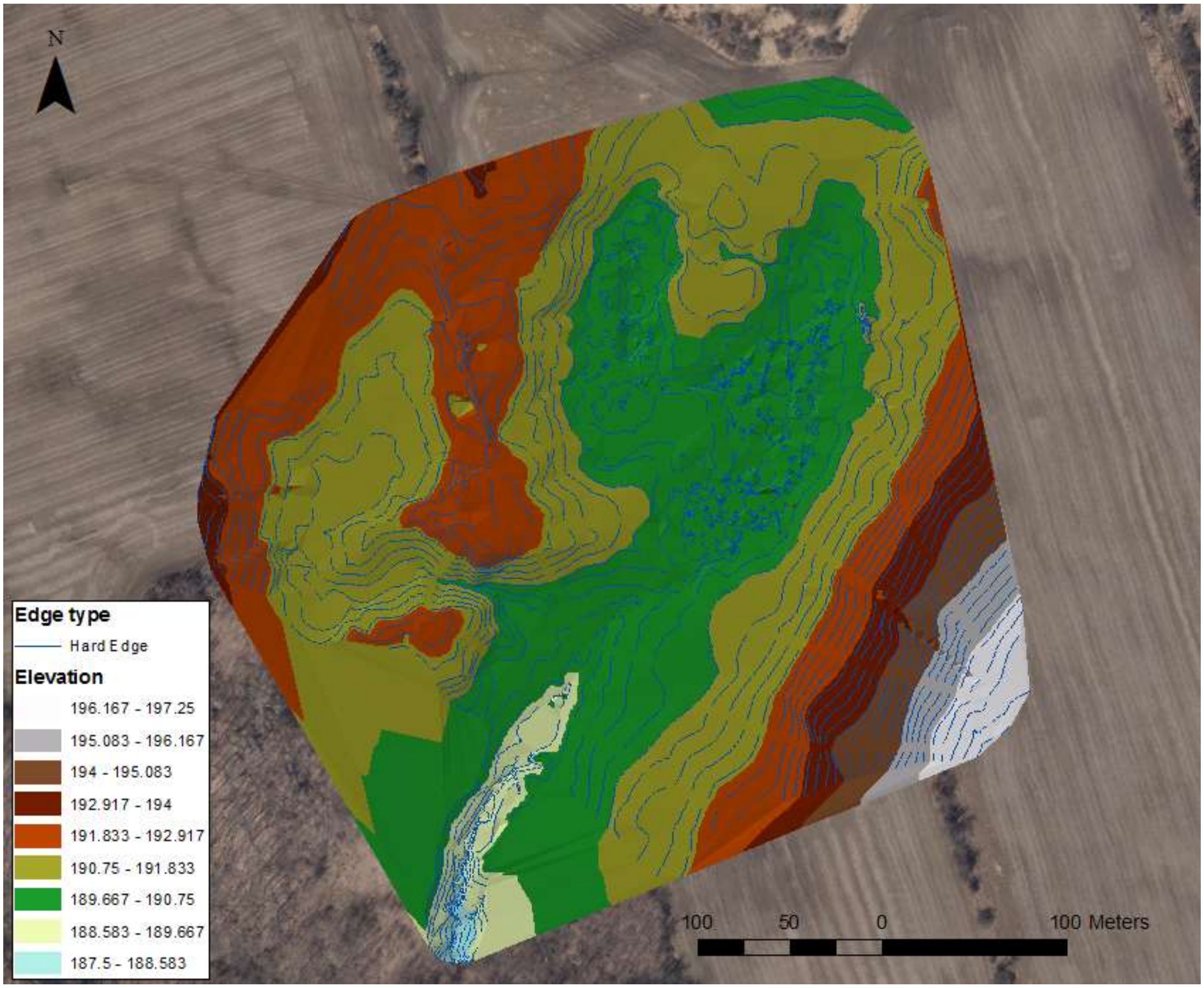


Figure 4: Sideline 26 Wetland Topography and Bathymetry

3.1.3 HEC-HMS: Calibration, Existing Conditions

Figure 5 shows the location of monitoring stations at Sideline 26. There were a set of three wells at four main locations in the wetland, each with a 30cm long screen. One well (SW well) had a screen from +0.05 to -0.25m relative to the surface, another well (1m well) had a screen from -0.7m to -1m relative to the surface, and the third well (2m well) had a screen from -1.7m to -2.0m relative to the surface. The SW well at *Transect 1 - 40m* was used to calibrate the west pool, and the SW well at *Transect 2 – 40* was used to calibrate the east pool. The water levels in the wetland were used for calibration instead of discharge for two main reasons. Firstly, the flume downstream of the wetland became blocked and was circumvented by flow, so there was not enough confidence in the monitored data to use it for calibration. Secondly, the water level in each pool is a variable that can be directly and easily used to assess impact on the ecological functioning of the wetland. Differences in observed water levels between the SW, 1m, and 2m wells were used to gain an understanding of the vertical hydraulic gradients for the monitored periods, and differences in observed water levels at the 1m wells between stations were used to gain an understanding of the horizontal hydraulic gradients for the monitored periods. These values were used to calculate time-series of percolation values from the reservoir commands that represent the wetland pools.

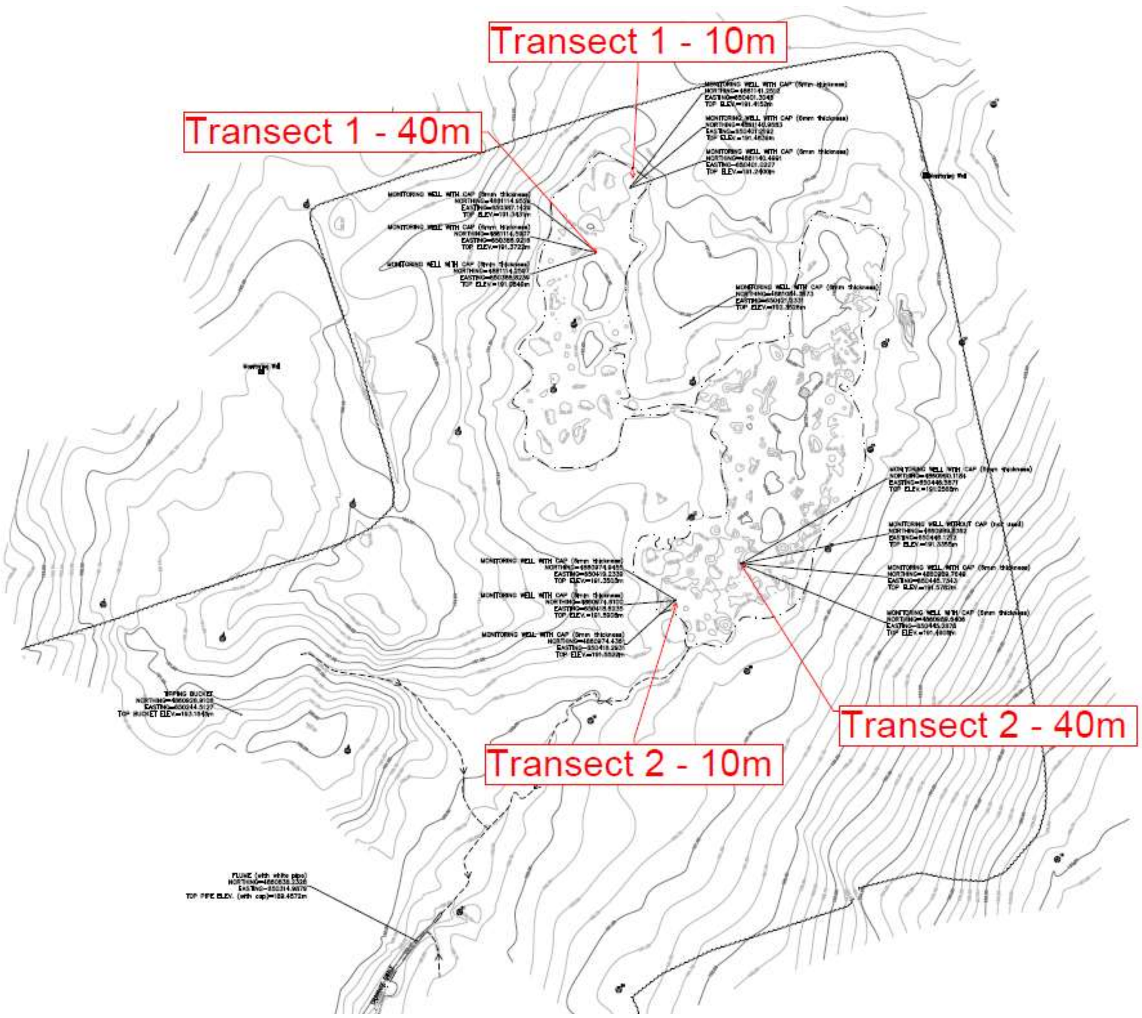


Figure 5: Sideline 26 Monitoring Stations

Observed data for 2013 was used to calibrate the model. The water level observations were recorded hourly, and converted to a daily average for the purpose of calibration. The model was run with an hourly time step, and daily average output was used for comparison with observed data.

After achieving a reasonable visual match, the procedure was repeated twice using data from 2014 and 2015 in order to validate the calibration. The initial model calibrations did not produce simulation results that closely matched observed data for the validation years, so the calibration process was iterated until all three years showed reasonable results.

Table 1 shows the main parameters that were modified from initial parameters during the calibration and validation process.

3.1.4 HEC-HMS: Validation, Existing Conditions

Table 1: HEC-HMS calibration parameters

Parameter	Units	Initial Value	Calibrated Value
Canopy: Max Storage	mm	1 to 2.7	1.03 to 1.2
SMA Loss: Max Infiltration	mm/hr	3 to 15	7
SMA Loss: Soil Storage	mm	121.75	153.2
Tension Storage	mm	39	39
Modeled stage-discharge curve for west pool	n/a	as modeled	elevation of first discharge and low flow discharge values were modified during calibration
Modeled stage-discharge curve for east pool			
Additional outlet for west pool percolation	m^3/s	0	1E-05 to 3E-05
Additional outlet for east pool percolation		0	1E-05 to 1.2E-04

After a reasonable visual match with all three years of data was achieved, three statistical measures were used to compare the goodness of fit between observed and simulated water level: Percent Difference (%D), coefficient of determination (R^2), and Nash-Sutcliffe simulation efficiency (E_{NS}).

Figures 6 through 11 show the calibration and validation results for the two wetland pools.

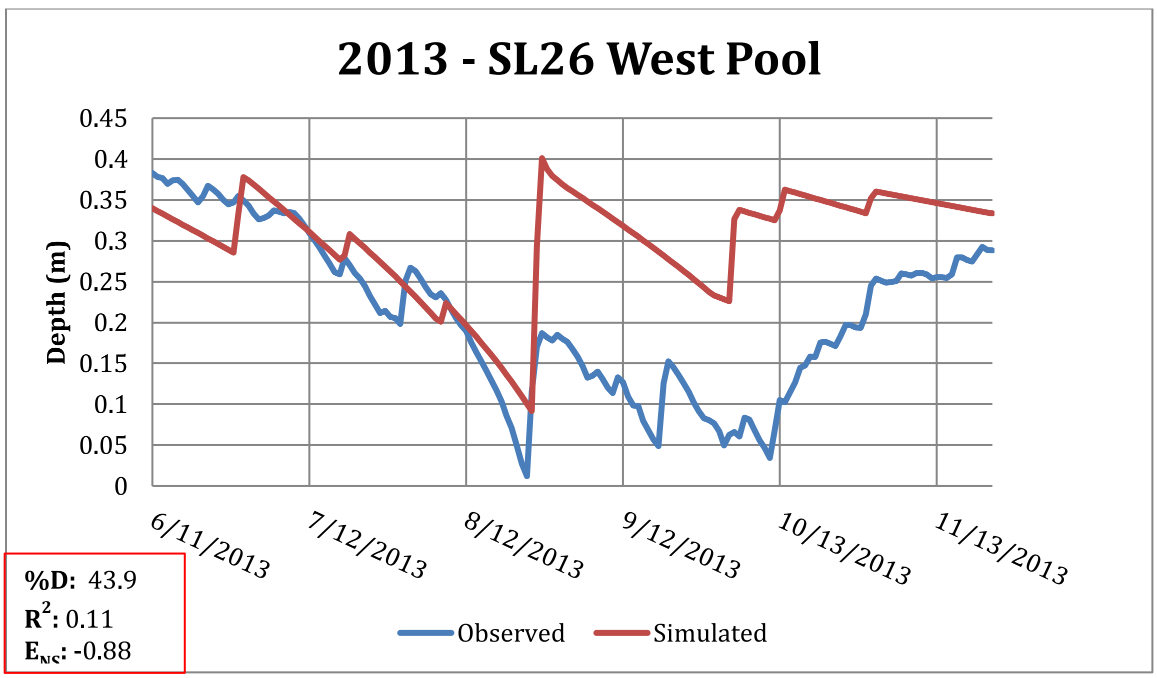


Figure 6: Sideline 26 West Pool Calibration with 2013 data

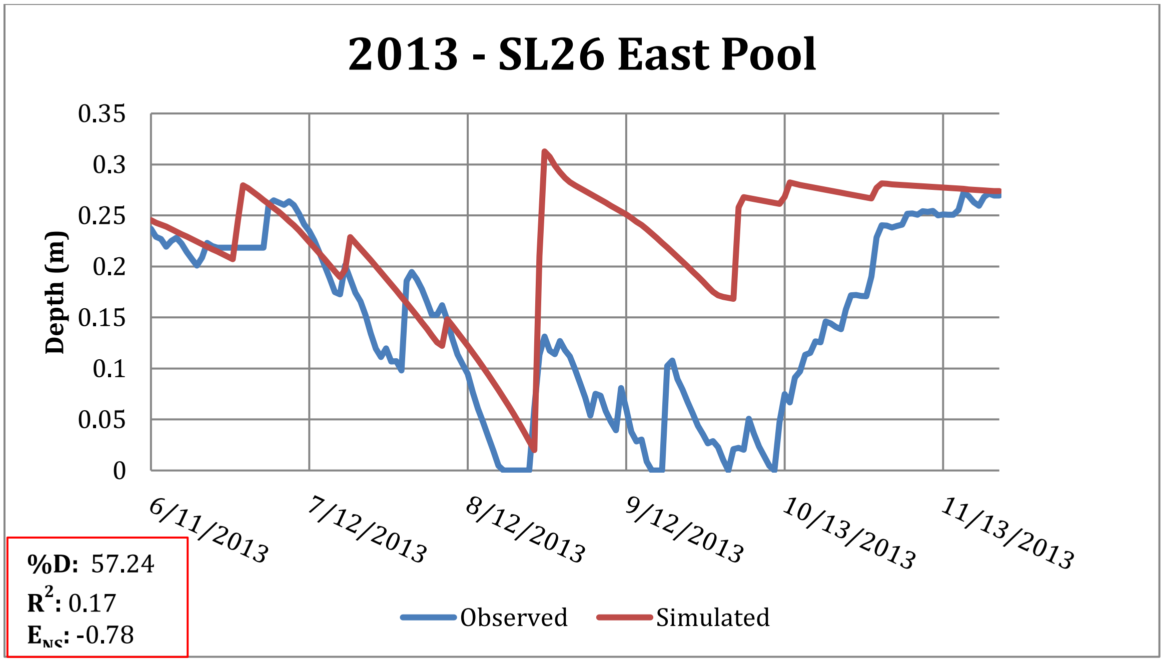


Figure 7: Sideline 26 East Pool Calibration with 2013 data

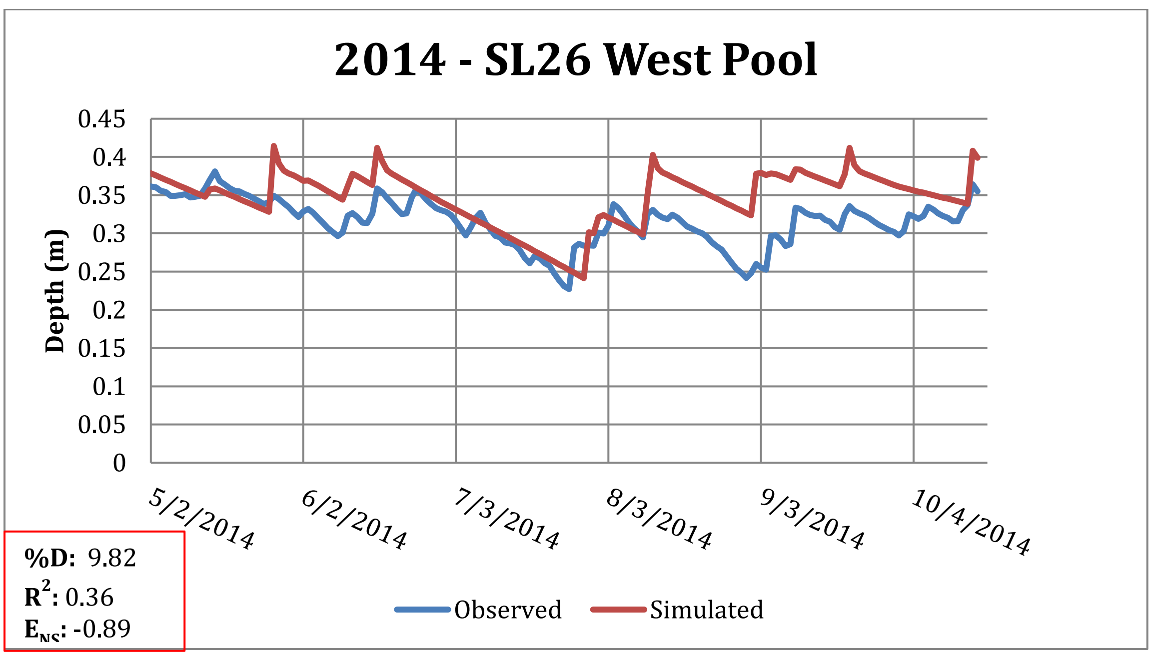


Figure 8: Sideline 26 West Pool Validation with 2014 data

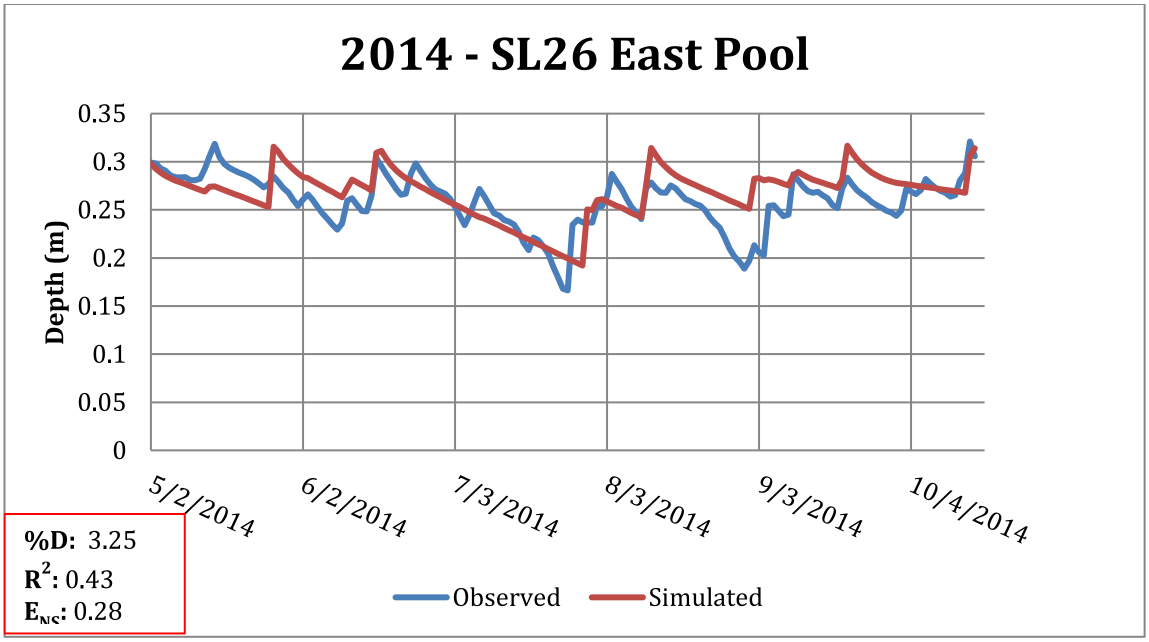


Figure 9: Sideline 26 East Pool Validation with 2014 data

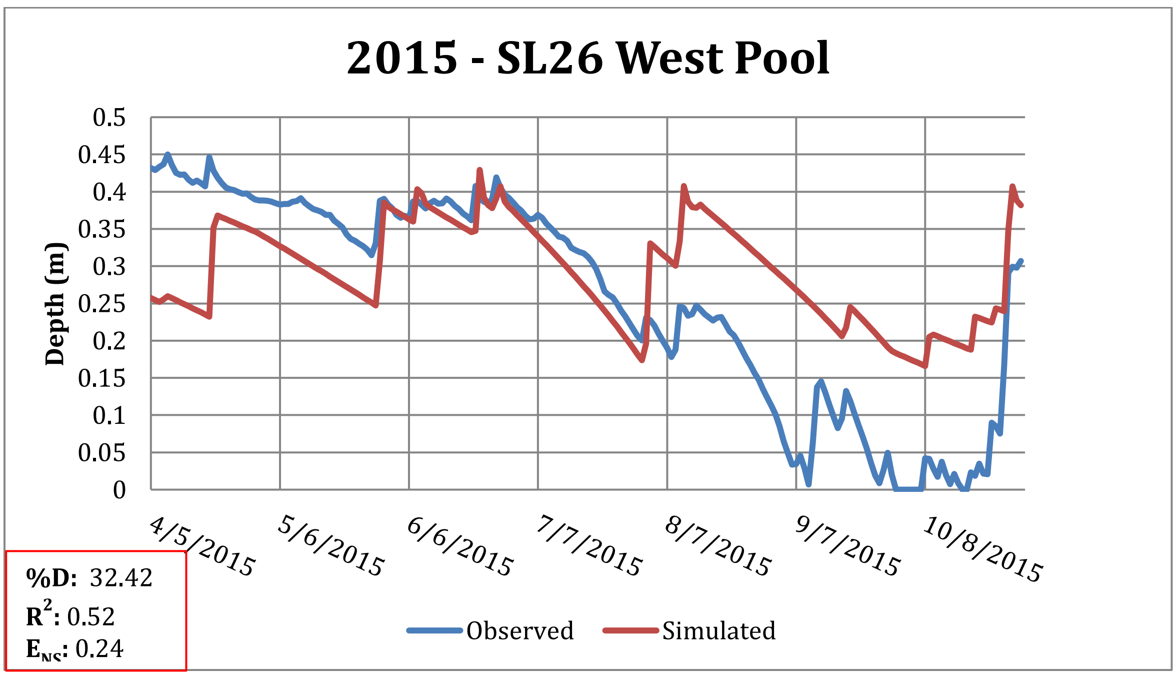


Figure 10: Sideline 26 West Pool Validation with 2015 data

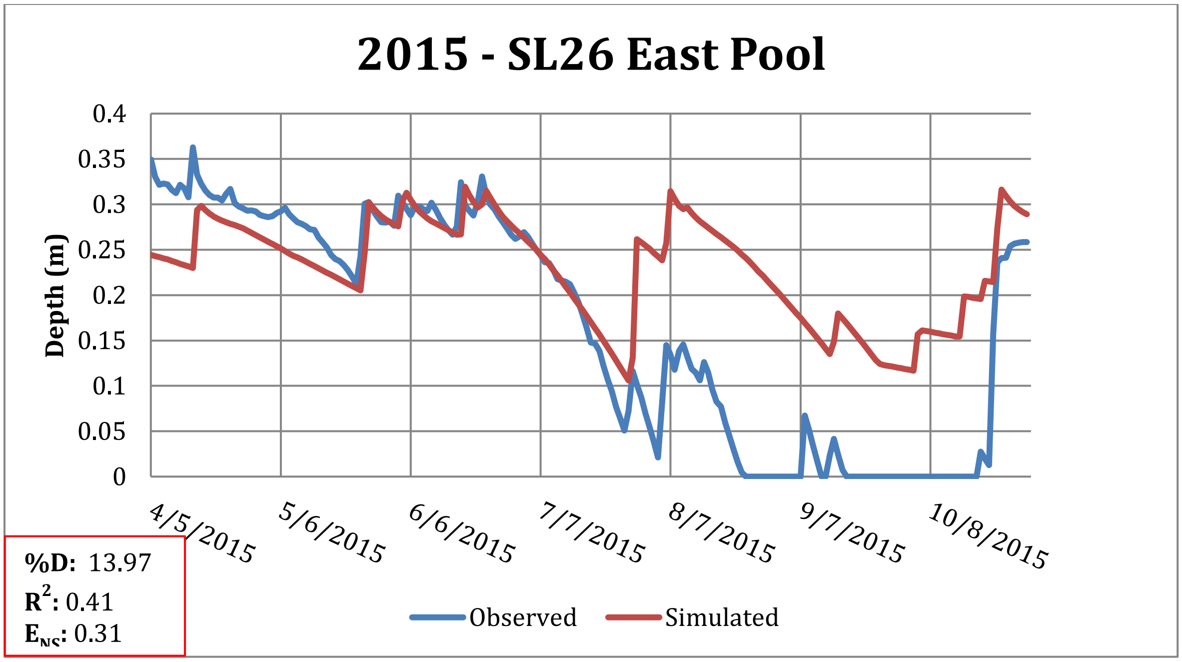


Figure 11: Sideline 26 East Pool Validation with 2015 data

3.1.5 HEC-HMS: Long-term Simulation, Proposed Conditions without Mitigation

Once the model was calibrated and validated, a post-development model was created. 3 hectares of farmland draining to the East Pool of the wetland was urbanized and diverted away from the wetland. A long-term simulation was conducted with the pre-development and post-development models in which 20 years of historical meteorological were used. These simulations used a daily time-step. Since the evaporation from the wetland is represented by fixed monthly values, the discharge to the wetland from the affected drainage area was compared instead of the wetland water level. Figure 12shows a comparison of pre and post development cumulative discharge volume from the disturbed drainage area.

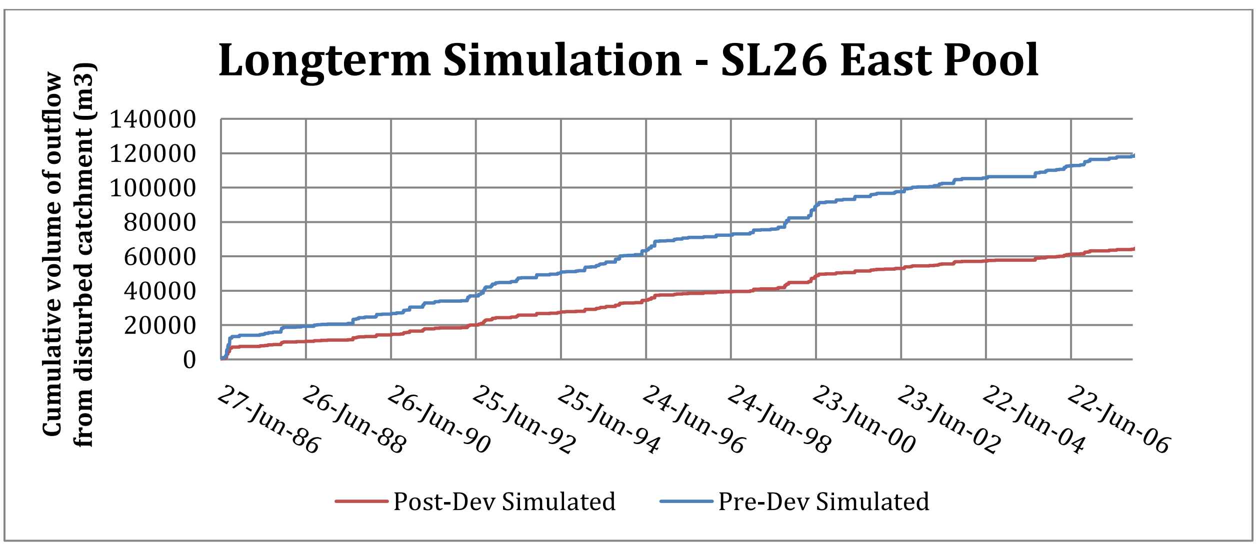


Figure 12: Long-term simulation for Pre-development and Post-development land use condition

3.1.6 HEC-HMS: Long-term Simulation, Proposed Conditions with Mitigation

A third model was created to inform the mitigation measures that would be required to ensure minimal changes to the wetland hydrology as a result of the land-use change. A percentage of the impervious area diverted away from the wetland was re-introduced to the wetland in order to maintain the existing-condition wetland hydro period. It was found that the discharge to the wetland was maintained when 11% of the 3 hectare urbanized catchment was allowed to drain to the wetland. A portion of clean runoff from the roof area of the new development equal to 11% of the 3 hectare urbanized catchment could be directed to the wetland's East Pool to maintain the wetland hydroperiod. Figure 13shows a comparison of the long-term simulations for the pre-development and mitigated post-development cumulative discharge volume from the disturbed drainage area.

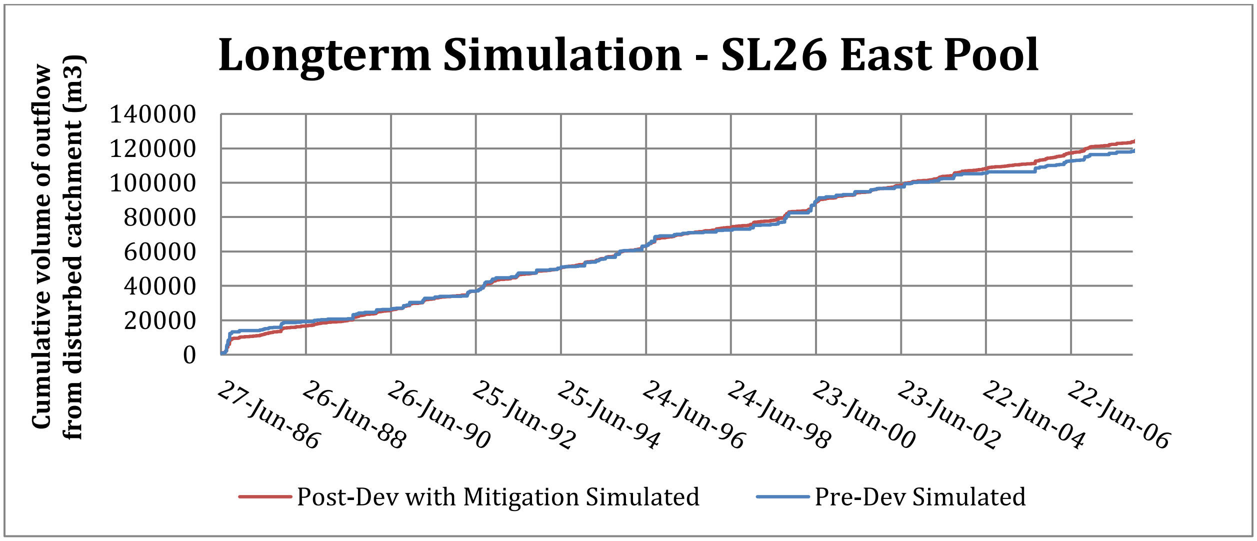


Figure 13: Long-term simulation for Pre-development and Mitigated Post-development land use condition

3.1.7 HEC-HMS: Benefits, Challenges, Recommendations and References

In conducting this case study, a number of benefits, challenges, and recommendations for using HEC-HMS for feature based water balance analysis were identified and summarized below.

Benefits

- User friendly interface, and very intuitive for new users
- Interception storage and crop coefficients can be variable based on time of year
- *Outflow Structures* reservoir method allows for multiple outlets, so percolation losses from the surface storage in the reservoir command can be accounted for separately from the stage-storage-discharge relationship
- The reservoir command allows for monthly evaporation to be accounted for
- Time-series simulation results for all model variables can be easily viewed and compared, which speeds up manual calibration and validation process.
- Quick model run-time
- Many low impact development measures could be easily represented through a combination of subbasin and reservoir commands

Challenges

- When modelling the wetland as a combination of a subbasin (to account for interception storage, underlying soil storage, and to generate runoff from the catchment area) and a downstream reservoir command (to accept flow from external drainage areas, and to account for the stage-storage-discharge relationship of the wetland surface) evapotranspiration must be partitioned between the subbasin and the reservoir commands.
- Evaporation from the reservoir command is represented by fixed monthly values. This introduces a source of error into the simulation, and it also greatly decreases the feasibility of conducting long-term simulations for the wetland water level. To avoid this drawback, long-term simulations could be conducted on the inflows to the wetland; the limitation being that if there are differences in the pre-development and mitigated post-development scenarios, the severity of those differences cannot be assessed with as much certainty as with a comparison of wetland water levels.
- When modelling the wetland as a combination of a subbasin and a downstream reservoir command, a calculation outside of the program is required to represent percolation from the reservoir command. This can become problematic during long-term simulations where monitored groundwater data is not available, especially if the percolation values are highly influenced by down-gradient soil and groundwater storage
- Dynamic interaction with groundwater that is outside of the surface drainage area of the wetland is not possible

Recommendations

- HEC-HMS may be suitable for conducting feature-based water balance analyses on low-medium risk wetlands that are surface-water driven
- Fixed monthly evaporation from the reservoir command is a major limitation when attempting to simulate and compare wetland water levels

References

Bennett, T.H. (1998). Development and application of a continuous soil moisture accounting algorithm for the Hydrologic Engineering Center Hydrologic Modelling System (HEC-HMS). MS thesis. Dept. of Civil and Environmental Engineering, University of California, Davis.

Feldman, A. (2000). Hydrologic Modelling System HEC-HMS Technical Reference Manual . U.S. Army Corps of Engineers Hydrologic Engineering Center, March 2000.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G. (1983). Precipitation-runoff modelling system user's manual, Water-Resources Investigations 83-4238. United States Department of the Interior, Geological Survey, Denver, CO.

Scharffenberg, W (2016). Hy drologic Modelling System HEC-HMS User's Manual. U.S. Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center, August 2016.

US Army Corps of Engineers, Hydrologic Engineering Center. *HEC-HMS.* Retrieved from http://www.hec.usace.army.mil/software/hec-hms/

3.2 Hydrologic Simulation Program – Fortran (HSPF)

3.2.1 HSPF: Background

The US Environmental Protection Agency (US-EPA) HSPF (Hydrologic Simulation Program-Fortran) program has its origin in the Stanford Watershed Model developed by Crawford and Linsley (1966). It can reproduce spatial variability by dividing the basin in hydrologically homogeneous land segments and simulating runoff for each land segment independently. A segment of land can be modeled as pervious or impervious. In pervious land segments HSPF models the movement of water along three paths: overland flow, interflow and groundwater flow. Snow accumulation and melt, evaporation, precipitation and other fluxes are also represented. HSPF uses a continuous simulation approach, and is a highly flexible model that aims to be comprehensive in its representation of watershed hydrology and water quality processes. The potential applications and uses of the model are comparatively large, and include flood control planning and operations, hydropower studies, river basin and watershed planning, storm drainage analyses, water quality planning and management, point and nonpoint source pollution analyses, soil erosion and sediment transport studies, evaluation of urban and agricultural best management practices, fate, transport, exposure assessment, and control of pesticides, nutrients, and toxic substances, and time-series data storage, analysis, and display (AQUA TERRA Consultants, 2011).

Figure 14 presents a conceptual model schematic for HSPF.

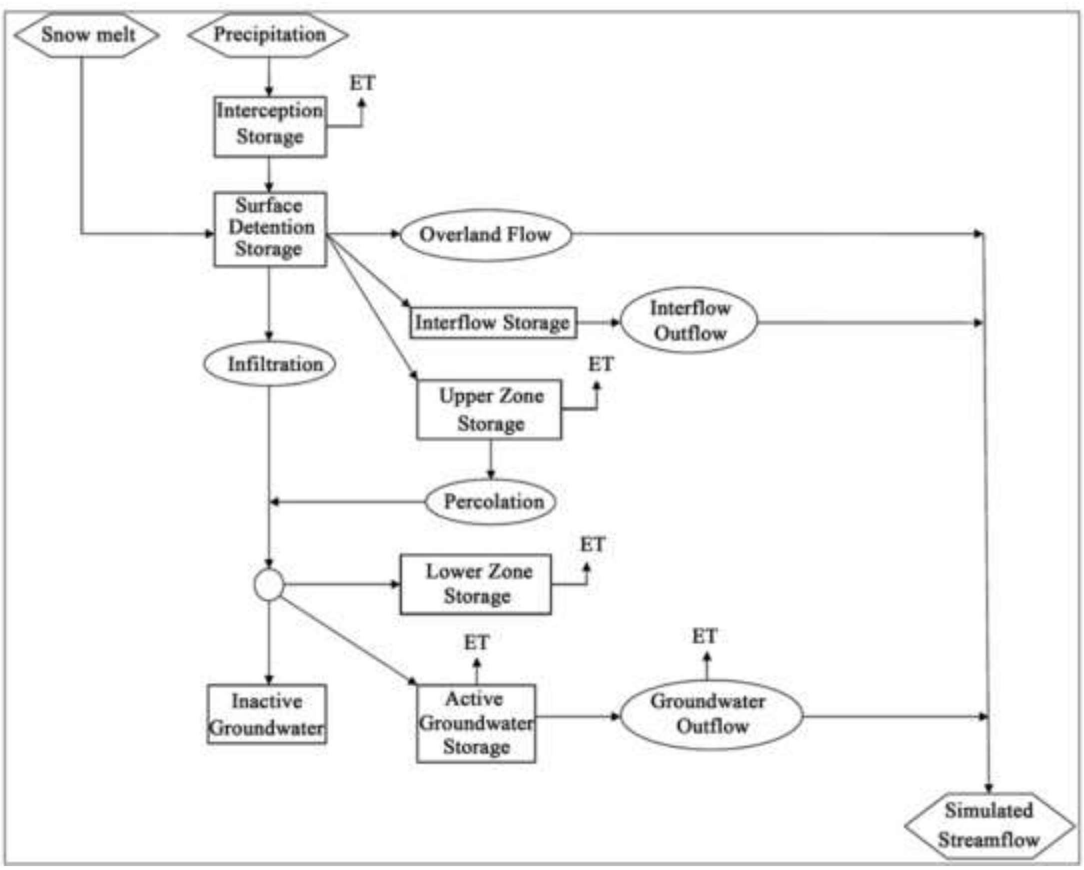


Figure 14: Conceptual Model Schematic for HSPF (Source: Amirhossien et al., 2015)

3.2.2 HSPF: Model Setup, Existing Conditions

The case study area used for evaluation is a wetland at Seaton Sideline 26, which is located in the City of Pickering within the Duffins Creek Watershed. Figure 2 shows the wetland and drainage areas, which were delineated using a 1m by 1m bare earth grid that was generated using LiDAR data from 2014. The wetland is divided into two pools. 2.05 hectares drain to the west pool of the wetland. The west pool drains overland to the east pool. The east pool receives runoff from an additional 7.31 hectares of land, for a total drainage area of 9.36 hectares.

Figure 3 shows the land use within the wetland drainage area, which includes farmland, forest, successional, and wetland. The drainage areas were further separated into these four land use categories, in order to use different parameters for each land use within the model. In particular, the difference in land use was reflected in different values for the interception storage capacity (CEPSC) and the lower zone evapotranspiration (LZETP) parameters.

The soil classification for the entire drainage area to the wetland is a Gleyed Gray Brown Luvisol. A soil description from Agriculture and Agri-Food Canada was used to generate initial parameters for Lower Zone Nominal Storage (LZSN) Infiltration (INFILT) and Upper Zone Nominal Storage (UZSN). In particular, the values for the volume of air in the soil at various pore pressures and the saturated hydraulic conductivity at the various soil horizons in the soil description were used to estimate the LZSN, INFILT, and UZSN parameters in the model.

Initial values for the groundwater recession rate (AGWRC) parameter were first estimated by observing the rate of decline of flow at a flume downstream of the wetland. Initial values for the initial active groundwater storage (AGWS) parameter were first estimated by observing the starting water level at the 2m deep well relative to the 1m deep soil column that was represented by the UZSN and LZSN parameters. Both of these parameters were used as calibration parameters. The initial values for the DEEPFR parameter (fraction of groundwater inflow which will enter deep inactive groundwater and thus be lost from the system as defined in HSPF) were initially set to zero, with the knowledge that they would be one of the main calibration parameters that determine how much moisture is lost from the system.

Figure 4 shows the topography and bathymetry of the wetland, which was generated from a site survey. The elevation information was used to create detailed stage-storage relationships for each of the two major wetland pools. In order to estimate the discharge at each stage, the wetland was modeled in HEC-RAS as two storage areas connected by a broad-crested weir, and discharging over a second broad-crested weir to the downstream channel. Cross-sections were cut at the outlet of each pool using the elevation information, and the cross-section information was used for the weir geometry. An unsteady simulation was performed, with flow rates gradually ramped up from a low flow to a high flow, in order to ensure that the results would have a good spread of stage-discharge information. Equations were fit to the resulting rating curves, so that discharge values could be calculated at each known elevation and storage for each pool. The resulting stage-storage-discharge information was used in two separate FTABLES in HSPF which represent the surface storage at the west pool and the east pool of the wetland. The exact elevation at which each pool begins to discharge, as well as the discharge estimates closest to these elevations were treated as a calibration parameters.

3.2.3 HSPF: Calibration and Validation, Existing Conditions

Figure 5 shows the location of monitoring stations at Sideline 26. There were a set of three wells at four main locations in the wetland, each with a 30cm long screen. One well (SW well) had a screen from +0.05 to -0.25m relative to the surface, another well (1m well) had a screen from -0.7m to -1m relative to the surface, and the third well (2m well) had a screen from -1.7m to -2.0m relative to the surface. The SW well at *Transect 1 - 40m* was used to calibrate the west pool, and the SW well at *Transect 2 – 40* was used to calibrate the east pool. The water levels in the wetland were used for calibration instead of discharge for two main reasons. Firstly, the flume downstream of the wetland became blocked and was circumvented by flow, so there was not enough confidence in the monitored data to use it for calibration. Secondly, the water level in each pool is a variable that can be directly and easily used to assess impact on the ecological functioning of the wetland.

In order to make the calibration process more intuitive, the observed water levels were converted into 'observed' surface storage volumes, so that differences between observed and simulated inputs, outputs, and storages could be more easily conceptualized during calibration. Observed water levels in the 2m wells were used to approximate initial groundwater storage values. Differences in observed water levels between the SW, 1m, and 2m wells were used to gain an understanding of the vertical hydraulic gradients for the monitored periods, and differences in observed water levels at the 1m wells between stations were used to gain an understanding of the horizontal hydraulic gradients for the monitored periods.

Observed data for 2013 was used to calibrate the model. The water level observations were recorded hourly, and converted to a daily average for the purpose of calibration. The model was run with an hourly time step, and daily average output was used for comparison with observed data.

Daily average observed water level was converted to daily average 'observed' storage, and visually compared with simulated daily average storage within the wetland. After achieving a good visual match, the procedure was repeated twice using data from 2014 and 2015 in order to validate the calibration. The initial model calibrations did not produce simulation results that closely matched observed data for the validation years, so the calibration process was iterated until all three years showed good results. All model parameters remained the same between simulations with two exceptions: AGWS (used to specify the initial active groundwater storage at the start of the simulation) and VOL (initial volume of water in the reach/reservoir) were different for each of the three years to account for the different observed water levels at the start of the simulation period for each of the three years.

Table 2 and Table 3 show the main parameters that were modified from initial parameters during the calibration and validation process.

Table 2: HSPF calibration parameters related to Pervious Land Segments

Parameter	Parameter Description	Units	Initial Value	Calibrated Value	Comments
PWAT-PARM2					
LZSN	Lower zone nominal storage	mm	128.2	319	Initially calculated as volume of voids in soil column (minus voids taken up by hygroscopic water) in A and B soil horizon minus 25.4mm for UZSN. Modified during calibration to include voids in C soil horizon (minus voids taken up by hygroscopic water), and to account for calibrated UZSN value
INFILT	Index to infiltration capacity of soil	mm/hr	7	3.3	Modified during calibration to allow for more surface runoff and interflow during higher intensity rainfall events
PWAT-PARM3					
DEEPFR	Fraction of groundwater that becomes inactive	fraction	0	0.73 to 0.8	Last parameter to be modified during calibration, once the other losses (PET fraction and percolation from RCHRES had been selected)
PWAT-PARM4					
UZSN	Upper zone nominal storage	mm	25.4	5	Modified during calibration to allow for more surface runoff and interflow during higher intensity rainfall events
PWAT-STATE1					
AGWS	Initial active groundwater storage	mm	1	1 to 12	Modified during calibration to reflect initial groundwater conditions and allow for difference in simulation between years that had different groundwater conditions

Table 3: HPSF calibration parameters related to Reach-Reservoir commands

Parameter	Parameter Description	Units	Initial Value	Calibrated Value	Comments
HYDR-INIT					
VOL	Initial volume of water in RCHRES	1.0E-6 m^3	n/a	n/a	Modified during calibration in conjunction with AGWS to ensure that initial volume in wetland matches with observed initial volume in wetland
FTABLES					
FTABLE for West Pool RCHRES	Stage-storage-discharge relationship	n/a	n/a	n/a	Because stage-discharge relationships were estimated using hydraulic models rather than measured, the elevation where discharge first occurs needed to be modified to match observed water levels.
FTABLE for East Pool RCHRES					
Additional outlet for West Pool RCHRES	To account for percolation from RCHRES	m^3/s	0	1.04E-05	A harmonic mean of saturated hydraulic conductivity estimates from Agriculture and Agri-food Canada's soil description, as well as a range of saturated hydraulic conductivity estimates from pumping tests conducted in the field were used in conjunction with observed lateral hydraulic gradients to provide estimates of percolation from the wetland pools.
Additional outlet for East Pool RCHRES			0	1.40E-04	
EXT SOURCES					
MultFact of POTEV for West Pool RCHRES	Fraction of PET applied to RCHRES	fraction	0	0.33	In order to calibrate using water level in a RCHRES, a fraction of the evapotranspiration needs to be deducted after the water enters the RCHRES
MultFact of POTEV for East Pool RCHRES	Fraction of PET applied to RCHRES	fraction	0	0.33	

After a good visual match with all three years of data was achieved, three statistical measures were used to compare the goodness of fit between observed and simulated water level: Percent Difference (%D), coefficient of determination (R^2), and Nash-Sutcliffe simulation efficiency (E_{NS}).

Figures 15 through 20 show the calibration and validation results for the two wetland pools.

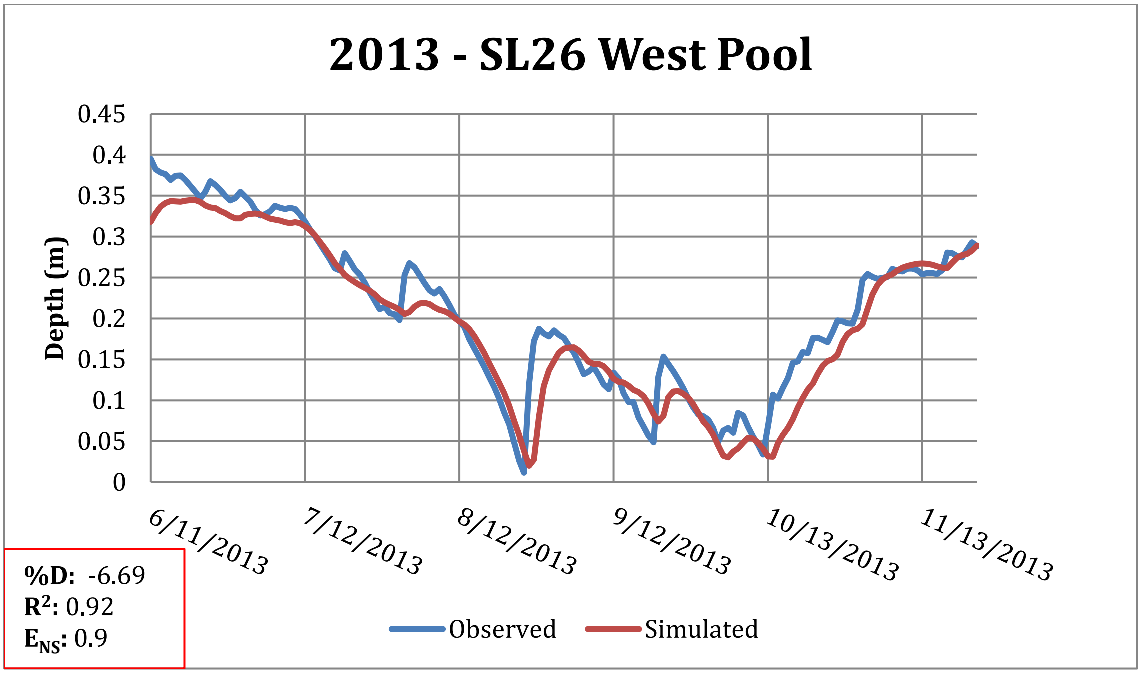


Figure 15: Sideline 26 West Pool Calibration with 2013 data

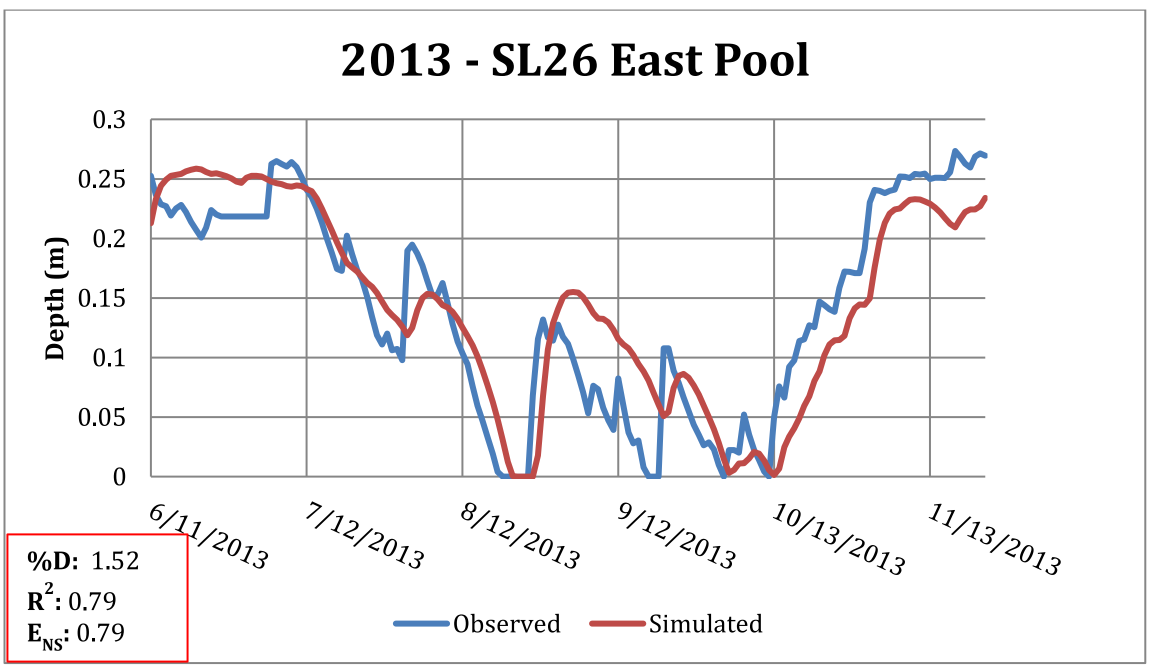


Figure 16: Sideline 26 East Pool Calibration with 2013 data

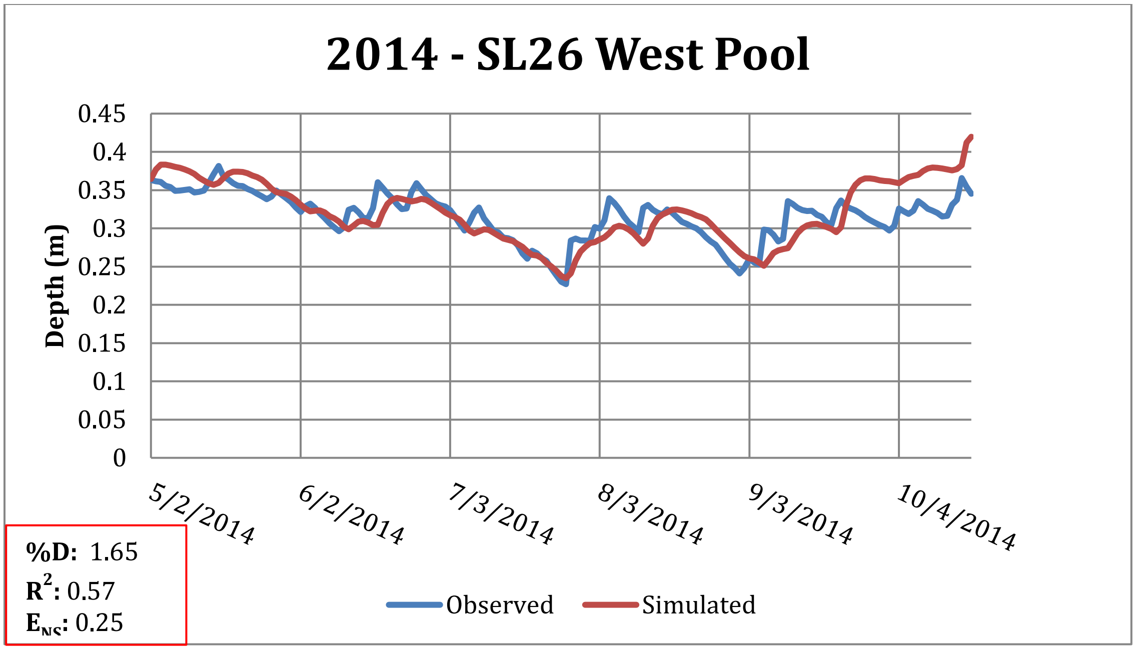


Figure 17: Sideline 26 West Pool Validation with 2014 data

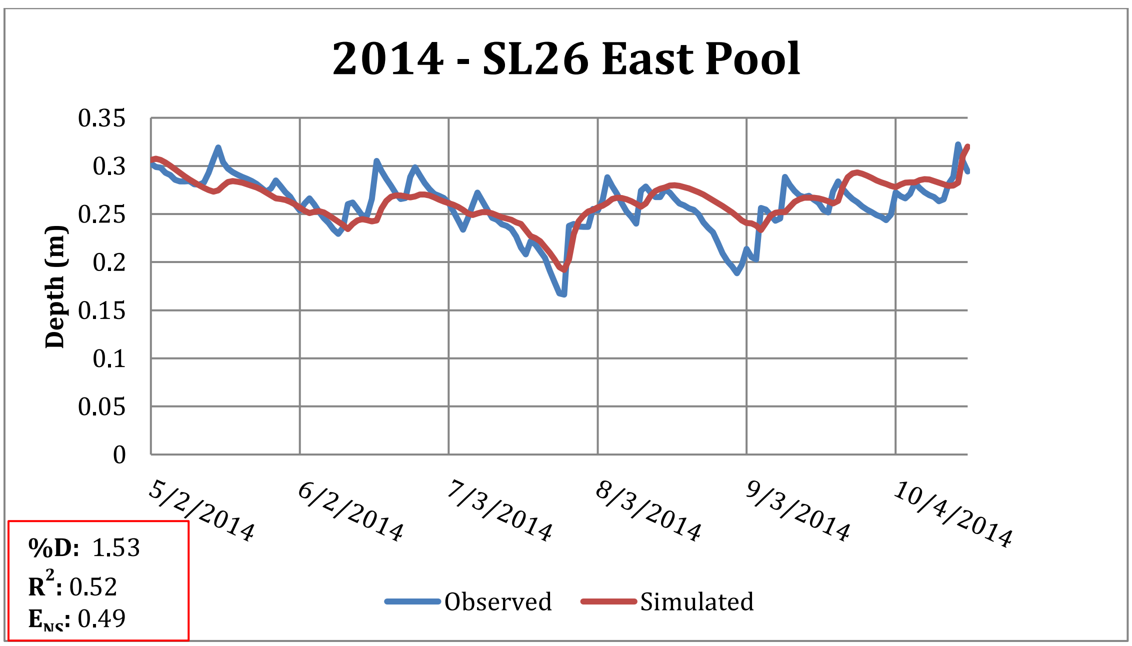


Figure 18: Sideline 26 East Pool Validation with 2014 data

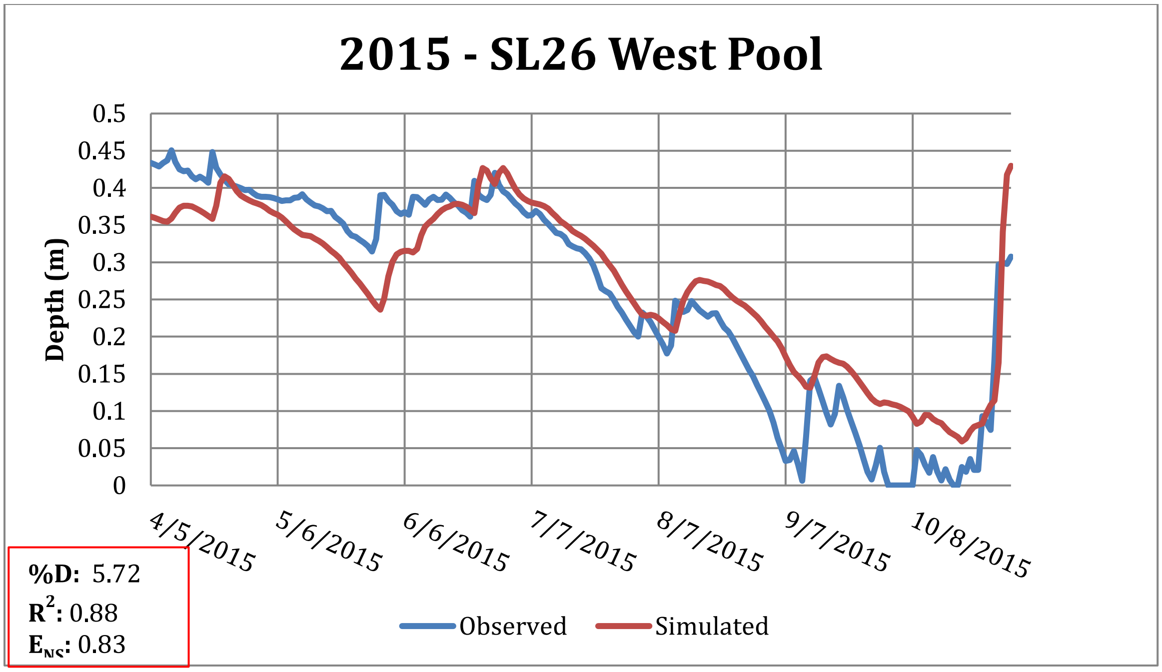


Figure 19: Sideline 26 West Pool Validation with 2015 data

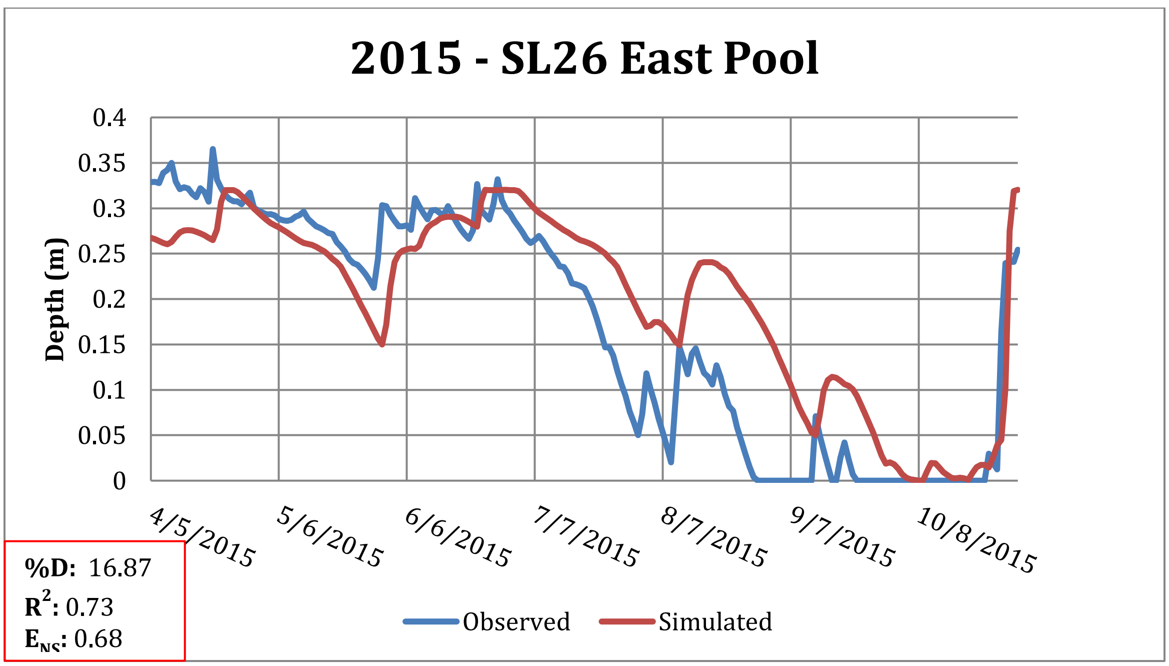


Figure 20: Sideline 26 East Pool Validation with 2015 data

3.2.4 HSPF: Long-term Simulation, Proposed Conditions without Mitigation

Once the model was calibrated and validated, a post-development model was created. 3 hectares of farmland draining to the East Pool of the wetland was urbanized and diverted away from the wetland. A long-term simulation was conducted with the pre-development and post-development models in which

20 years of historical meteorological were used. These simulations used a daily time-step, and the results were compared visually using a running monthly-average, as shown in Figure 21: Long-term simulation for Pre-development and Post-development land use condition.

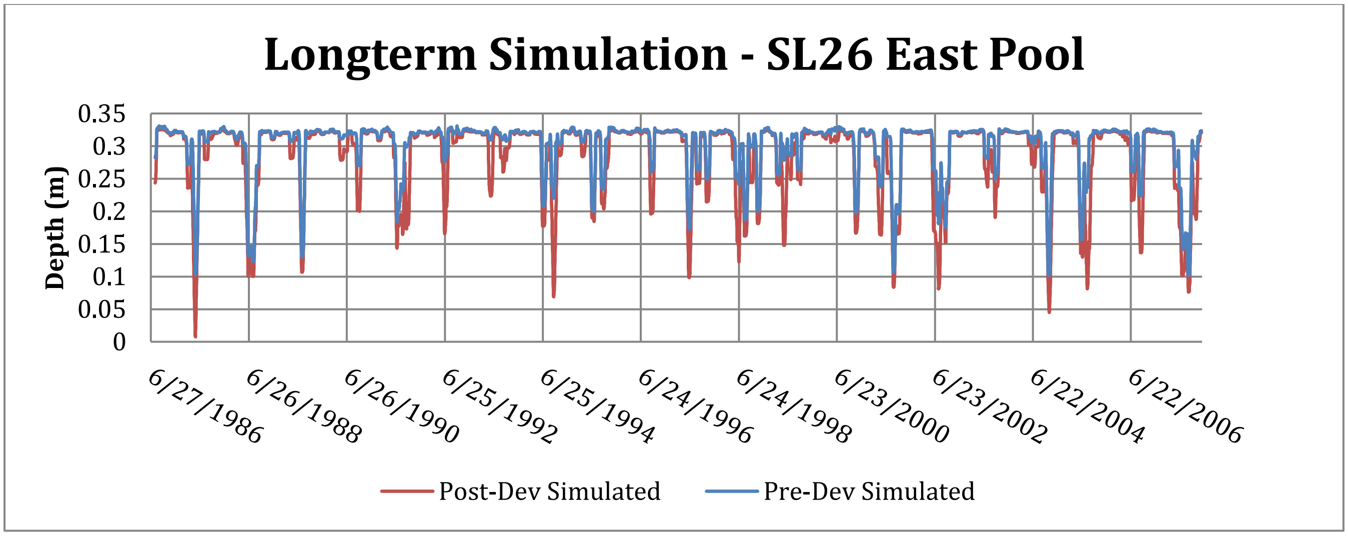


Figure 21: Long-term simulation for Pre-development and Post-development land use condition

3.2.5 HSPF: Long-term Simulation, Proposed Conditions with Mitigation

A third model was created to inform the mitigation measures that would be required to ensure minimal changes to the wetland hydrology as a result of the land-use change. A percentage of the impervious area diverted away from the wetland was re-introduced to the wetland in order to maintain the existing-condition wetland hydro period. It was found that the hydroperiod was maintained when 25.9% of the 3 hectare urbanized catchment was allowed to drain to the wetland. A portion of clean runoff from the roof area of the new development equal to 25.9% of the 3 hectare urbanized catchment could be directed to the wetland's East Pool to maintain the wetland hydroperiod. Figure 22 shows a comparison of the long-term simulations for the pre-development and mitigated post-development scenarios.

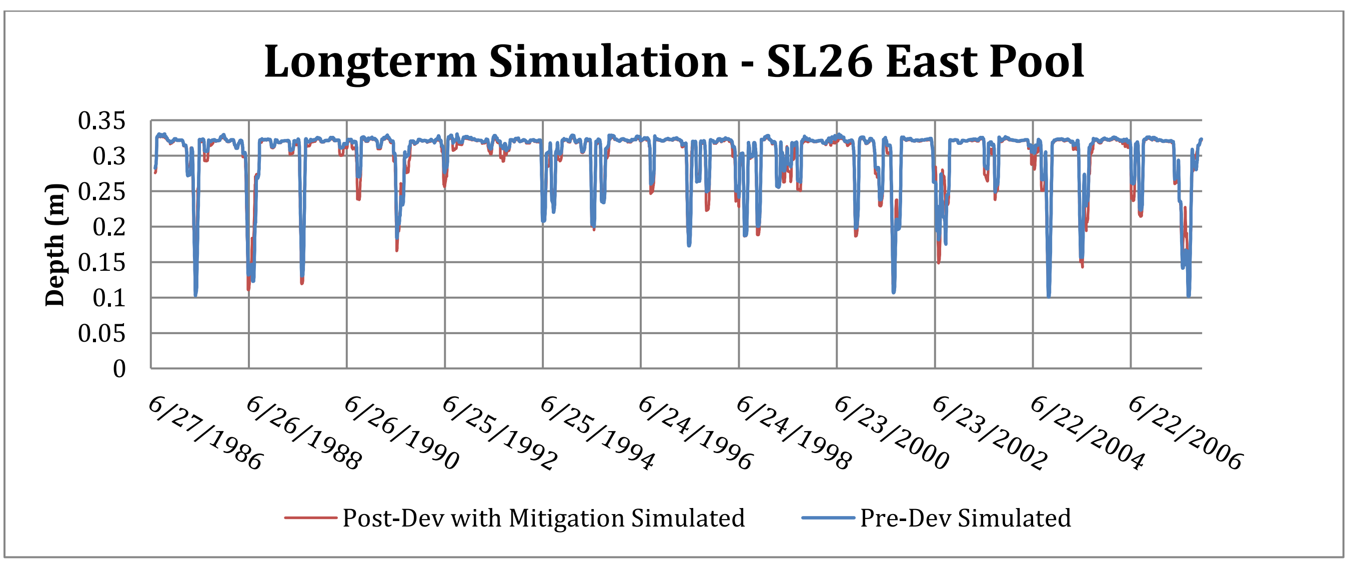


Figure 22: Long-term simulation for Pre-development and Mitigated Post-development land use condition

3.2.6 HSPF: Benefits, Challenges, Recommendations and References

In conducting this case study, a number of benefits, challenges, and recommendations for using HSPF for feature based water balance analysis were identified and summarized below.

Benefits

- The WinHSPF 3.0 interface is helpful for new users to parameterize the model after the User Control Input (UCI) file has been created.
- Many key parameters can be varied monthly
- Time-series simulation results for all model variables can be viewed and compared using Basins, which speeds up manual calibration and validation process.
- Potential Evapotranspiration time-series can be used for both land segments and the reach/reservoir storage-discharge relationships. For modelling of wetlands, it is critical that evapotranspiration can be accounted for after the runoff and/or groundwater discharge enters the reach/reservoir command.
- Shallow water table conditions can be simulated by including the PWAT-PARM6 and PWAT-PARM7 tables, which allow for the water table to rise above groundwater storage and fill upper and lower zone soil storages.
- Reach/Reservoir command allows for multiple outlets, so percolation losses from the surface storage in the reach/reservoir command can be accounted for separately from the stage-storage-discharge relationship
- Quick model run-time
- Many low impact development measures could be easily represented through a combination of land segment and reach/reservoir commands
- BMP Reach Toolkit in Win HSPF 3.0 helps with parameterization of BMP’s for infiltration-based stormwater control practices

Challenges

- Creating an initial UCI file can be time-consuming for new users
- WDMUtil tool for managing the time-series WDM files is not currently available for download on the Aqua Terra Website
- When modelling the wetland as a combination of a pervious land segment (to account for interception storage, underlying soil storage, and to generate runoff from the catchment area) and a downstream reach/reservoir command (to accept flow from external drainage areas, and to account for the stage-storage-discharge relationship of the wetland surface) evapotranspiration must be partitioned between the pervious land segment and the reach/reservoir commands.
- When modelling the wetland as a combination of a pervious land segment and a downstream reach/reservoir command, a calculation outside of the program is required to represent percolation from the reach/reservoir command. This can become problematic during long-term simulations where monitored groundwater data is not available, especially if the percolation values are highly influenced by down-gradient soil and groundwater storage
- Dynamic interaction with groundwater that is outside of the surface drainage area of the wetland must be calculated outside of the program.
- Calibration process can be challenging and time-consuming. In particular, the DEEPFR (fraction of groundwater inflow which enters deep inactive groundwater) has a large influence on

simulation results, and appropriate values of this parameter are highly dependent on the spatial scale of the model and the particular feature of interest.

Recommendations

- HSPF is generally well-suited for conducting feature-based water balance analysis
- Calibration in HSPF using wetland water level is possible, but can be time-consuming
- For wetlands with significant groundwater contribution from outside of the surface-water drainage areas, many calculations external to the model would be required

References

Amirhossien, F., Alireza, F., Kazem, J. and Mohammadbagher, S. (2015). A Comparison of ANN and HSPF Models for Runoff Simulation in Balkhichai River Watershed, Iran. *American Journal of Climate Change*, **4**, 203-216.

AQUA TERRA Consultants (2011). *HSPF Support.* Retrieved from http://www.aquaterra.com/resources/hspfsupport/index.php

United States Environmental Protection Agency, Office of Water (2000). EPA BASINS Technical Note 6 Estimating Hydrology and Hydraulic Parameters for HSPF. United States Environmental Protection Agency, Office of Water, July 2000.

Phillips, Andrew. Rural HSPF modelling Technical Guide. Catchment Science Centre, University of Sheffield. Retrieved from https://www.sheffield.ac.uk/polopoly_fs/1.483500!/file/C2C_HSPF_Rural_Modelling__Technical_Guide.pdf

Bicknell, B., Imhoff, J., Kittle, J., Jobes, T., Donigian, A (2005). HSPF Version 12.2 User's Manual. National Exposure Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Athens, Georgia (July 2005).

3.3 MIKE SHE

3.3.1 MIKE SHE: Background

MIKE SHE is a physically-based distributed model that represents an extension of the Systéme Hydrologique Européen (SHE) model, and is maintained and distributed by DHI. MIKE SHE is flexible in terms of the level of detail in which each hydrologic process is simulated. The choice of the appropriate methodology to use for each of the simulated components is a function of a) the specific questions that need to be addressed by the model, and b) the availability of input data with which to construct and calibrate the model. The model has a long history (relative to other integrated flow models) and is used worldwide.

Figure 23 presents the process schematic for MIKE SHE. With the exception of channel routing, all calculations, including precipitation, unsaturated flow, overland flow, and saturated flow are calculated on the same (uniform) grid basis. MIKE SHE links to MIKE-11, DHI's 1D hydraulic model, for channel routing. Table 4 summarizes the major model features in MIKE SHE

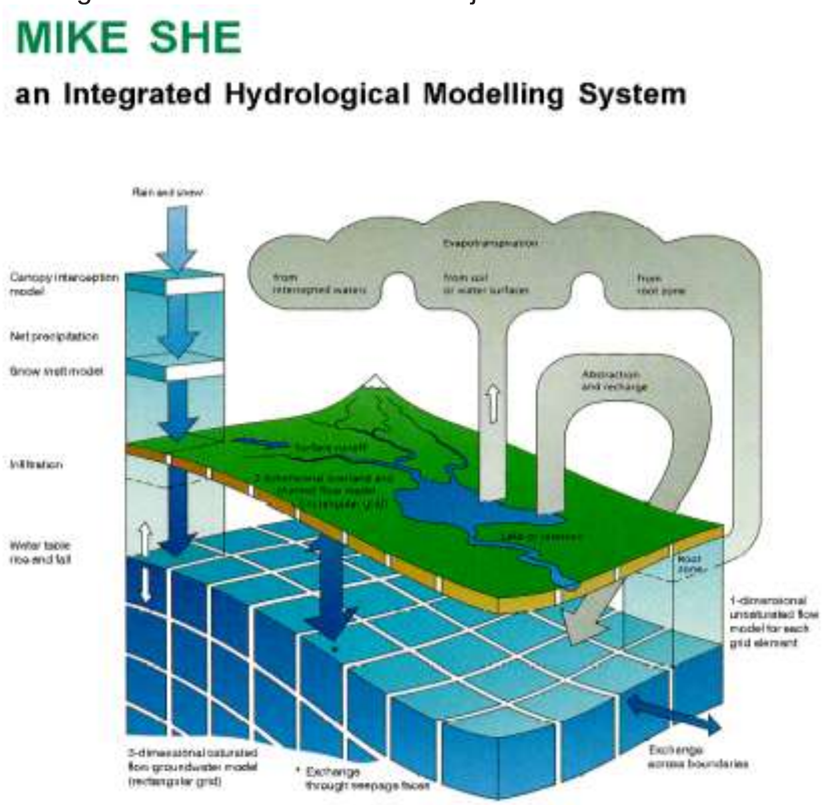


Figure 23: MIKE SHE Process Schematic (Source: DHI, 2009a)

Table 4: MIKE SHE Model Features

Model Features	MIKE SHE
Model Type	Physically-based distributed parameter/lumped parameter
Simulation Type	Continuous/ single-event
Precipitation	Multiple/single hyetograph

Snow Melt	Modified Degree-day approach
Evapotranspiration	Vegetation-based ET (LAI/Rooting Depth)
Infiltration	Fully Richards equation
	Gravity Flow equation
	Two-Layer Water Balance plus Green-Ampt for dry soil condition
Overland Flow	2D diffusive wave approximation/lumped sub-catchment-based
Subsurface Soil Water Flow	1D unsaturated flow
Channel/Reservoir	1D fully dynamic wave approximation
	1D diffusive wave approximation
	1D kinematic wave flow
	Muskingum /Muskingum-Cunge Routing
Groundwater Flow	3D groundwater flow/Linear Reservoir Approach
GIS interface	Accept GIS format data including point/contour/polygon/polyline/ASCII

Applications of the MIKE SHE model have a very long publication record including the recent work of Vazquez et al. (2008), Hansen et al. (2007) and Thompson et al. (2004). Additionally, MIKE SHE has consistently ranked high in a number of model comparison studies including Gordon et al. (2005), Weber et al. (2004) and Camp Dresser & McKee (2001). Because the model is proprietary, the source code is not available. The model is well-documented and actively being maintained and updated. DHI, the developers of MIKE SHE, also provide numerous training courses on their software at locations around the world. MIKE SHE can be purchased online at: www.mikepoweredbydhi.com. The cost of the code varies depending on the options the user wishes to include. Prices range from approximately CAD $14,160 for government agencies to CAD $17,700 for standard commercial use for a perpetual license that includes the first year of technical support and upgrades. While the perpetual license does not time-out, an annual service and maintenance fee is required after the first year in order to continue receiving technical support and software updates. The annual cost of the service agreement is approximately CAD $5,000.

3.3.2 MIKE SHE: Model Setup, Existing Conditions

The case study area used for evaluation is Seaton Sideline22 Wetland area, which is located in City of Pickering within Duffins Creek watershed. Total drainage area is 17.34ha, and wetland pool area is 0.58ha. A1-m LiDAR map (Figure 24) shows the topography of the area. In the study area land cover is dominated by agricultural fields and wood areas (see Figure 25), and soil is dominated by sandy loam/loam. An existing regional groundwater model (MODFLOW) was available covering most of TRCA's jurisdiction. Table 5: MIKE SHE data sourcesTable 5 summarizes the available data collected for this study.

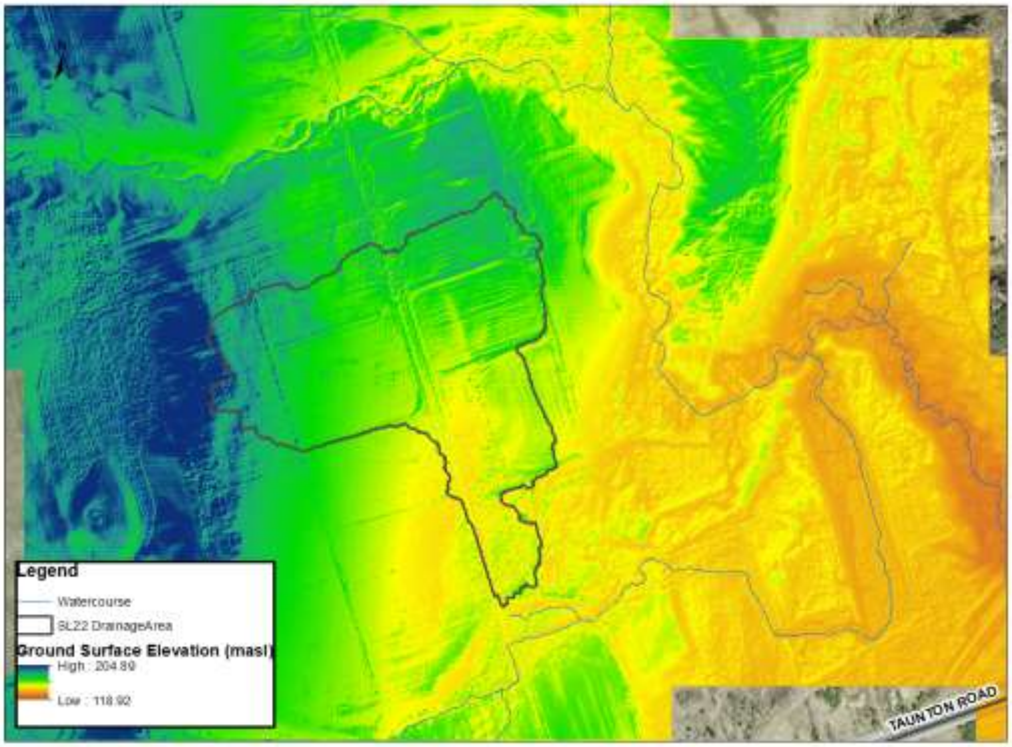


Figure 24: 1-m LiDAR Data in Seaton Sideline 22

Figure 25: Land use map of Seaton Sideline 22

Table 5: MIKE SHE data sources

Data Type	Data Sources
Topography	10-m DEM, 1-m LiDAR, wetland bathymetry
Climate data	5-min precipitation, temperature, and daily Potential ET (2013 – 2015) estimated using Hargreaves Equation
Land use	TRCA Existing Land use, and Land use for Post Development
Soil data	Detailed Soil Database from Agriculture and Agri-Food Canada
Channel	TRCA water-course layer and cross-sections cut from 1-m LiDAR data
Groundwater Model	Import from broader regional groundwater model provided by Oak Ridges Moraine Groundwater Program
Water Level Monitoring	1-hr water level data at 0m, -1m and -2m (reference to ground surface) within/near wetland area (2013 – 2015)

Model Domain

In order to have proper groundwater boundary conditions, a regional MIKE SHE model was first built and initially calibrated against observed water levels and then a local-scale MIKE SHE model was built using extracted groundwater boundaries from the regional model. shows the regional model domain and local-scale model domain. Regional model has 100m by 100 grid cell size, and local-scale model has 10m by 10m grid cell size. Table 6 summarizes the processes included in the model and approaches associated to each process.

Table 6: MIKE SHE model process approaches

Model Process	Approach
Precipitation	5-min hyetograph
Snow Melt	Modified Degree-day approach
Evapotranspiration	Kristensen and Jensen, Vegetation-based ET (time varying LAI/Rooting Depth)
Unsaturated flow	1D Fully Richards equation
Overland Flow	2D diffusive wave approximation of the St. Venant equations of flow.
Channel/Reservoir	1D fully dynamic wave approximation of the St. Venant equations of flow.
Groundwater Flow	3D Finite Difference implementation of Darcy's equation.

Climate

For calibration and validation of the model, simulation period was used for this study is year of 2013 – 2015, and year of 2013 was used as calibration period and years of 2014 and 2015 were used for validation/verification periods. As with any hydrologic model, climate data is a critical input. Climate data from the TRCA climate station (HY009) was used to represent the climate for the study area. Available data fields are maximum/minimum 5-min temperature, 5-min precipitation. Daily potential evapotranspiration rates were generated by Hargreaves potential evapotranspiration method (Hargreaves et al, 1985). This method considers daily temperature maximum and minimum as well as daily solar radiation to compute an estimate of potential evapotranspiration.

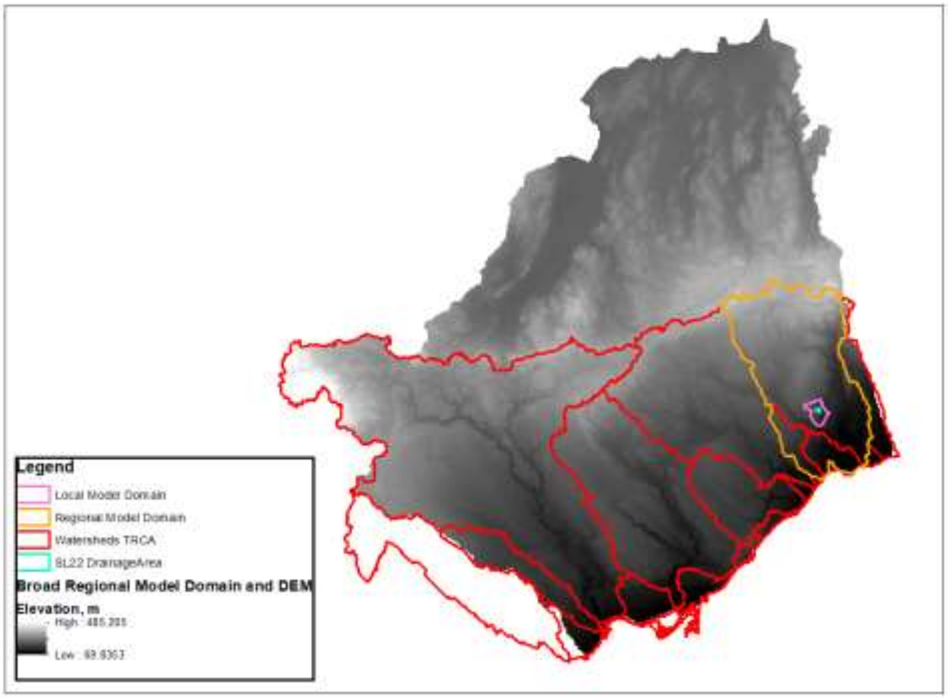


Figure 26: MIKE SHE Regional Model Domain and Local-scale Model Domain

Land use

Land use is used within hydrologic models to consider the effects of the land surface on hydrologic processes such as overland flow, infiltration, evapotranspiration and unsaturated soil zone processes. Based on the land use categories and TRCA standard Manning's n values shown in Table 7, a spatial distribution of overland roughness was generated. These coefficients were then adjusted during the calibration process. Land use data are also used to generate vegetation-specific datasets, specifically the leaf area index (LAI) and the rooting depth. LAI has significant seasonal variation, and it normally reaches a lower limit during winter time and an upper limit during summer time with full leaf cover. No specific information is available for LAI in the study area, thus values from scientific literature (Scurlock et al., 2001) and professional judgement were used in the model. MIKE SHE utilizes a rooting depth parameter to represent the maximum depth of vegetation roots. Significant seasonal variations in the rooting depth are typical for annual and deciduous plants, whereas for many perennial and evergreen plants, rooting depth values remain relatively constant throughout the year. The primary function of the rooting depth specification in MIKE SHE is in establishing the depth to which plants can remove water from the subsurface for transpiration. Specific rooting depth values were not available for the study area, therefore the values used in the model represent literature values for similar vegetation, climate, and soil conditions (Schenk and Jackson, 2003).

Table 7: MIKE SHE catchment parameters by land use type

Land Use Type	Manning's n Value
Farm	0.08
Meadow	0.05
Road	0.025
Wetand	0.035
Forest	0.08

Soil

The materials present at the ground surface play a critical role in partitioning precipitation into runoff and infiltration. To represent these materials, either soils or surficial geology mapping is used in hydrologic investigations. For this study, soil data is from detailed Soil Database from Agriculture and Agri-Food Canada, and it includes soil horizon, soil texture, saturated conductivity, water contents at different pressure levels.

Stream Network

MIKE SHE relies on the MIKE 11 1D hydraulic model to represent the stream network. The MIKE SHE/ MIKE 11 linkage uses a two-way exchange to collect overland flow, calculate exchange flux between the surface and groundwater systems, and route streamflow downstream. The stream network included in the model included the major rivers and tributaries in the local-scale model. In total, 14 branches are included, and are shown in Figure 27: MIKE 11 1D River network. Cross sections were extracted from the 1 m LiDAR with 30m spacing in order to capture the conveyance of those complexes. In total, 372 cross sections were used in the model.

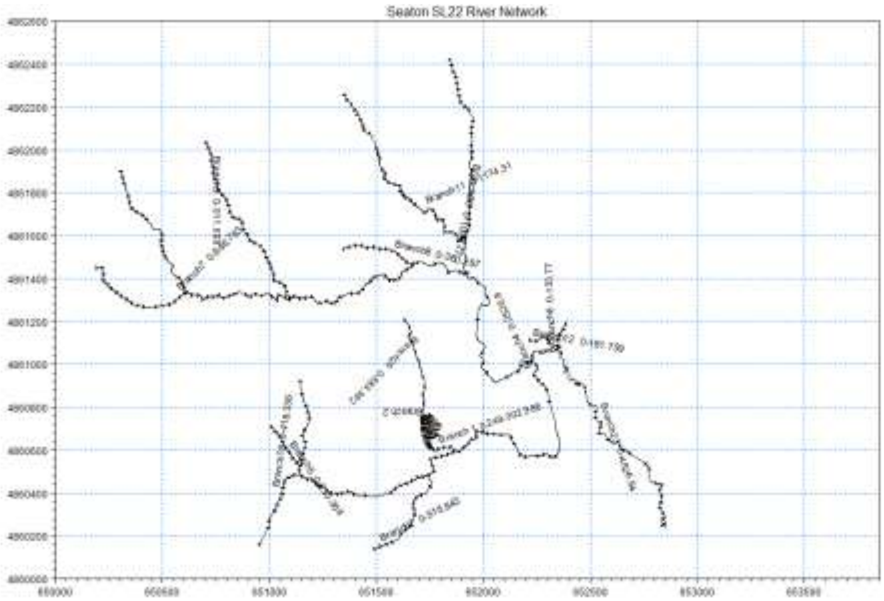


Figure 27: MIKE 11 1D River network

Groundwater

To simulate the groundwater flow system, the properties of the subsurface materials (e.g., hydrostratigraphic layer elevations, hydraulic conductivity distributions) must be specified. All saturated zone properties for the MIKE SHE model were directly taken from existing regional MODFLOW model provided by Oak Ridges Moraine Groundwater Program. This includes layer elevations, hydraulic conductivities, specific storage and specific yield values. As mentioned in Model Domain section, a regional MIKE SHE model was first developed and initially calibrated. For local-scale model, the initial groundwater heads and external boundary conditions were extracted from regional MIKE SHE model.

3.3.3 MIKE SHE: Calibration, Existing Conditions

There are nine water level monitoring wells installed within/near wetland pool area (see **Figure 28**), and water levels were collected at 0m, 1m and 2m below ground surface with 5-min interval for 2013, 2014 and 2015. The year of 2013 was used as calibration period, and the years of 2014 and 2015 were used as validation period.

Figure 28: Location of water level monitoring wells at Sideline 22

When working with a highly parameterized model like MIKE SHE, it is critical to identify which parameters are most sensitive so that the calibration effort can be focused on a subset of the available model parameters. An additional consideration is the degree to which a given parameter is known. For those parameters that are well-constrained by measurements or detailed studies there is less justification for making adjustment. On the other hand, some parameters are based on limited or no site-specific information or are known to have a wide range of reasonable values. For the latter group of parameters, there is significantly more leeway with which to make adjustments. For all parameters, however, it is important to consider the upper and lower bounds of reasonable values to ensure that all model parameter values remain realistic. Table 8summarizes the major calibration parameters in MIKE SHE model.

Table 8: List of parameters adjusted during MIKE SHE calibration process

Model Parameter	Description
Detention Storage	This parameter is used to limit the amount of runoff that the model produces as well as control the timing of runoff relative to precipitation. The parameter also has an indirect effect on infiltration and ET

Riverbed Leakage Coefficient	This parameter regulates the exchange of water between the groundwater and channel flow components of the model.
Soil Moisture Contents	This set of parameters influences the amount of ET, infiltration, and groundwater recharge and indirectly affects the timing and magnitude of runoff.
Saturated Hydraulic Conductivity	This parameter controls the infiltration rate and indirectly affects the rate of groundwater recharge, ET, and runoff.
Manning's Roughness	This parameter controls the timing and magnitude of runoff.
Horizontal/Vertical Hydraulic Conductivity	This set of parameters controls the groundwater flow rate and direction, and interactions with rivers, soils and overland flow.

During simulation, MIKE SHE generates calibration plots at each selected calibration locations, and also produces calibration statistics for each plot with available observation data. Table 9 lists available statistics generated in MIKE SHE calibration plot, and Figures 29 through 32 show calibration plots.

Table 9: MIKE SHE statistical performance metrics

Statistics	Description
ME	Mean Error
MAE	Mean Absolute Error
RMSE	Root Mean Square of Error
STDres	Standard Deviation of Residual (Error)
R(Correlation)	Correlation Coefficient
R2(Nash_Sutcliffe)	Nash Sutcliffe Correlation Coefficient

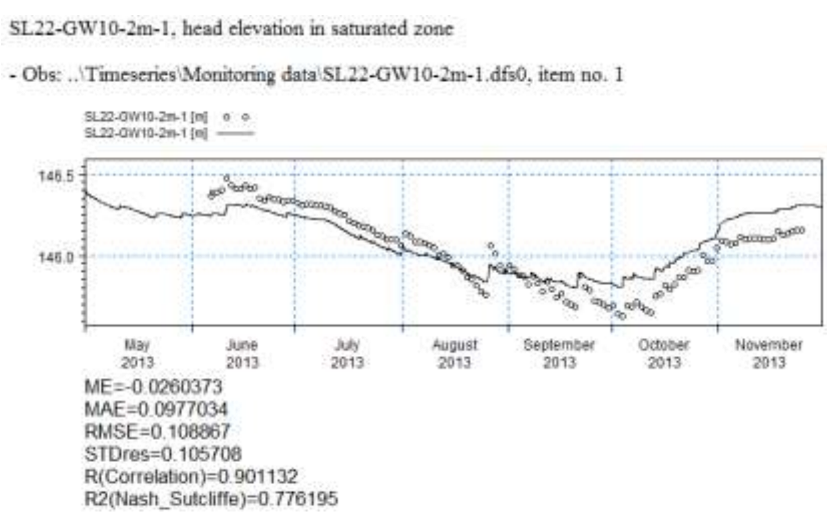
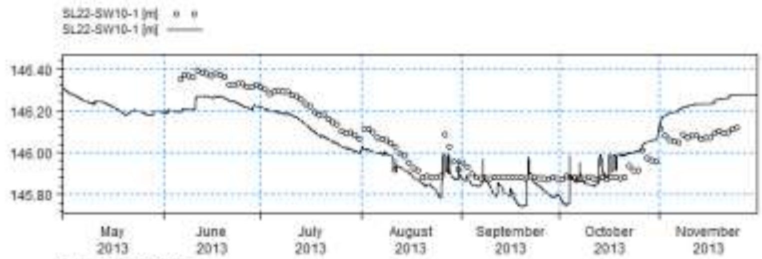


Figure 29: Sideline 22 calibration with 2013 data (1)

SL22-SW10-1, head elevation in saturated zone

- Obs: ..\Timeseries\Monitoring data\SL22-SW10-1.dfs0, item no. 1

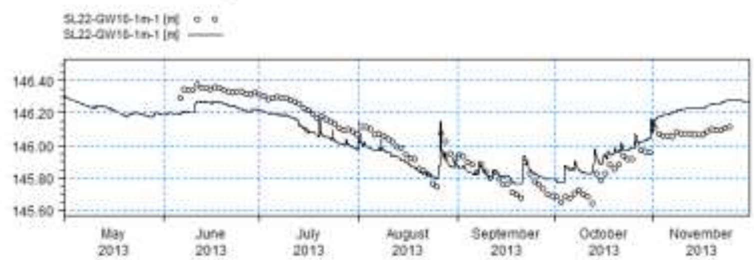


ME=0.0280615
MAE=0.0866865
RMSE=0.0955888
STDres=0.0913771
R(Correlation)=0.854547
R2(Nash_Sutcliffe)=0.688697

Figure 30: Sideline 22 calibration with 2013 data (2)

SL22-GW10-1m-1, head elevation in saturated zone

- Obs: ..\Timeseries\Monitoring data\SL22-GW10-1m-1.dfs0, item no. 1

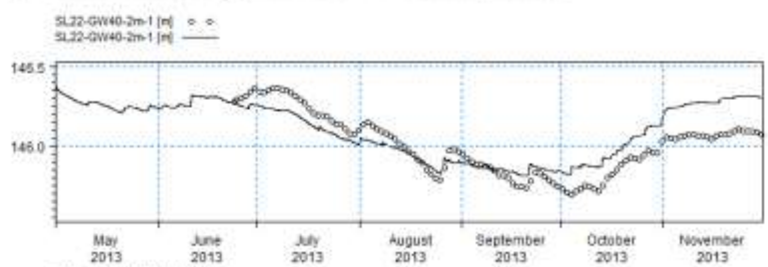


ME=-0.00248879
MAE=0.092044
RMSE=0.101217
STDres=0.101187
R(Correlation)=0.883944
R2(Nash_Sutcliffe)=0.772946

Figure 31: Sideline 22 calibration with 2013 data (3)

SL22-GW40-2m-1, head elevation in saturated zone

- Obs: ..\Timeseries\Monitoring data\SL22-GW40-2m-1.dfs0, item no. 1



ME=-0.0441166
MAE=0.10505
RMSE=0.122955
STDres=0.114767
R(Correlation)=0.797729
R2(Nash_Sutcliffe)=0.570157

Figure 32: Sideline 22 calibration with 2013 data (4)

3.3.4 MIKE SHE: Validation, Existing Conditions

After calibration, next step is to validate the model against different set of monitoring data with calibrated parameters. The years of 2014 and 2015 were used as validation period. Figure 33 through Figure 36 show the validation plots.

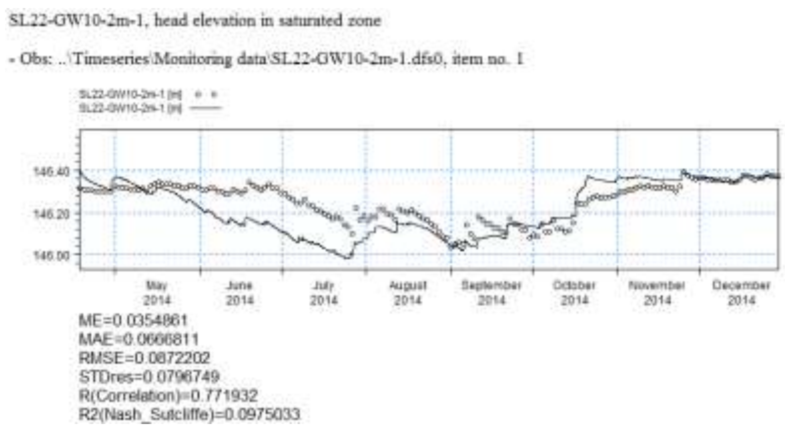


Figure 33: Sideline 22 validation with 2014 data (1)

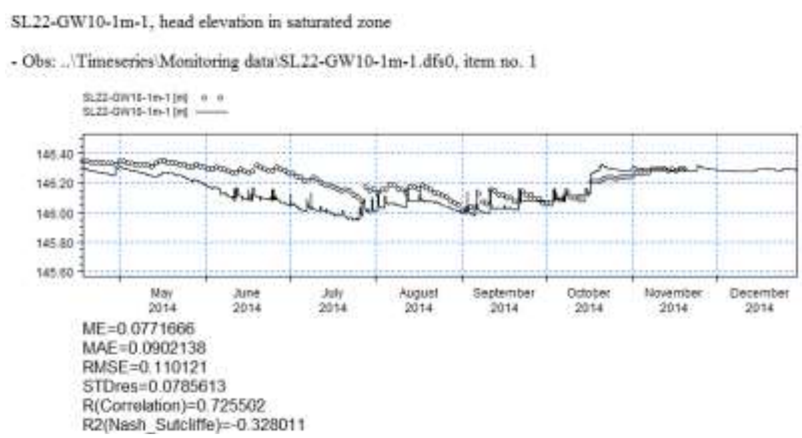


Figure 34: Sideline 22 validation with 2014 data (2)

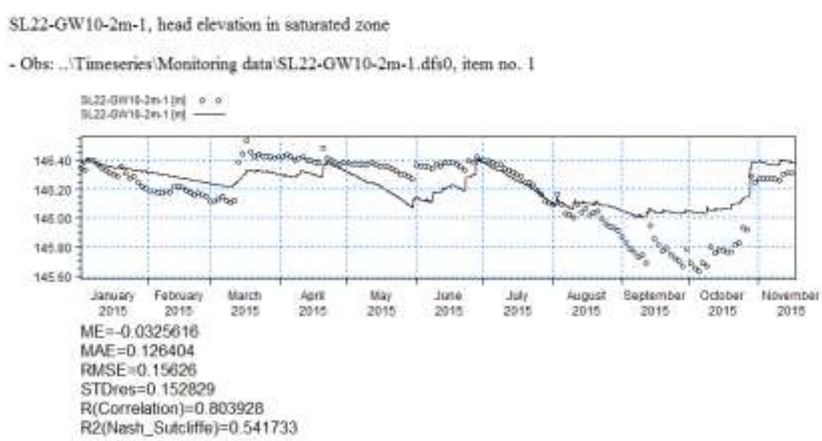


Figure 35: Sideline 22 validation with 2014 data (3)

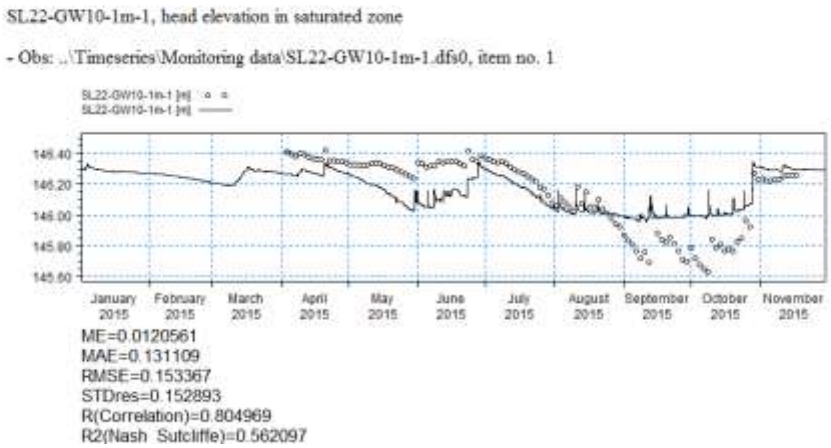


Figure 36: Sideline 22 validation with 2014 data (4)

3.3.5 MIKE SHE: Long-term Simulation, Proposed Conditions without Mitigation

The proposed development area in SL22 is North Division which is shown in Figure 37: Location of Proposed Development Area - North Division. The assumption is 60% of North Division is paved surface but there is no grading change, i.e. ground surface in North Division remained unchanged.

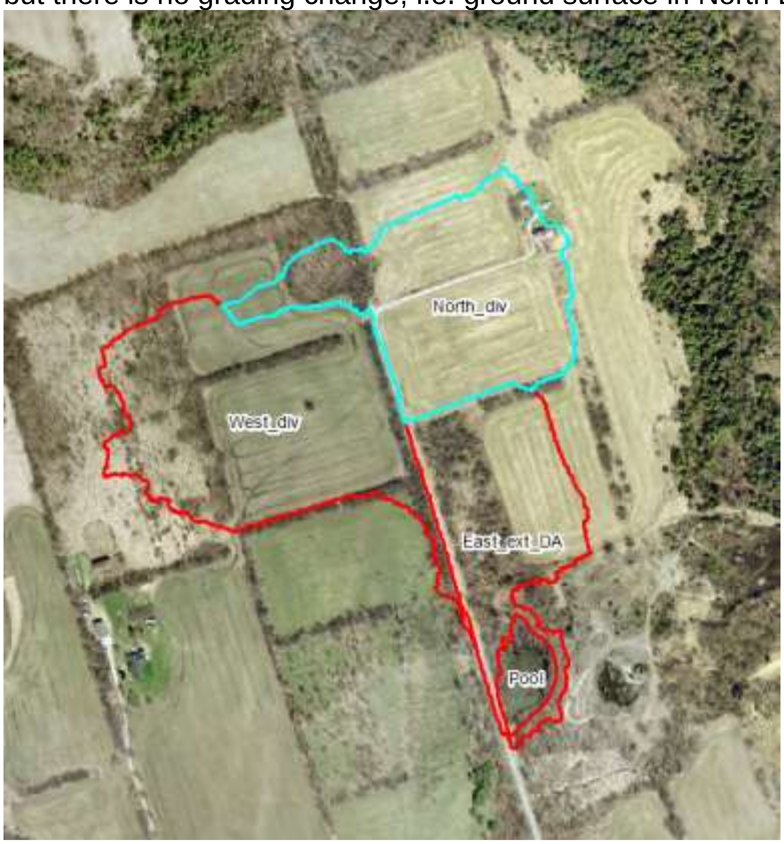


Figure 37: Location of Proposed Development Area - North Division

MIKE SHE's Ponded Drainage Feature was used to implement development area, and this feature was developed to support green infrastructure such Low Impact Developments (LIDs) and Sustainable Urban Drainage (SUDs). MIKE SHE's Ponded Drainage Feature allows directly drain storm water to internal depressions, boundaries and streams and paved surface areas was integrated into reduced surface-subsurface leakage function.

A long term simulation was carried out for period of 6/1/1996 – 12/30/2009 (13 years) without mitigation measure for post condition.

3.3.6 MIKE SHE: Long-term Simulation, Proposed Conditions with Mitigation

A long term simulation was carried out for period of 6/1/1996 – 12/30/2009 (13 years) with mitigation measure for post condition by diverting surface runoff from paved surface directly to wetland using MIKE SHE Ponded Drainage Feature. Figure 38 shows the diverted flow from paved surface in North Division to wetland, Figure 39 shows the comparison of water levels between No Mitigation and With Mitigation and Figure 40 shows the comparison of wetland depth and extent between No Mitigation and With Mitigation.

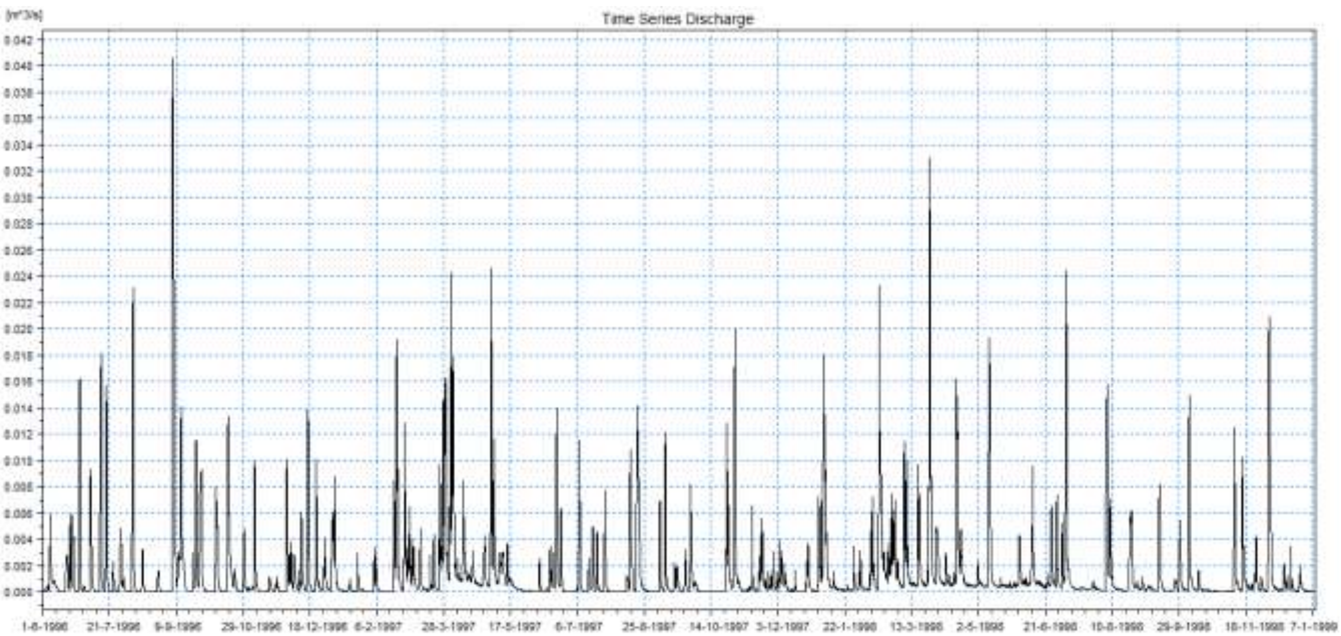


Figure 38: Diverted flow from North Division to Wetland

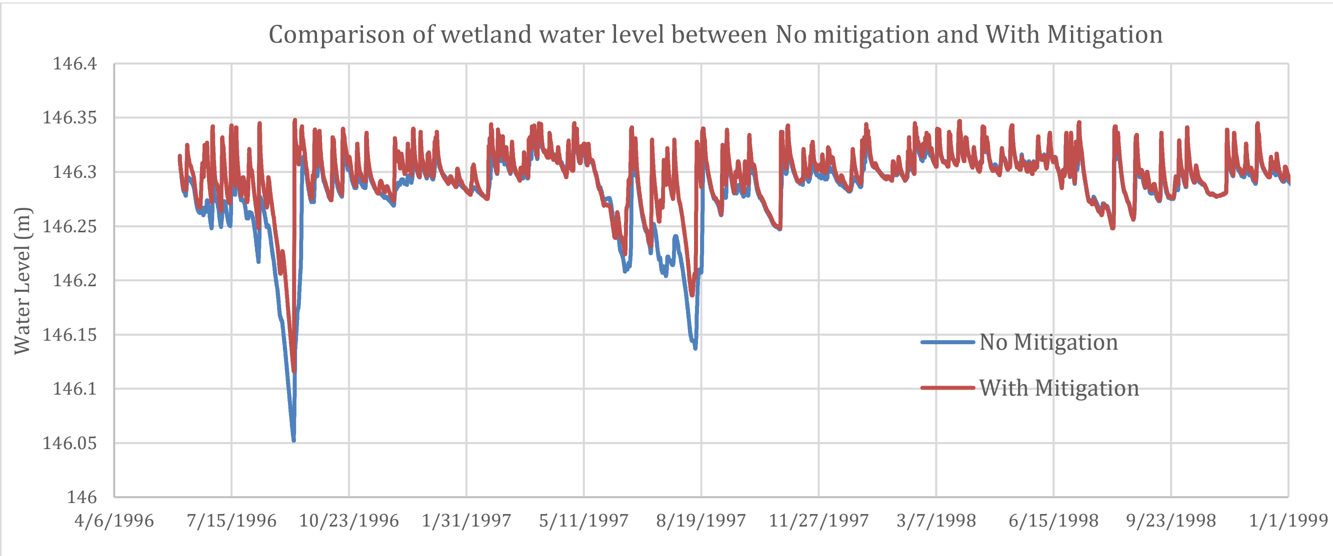


Figure 39: Comparison of wetland water levels between No Mitigation and With Mitigation scenarios

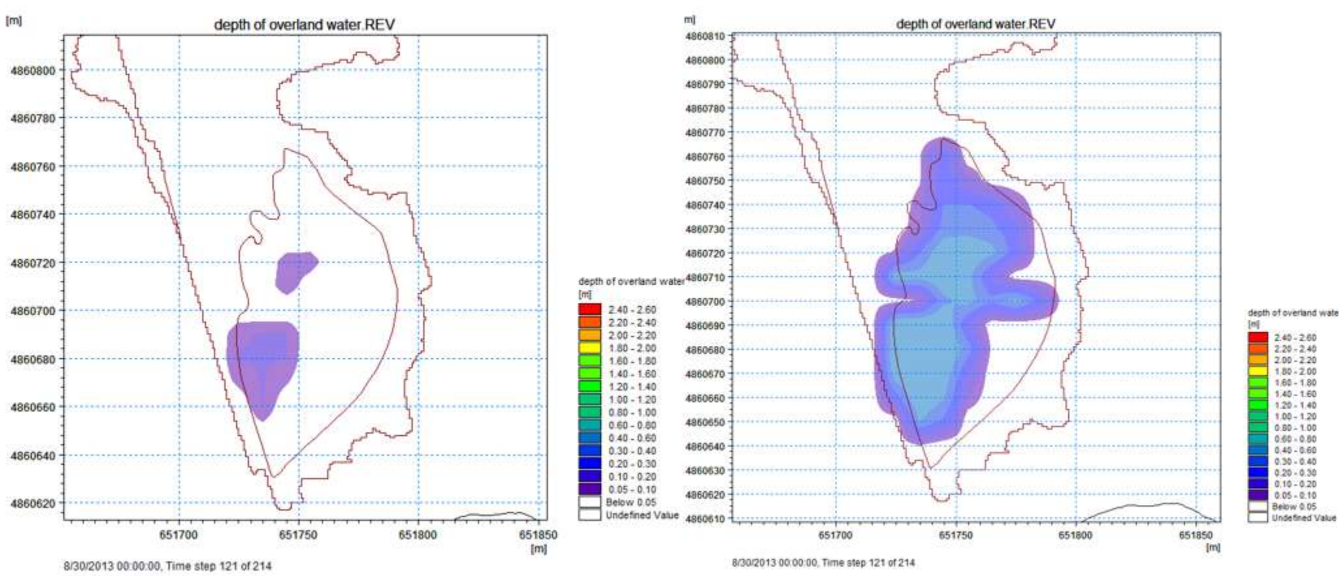


Figure 40: Comparison of wetland water depth and extent between No Mitigation (left) and With Mitigation (right)

3.3.7 MIKE SHE: Benefits, Challenges, Recommendations and References

Benefits

- A well-developed graphical user interface that strongly aids in model construction, debugging and calibration phases as well as ongoing pre and post processing of model data during these phases.
- The ability to import input data as GIS surfaces or shape files directly into the model greatly expedites the model construction phase and reduces the possibility of data conversion errors.
- Input dataset can have different spatial resolution (e.g. finer grid than model grid) and time interval (e.g. shorter time interval than model time steps) as model used.
- Scalable modular structure and multiple algorithms allow certain processes to be simplified, and allow to focus on properly representing other processes.

- MIKE SHE generates calibration plots with common used statistics during simulation that helps speed up the calibration process.
- MIKE SHE includes Ponded Drainage feature that supports LIDs and SUDs green infrastructure and makes implementation of proposed development much easier.
- MIKE SHE includes water budget calculation tool that can calculates water balance on both model domain basis and sub-catchment/area basis, and produces water balance items such as precipitation, actual evapotranspiration, infiltration/recharge, surface runoff, exchange flow between river/wetland and aquifer etc.
- MIKE SHE generates variety of output (timeseries, 2D time varying outputs and 3D groundwater outputs), especially 2D time varying depth of overland output that can be used to analyze wetland hydroperiod.

Challenges

- MIKE SHE uses uniform grid. By not being able to increase the spatial resolution locally within areas of interest, the modeler needs to increase the resolution globally or create a regional model prior to build a local scale model focusing on area of interest. This increases the level of complexity throughout the model, and adds considerably to the computational requirements or effort of model construction.
- MIKE SHE is physical-based, highly parameterized model, and therefore requires extensive model data and physical parameters. Calibration of model can be challenge sometime.
- Model use requires a great deal of technical expertise and the learning curve is steep for new modelers.
- Source code is not available to the public. The proprietary source code of MIKE SHE is also a limitation in that users cannot examine or modify the source code of the model.
- MIKE SHE is not free software. Prices range from approximately CAD $14,160 for government agencies to CAD $17,700 for standard commercial use, and the annual cost of the service agreement is approximately CAD $5,000.

Recommendations

- MIKE SHE is well suitable for wetland study for both short-term and long-term simulations.
- MIKE SHE has capability to model impact of development due to land use change and model mitigation measure using Ponded Drainage feature.

References

DHI, 2009a. MIKE SHE Volume 1: User Guide. (2009 Edition). 230p

Gordon, S., Jones, J.P., Jackstiet, R. and Diiwu, J., 2005. Review of groundwater and surface water interaction - knowledge and modelling approaches for streamflow prediction in Alberta. Prepared by the Alberta Research Council for Michael Seneka of Alberta Environment.

Camp Dresser and McKee, 2001. Evaluation of Integrated Surface Water and Groundwater Modelling Tools. Water Resources Research & Development Program.

Hansen, J.R., J.C. Refsgaard, S. Hansen and V. Ernstsen, 2007. Problems with heterogeneity in physically based agricultural catchment models. Journal of Hydrology, 342: 1-16.

Hargreaves, G. H., & Samani, Z. A. (1985). Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture, 1(2), 96–99.

Scurlock, J.M.O., G.P. Asner and S.T. Gower, 2001. Worldwide Historical Estimates and Bibilography of Leaf Area Index, 1932-2000. ORNL Technical Memorandum TM-2001/268. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

Thompson, J.R., H. R. Sorenson, H. Gavin and A. Refsgaard, 2004. Application of the MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. Journal of Hydrology, 293: 151-179.

Vazquez, R.F., P. Willems and J. Feyen, 2008. Improving the predictions of MIKE SHE catchment-scale application by using a multi-criteria approach. Hydrological Processes, 22: 2159-2179.

Weber, M., S. Gordon, I. Judd-Henrey and J. Beckers, 2004. Management Strategies to Reduce Vulnerability to Climate Change in the South Saskatchewan River Basin. Prepared by the Alberta Research Council for Andy Ridge of Alberta Environment.

3.4 Visual Otthymo 5 (VO5)

3.4.1 VO5: Background

Visual OTTHYMO (VO) is a hydrologic modelling software which primarily uses the HYMO model engine developed by J.R. Williams in 1973. This engine was further developed at the University of Ottawa, where it was named OTTHYMO 83. The first graphical interface was developed by the founder of Civica in 1998 (Visual OTTHYMO 1.0). VO is currently being developed by Civica Infrastructure, and additional features and commands continue to be added.

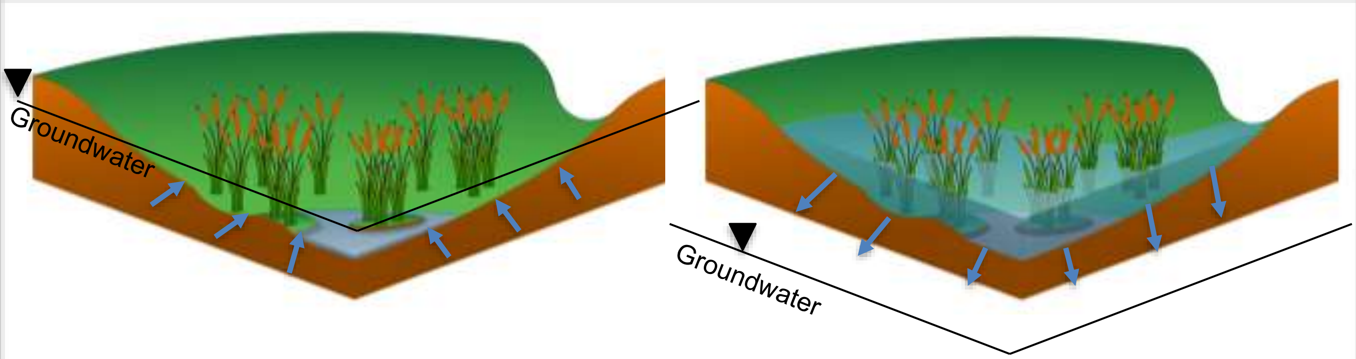
The continuous version of VO (5.0) was released in 2017 with the ability to simulate snow melt, infiltration, evapotranspiration and groundwater infiltration. Continuous VO uses the same commands as the single event simulation (with some additional parameters required for continuous modelling). The approach used for the continuous engine is as follows:

- Snow accumulation, compaction, refreezing and melt is modelled using the approach in GASWER model;
- Infiltration is modeled using the SCS equation to account for soil moisture and unit hydrographs are used to transform the excess rainfall to runoff;
- Flow is routed through channels and reservoirs using the variable storage coefficient method;
- Routing through reservoirs is modeled using the storage indication method.
- Evapotranspiration can be entered as Potential evapotranspiration,

The wetland command is a new feature added to VO 5.0 in 2018. This command is designed to model all the hydrologic processes in a wetland including inflow, evaporation, seepage and outflow. The interface for the wetland command is similar to that used in continuous VO, however a groundwater component has been added to the wetland. Groundwater seepage into and out of the wetland are calculated using Darcy's equation and the difference in elevation between the ground water and either the stored water or, if the wetland is dry, the bottom of the wetland.

Features specific to the VO5 water balance are as follows:

Ground water elevations are treated as model parameters and are entered as a time series similar to the way precipitation is added to a model. This means you do not have to calibrate an aquifer component in your model to represent the ground water interactions with a wetland.

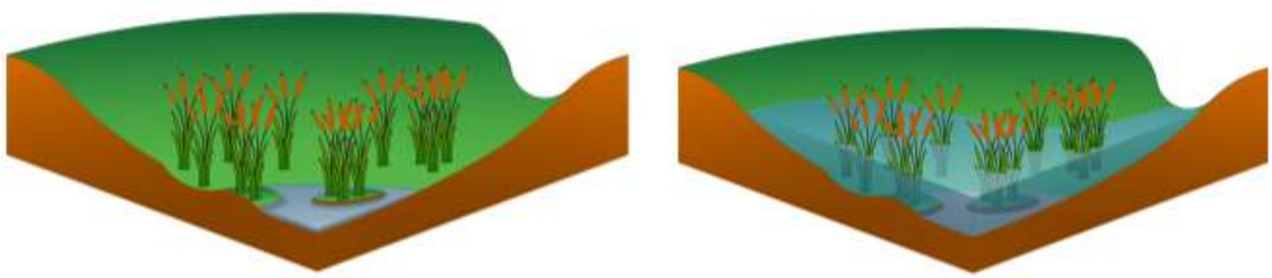


If the groundwater is higher than the surface water, ground water seeps into the wetland.

If the groundwater is lower than the surface water, then surface water seeps into the ground.

Figure 41: Groundwater Impacts on Wetland

The wetland command combines a rural runoff command (NasHYD) and a Route Reservoir command to model dry and wet areas of the wetland. These areas change size as the wetland storage area fills and drains. This allows users to more accurately model the runoff generated by the dry area of a wetland.



Dry Area = 9.0 ha
Storage Area = 1.0 ha
Wetland Area = 10 ha

Dry Area = 3.0 ha
Storage Area = 7.0 ha
Wetland Area = 10 ha

Figure 42: Dynamic wet and dry areas in wetland

The user interface for this model is simple to use and guidance on parameter selection is provided through direct links to the user manual. The model also provides tools for model calibration and produces easy to follow result summaries and scenario comparison reports.

3.4.2 VO5: Model Setup, Existing Conditions

The VO5 model was simple to set up; only an upstream drainage area and the wetland were included in our model. The data required to complete the wetland water balance in VO5 is summarized in Table 10.

Table 10: Data required for VO5 Wetland Water Balance model

	Upstream catchment	Wetland
Command Used	NasHYD	RouteWetland
Topography	10-m DEM, 1-m LiDAR, wetland bathymetry Provided by TRCA	Depth/area and depth/outflow curves provided by TRCA
Land Cover	Air photo and TRCA land use classification (Refer to **Figure 43**)	
Soil data	Data from existing geotechnical reports	
Ground water levels	1-hr groundwater level data from piezometers at multiple depths within wetland; data Provided by TRCA	
Water Levels	1-hr surface water level data from piezometers at multiple depths within wetland; data Provided by TRCA	
Precipitation (Rain / Snow)	5-min precipitation from nearby Brock West Landfill station (provide by TRCA)	
Evapotranspiration	Daily PET calculated by TRCA using Hargreaves Equation	
Temperature	Daily min / max temperature provided by TRCA	

The data summarized in Table 10 was used to assign parameters to the upstream drainage area and wetland. Model parameters for the wetland are summarized in **Figure 43: Land Use for Sideline** 26 **Wetland**

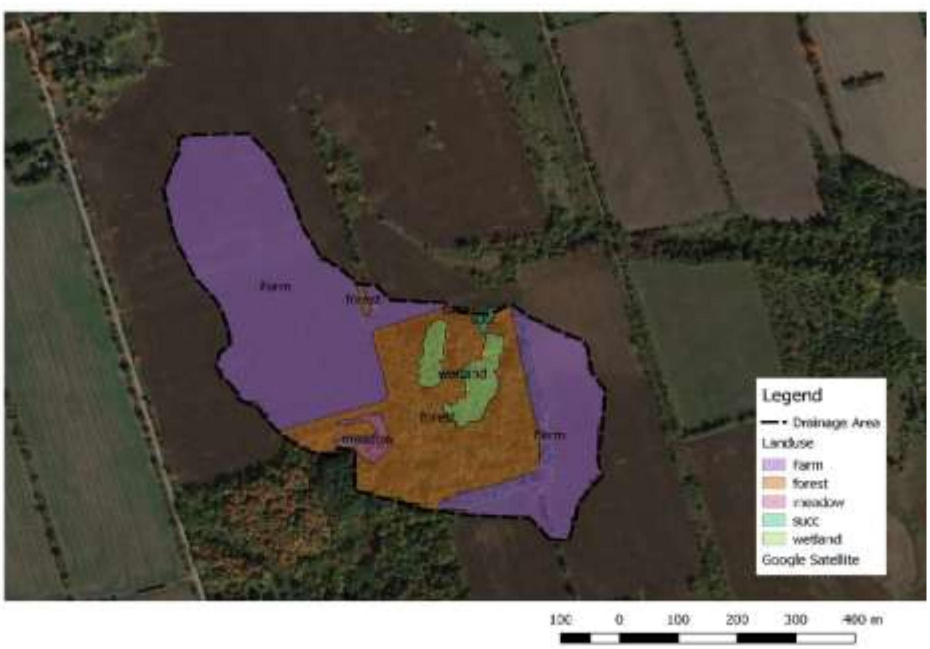


Table 11 and Table 12**.**

Figure 43: Land Use for Sideline 26 Wetland

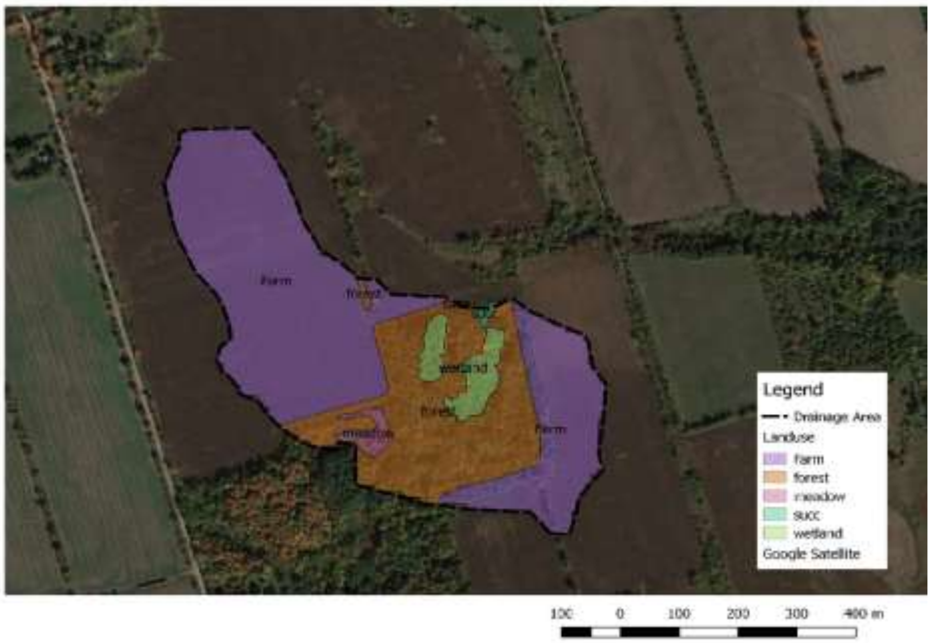


Table 11: Continuous NasHyd Parameter Table (Sideline 26)

Parameter	Description	Upstream Drainage Area
Command		NasHyd
Area (ha)	Drainage area calculated using topography and watercourse layers	28 ha
CN	Curve number used for SCS	68
IA (mm)	Pervious Area Depression Storage	8 mm
Inter event time	Minimum amount of time without precipitation required to define a new event	4 hr
N	Number of linear reservoirs	3.0
TP (hr)	Time to peak	0.66 hrs
Land Cover	General description of vegetation	Crops to shoulder height
K	K = GI /Pan Evaporation - Growth index of a crop / Pan Evaporation. Used to estimate potential evapotranspiration.	1.4
VEGK3	ET opportunity coefficient, used to calculate ET from soil	6.0
Soil Texture	Description of soil base on relative content of sand, silt, clay particles	Clay Loam
Total Porosity	Fraction of soil that is made up of spaces (pores) between particles	0.464

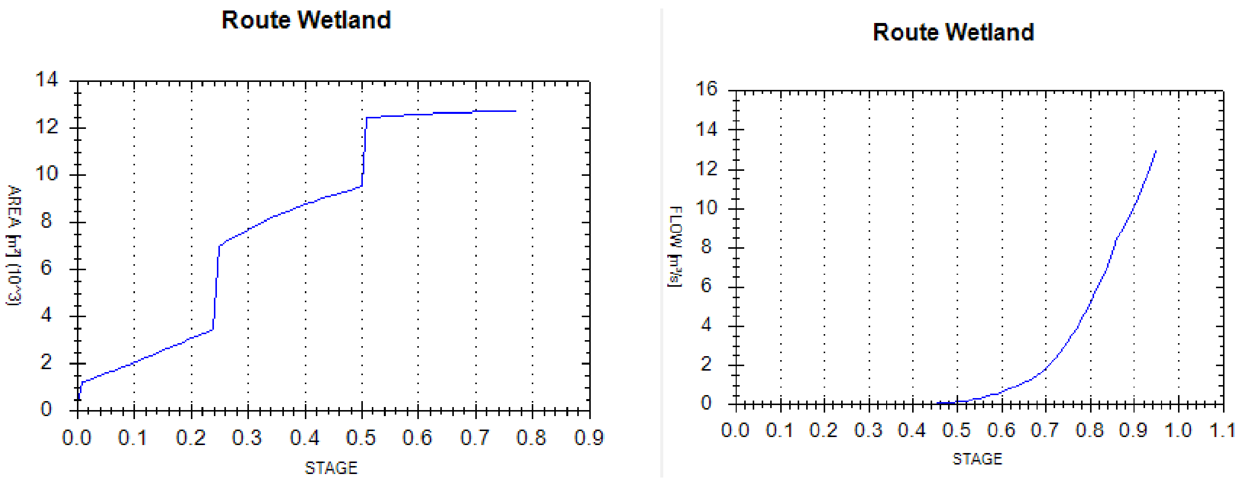
Field Capacity	Soil moisture held in soil after excess water has drained away	0.310
Wilting Point	Moisture left in dry soil that is not accessible to plants, causing them to wilt	0.187
Saturated K (mm/day)	Hydraulic conductivity of the soil when saturated, represent the ease at which moisture can move through a soil in which all easily drained pore spec is filled with liquid.	24.38 mm/day

Table 12: Wetland Parameter Table (Sideline 26)

Parameter	Description	Wetland
Command		RouteWetland
Storage Area Geometry		
Initial water Depth (m)	Depth of water in the wetland at the start of a model run	0.40m
Bottom Elevation (m)	Elevation at the lowest point in the wetland	189.96m
Depth Area Curve	Depth area curve for the entire wetland (Dry and wet areas), Starts at the bottom elevation of the wetland	See Error! Reference source not found.
Storage Area - Soil		
Soil Thickness (m)	Thickness of the soil layer constraining movement between surface and ground water	1.5m
Hydraulic Conductivity (mm/day)	Saturated hydraulic conductivity for soils in areas with ponded water, represent the ease at which moisture can move through a soil in which all easily drained pore space is filled with liquid	1800 mm/day
Fringe Area		
Soil Texture	Description of soil base on relative content of sand, silt, clay particles	Clay Loam
Total Porosity	Fraction of soil that is made up of spaces (pores) between particles	0.464
Field Capacity	Soil moisture held in soil after excess water has drained away	0.310
Wilting Point	Moisture left in dry soil that is not accessible to plants, causing them to wilt	0.187
Saturated K (mm/day)	Hydraulic conductivity of the soil in dry areas when saturated, represent the ease at which moisture can move through a soil in which all easily drained pore spec is filled with liquid	24.38 mm/day
CN	Curve number used for SCS	68
IA (mm)	Pervious Area Depression Storage	10 mm
Evapotranspiration		
Land Cover	General description of vegetation	Crops to shoulder height
k	K = GI /Pan Evaporation - Growth index of a crop / Pan Evaporation	1.4
VEGK3	ET opportunity coefficient, used to calculate ET from soil	6.0
Outlet		
Type	Choice of method for defining outlet (Currently only Stage Discharge is available)	Stage Discharge

Discharge Curve	Depth discharge curve for the wetland, depth is defined from the bottom elevation of the wetland	Refer to Error! Reference source not found.

Figure 44: Depth Area and Depth Discharge Curves for the Sideline 26 Wetland



Stage vs Area Curve

Stage vs Discharge Curve

Although there are two distinct pool in this wetland only one stage area curve was used, this being the total area in the wetland for each depth starting with the lowest elevation in the wetland. Figure 45 shows the user interface once the upstream area and wetland were linked together in the model.

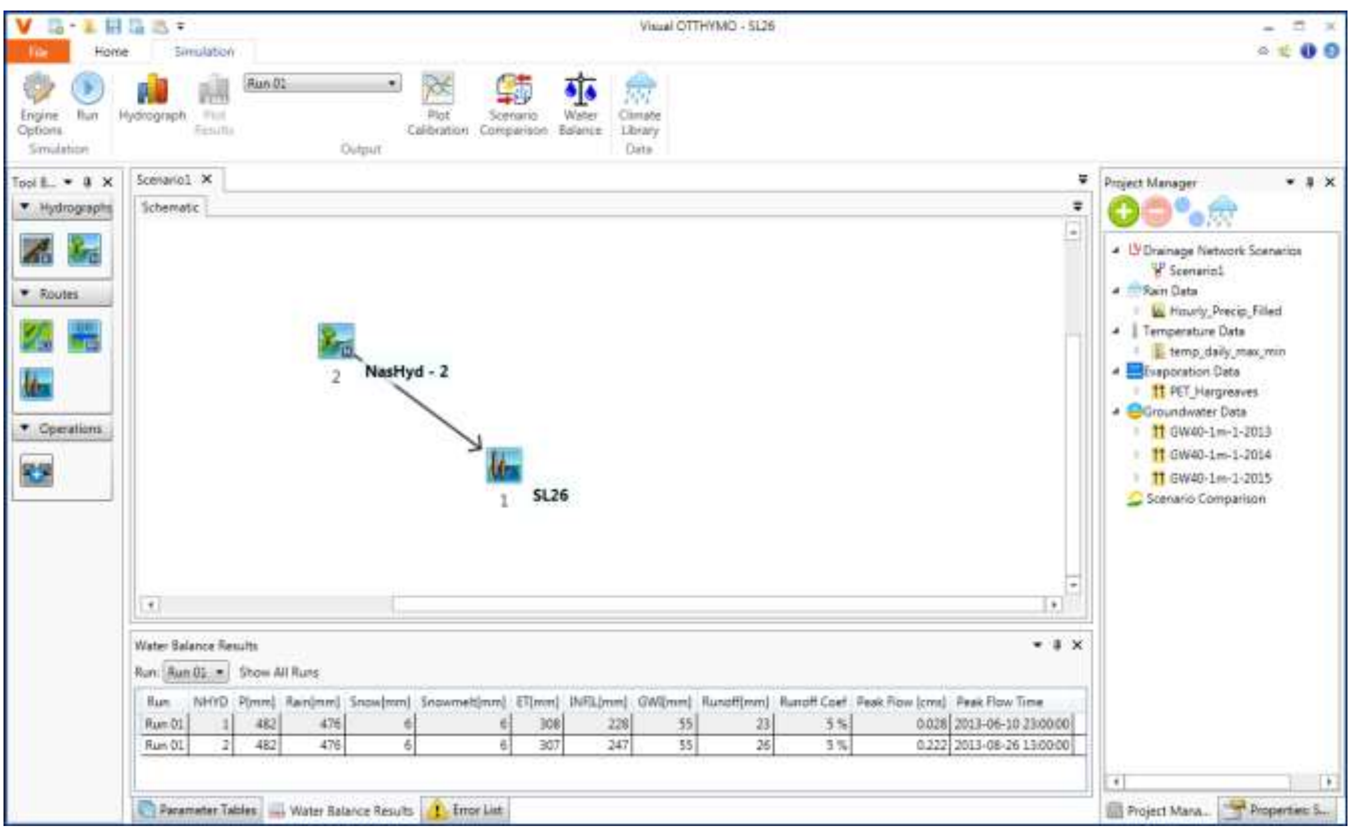


Figure 45: VO5 model schematic

For more complex wetland systems multiple wetland and drainage areas can be added to the model and either diretly linked or linked through route channel and route pipe commands. For a simple wetland such as this one the model build time is approximately 2 days to review and convert data to the appropriate file formats and 2 hours to build the model. Climate data and groundwater time series are .csv files formated as follows:

- Precipitation
  - Column 1 – Date / Time (year/month/day hour:minutes:seconds)
  - Column 2 – Value (mm)
- Temperature
  - Column 1 – Date (year/month/day)
  - Column 2 – Minimum Value (^{0}C)
  - Column 3 – Maximum Value (^{0}C)
- Evapotranspiration
  - Column 1 – Date (year/month/day)
  - Column 2 – Value (mm)
- Groundwater Elevations (at the lowest point in the wetland)
  - Column 1 – Date / Time (year/month/day hour:minutes:seconds)
  - Column 2 – Value (masl)

3.4.3 VO5: Calibration, Existing Conditions

Once the wetland was built, the model was calibrated using the monitoring data for 2013. The VO5 calibration interface allows users to graph modeled and monitored water levels providing users with a visual representation of the calibration after each run. Statistics (percent difference in water level, Coefficient of determination (R^2) and Nash Sutcliffe (NSE)) are shown at the bottom of the graph to quantify the calibration results.

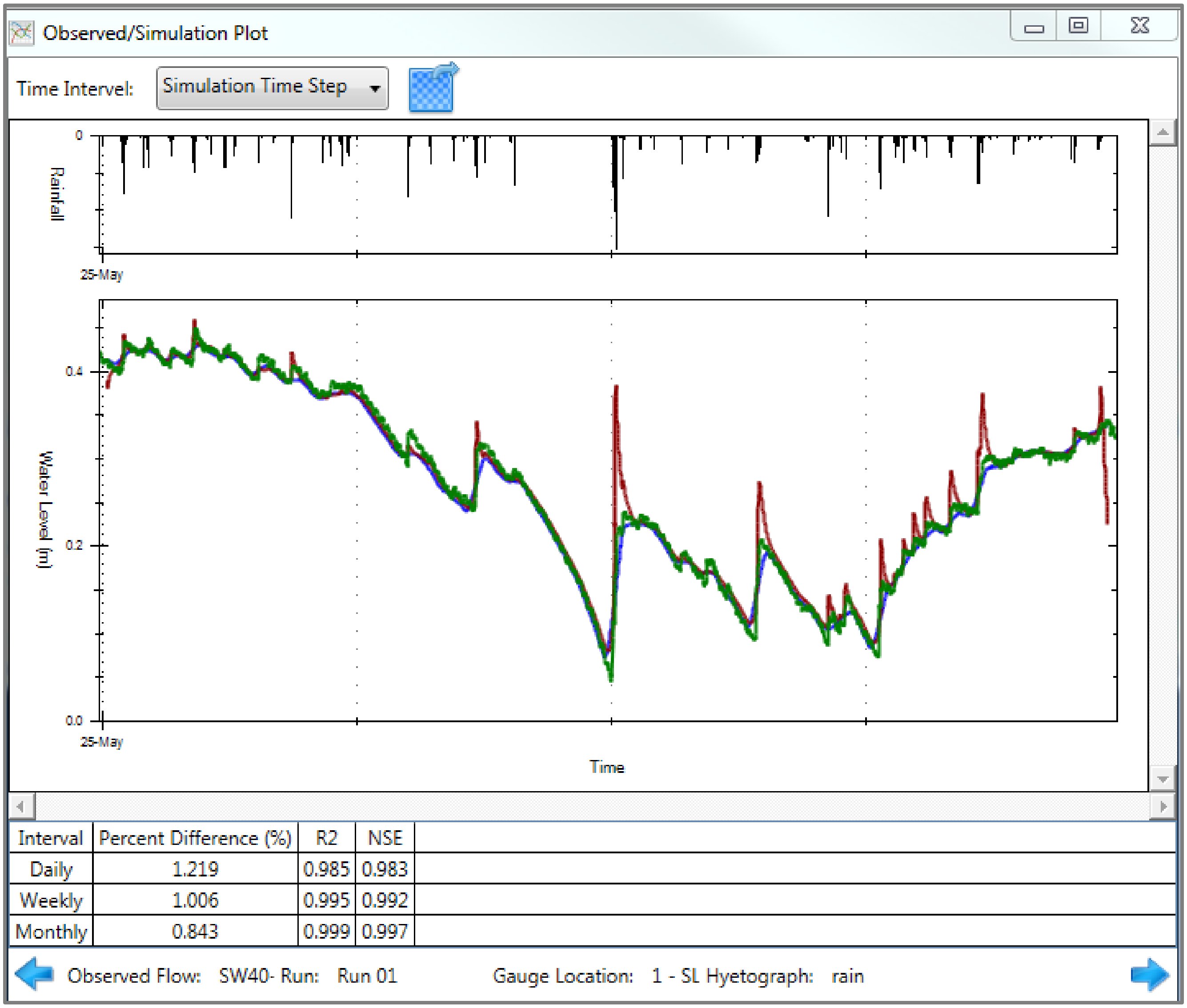
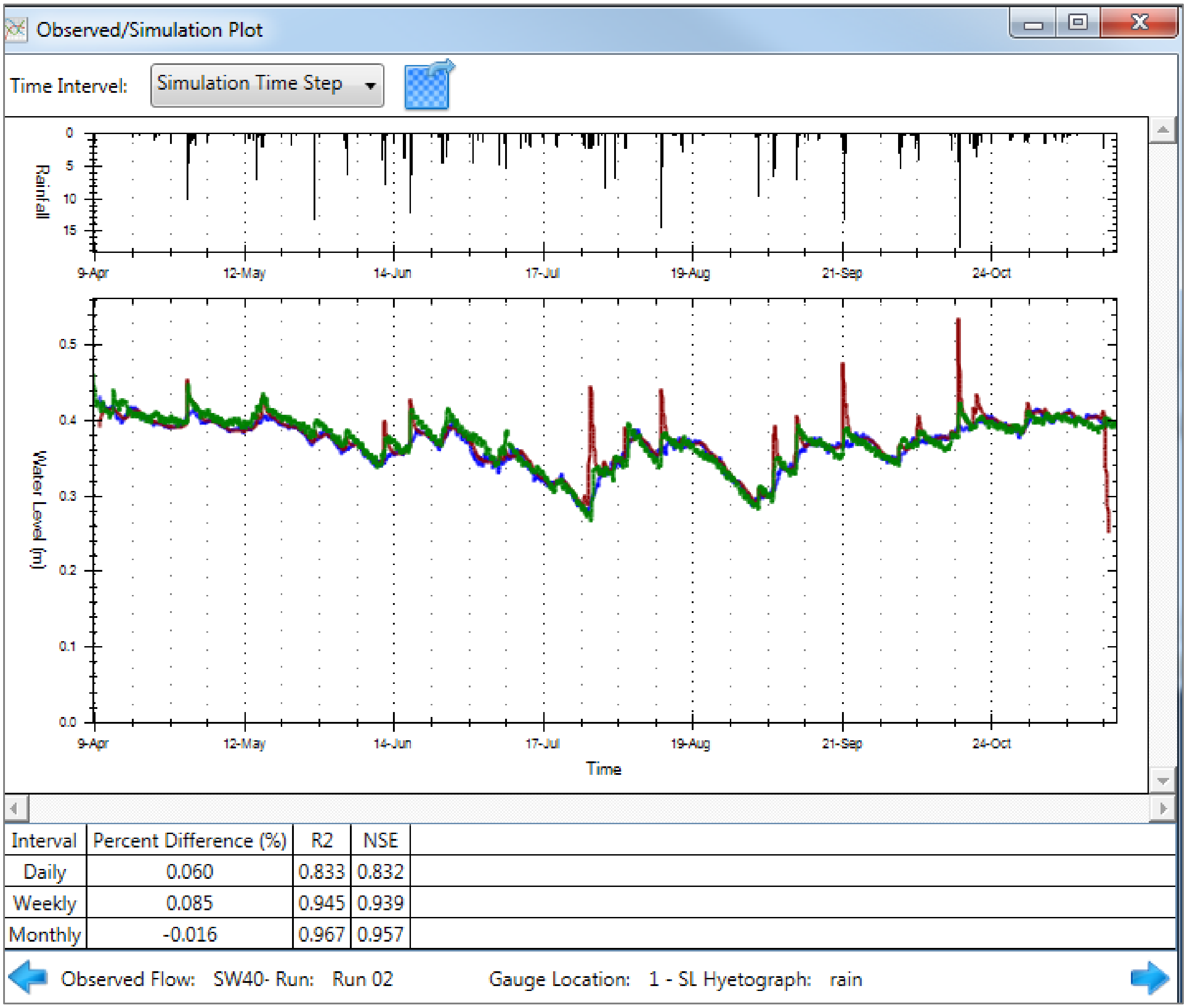


Figure 46: Sideline 26 Wetland Calibration Results (2013)

As can be seen in Figure 46 the modeled data (shown in red) matches closely with the monitored data (shown in green). The blue line shows the ground water elevations used in the model. The statistics provided at the bottom of the graph also support a strong correlation between modeled and monitored data.

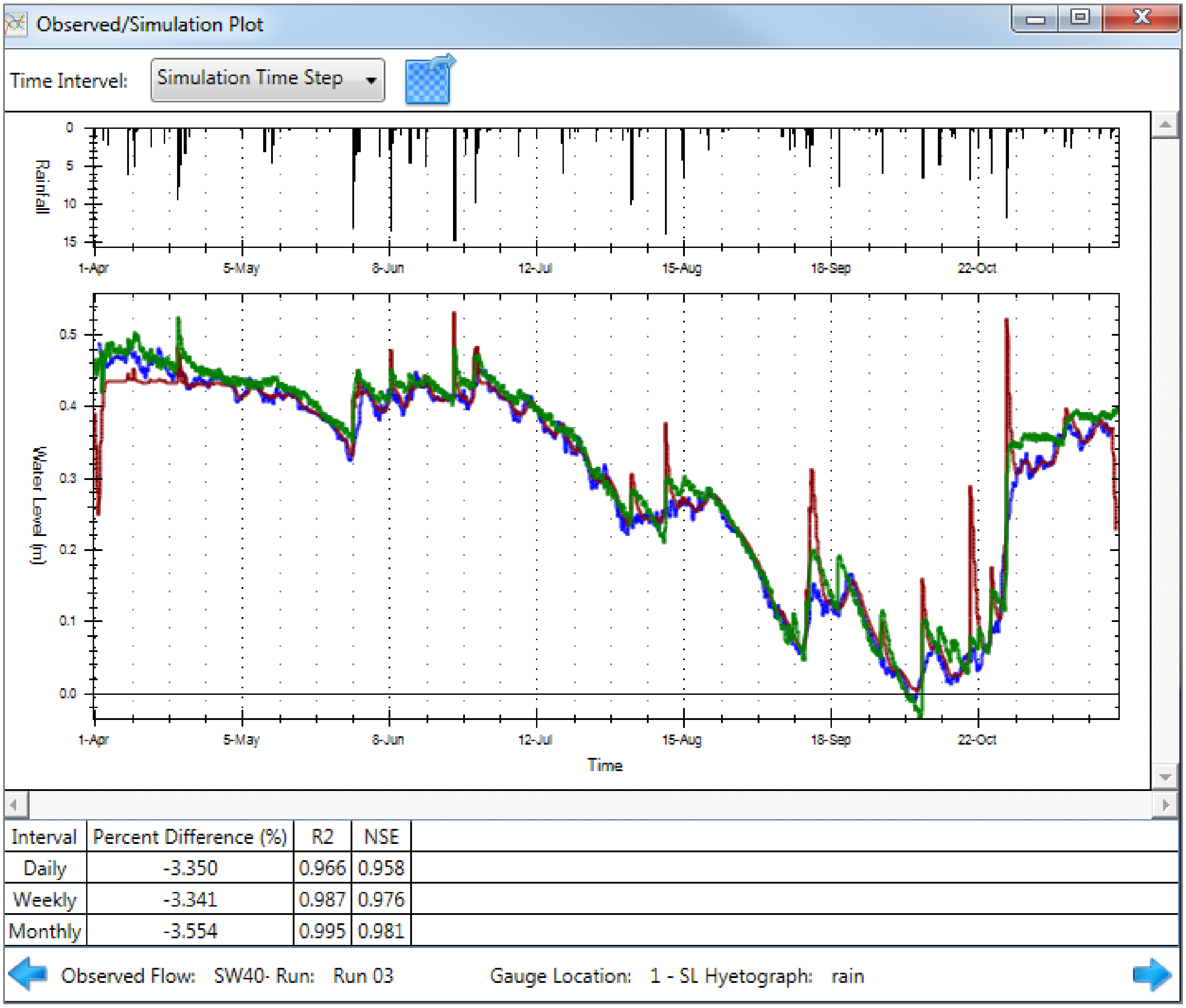
3.4.4 VO5: Validation, Existing Conditions

The model was then validated using monitored data from 2014 and 2015. Model validation results are provided in Figure 47 and **Figure 48** respectively. As with the model calibration the validation runs show a close match to the monitored data.



Interval	Percent Difference (%)	R2	NSE
Daily	0.060	0.833	0.832
Weekly	0.085	0.945	0.939
Monthly	-0.016	0.967	0.957

Figure 47: Sideline 26 Wetland Validation Results (2014)



Interval	Percent Difference (%)	R2	NSE
Daily	-3.350	0.966	0.958
Weekly	-3.341	0.987	0.976
Monthly	-3.554	0.995	0.981

Figure 48: Sideline 26 Wetland Validation Results (2015)

3.4.5 VO5: Long-term Simulation, Proposed Conditions without Mitigation

Once the model provided a satisfactory representation of the wetland water levels for three years of monitoring data, set up was completed for the long-term simulation. This included inputting precipitation, temperature and evapotranspiration data provided by TRCA for 1991 – 2007 into the model. As groundwater levels were not available for this time period, the average values from the three years of data available were used, these groundwater patterns were repeated for each year.

A development scenario was then created in which 50% of the catchment area was diverted away from the wetland to simulate runoff being routed to a different outlet location. Given the current regulations protecting wetlands, this is often done in order to prevent large volumes of water from drowning the wetlands. The results of this flow diversion are shown on Figure 49 - Figure 51. Comparing the maximum water levels over the long-term scenario shows that the max water depth in the wetland drops from 0.553m to 0.520m while the average water level drops from 0.330m to 0.327m.

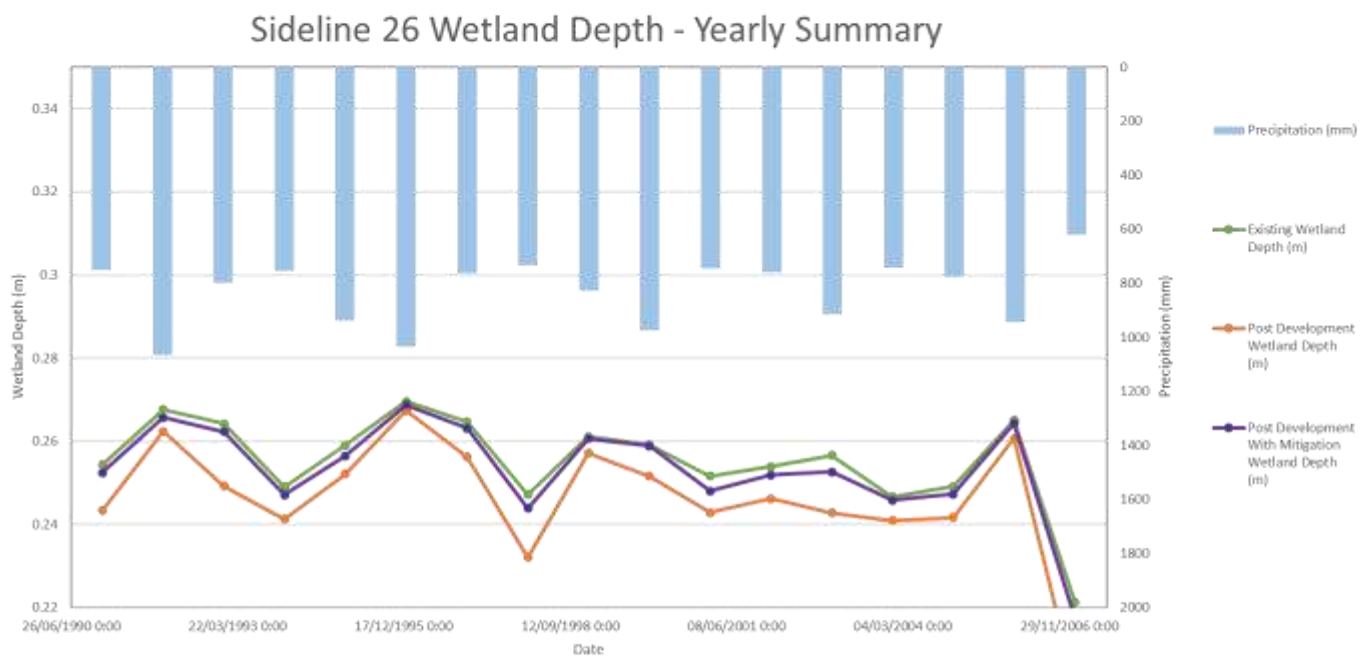


Figure 49: Average Annual Depth in Sideline 26 Wetland

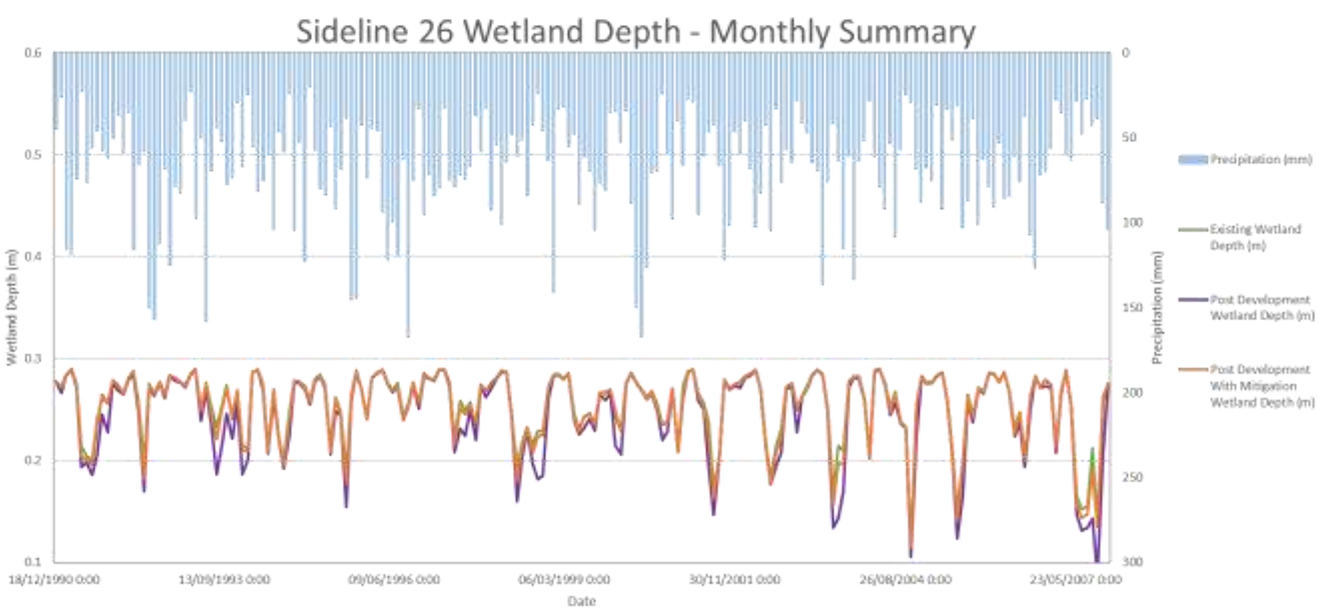


Figure 50: Average Monthly Depth in Sideline 26 Wetland

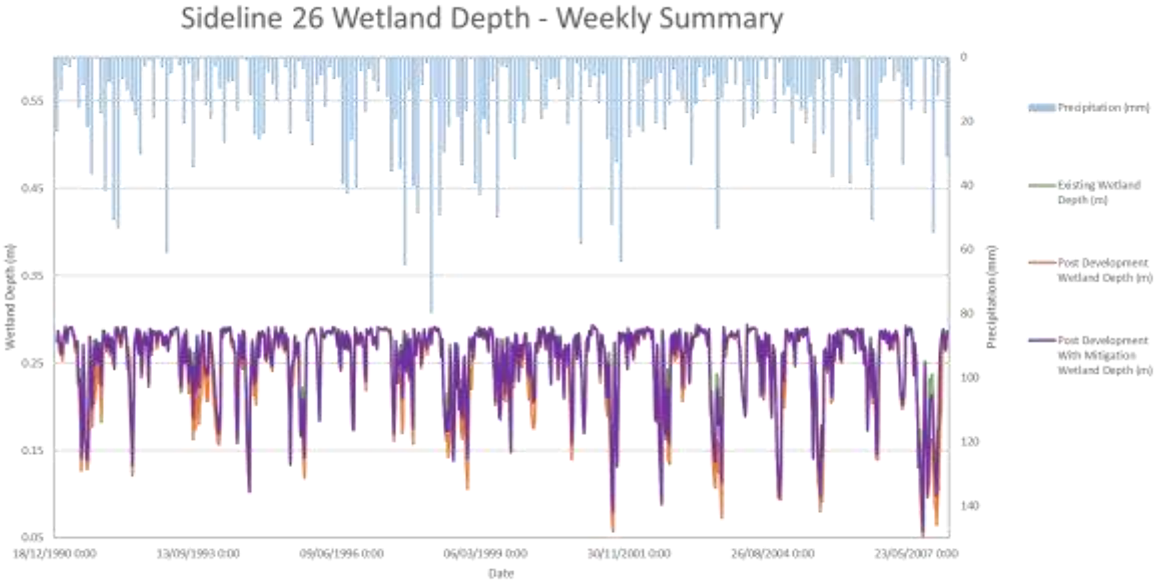


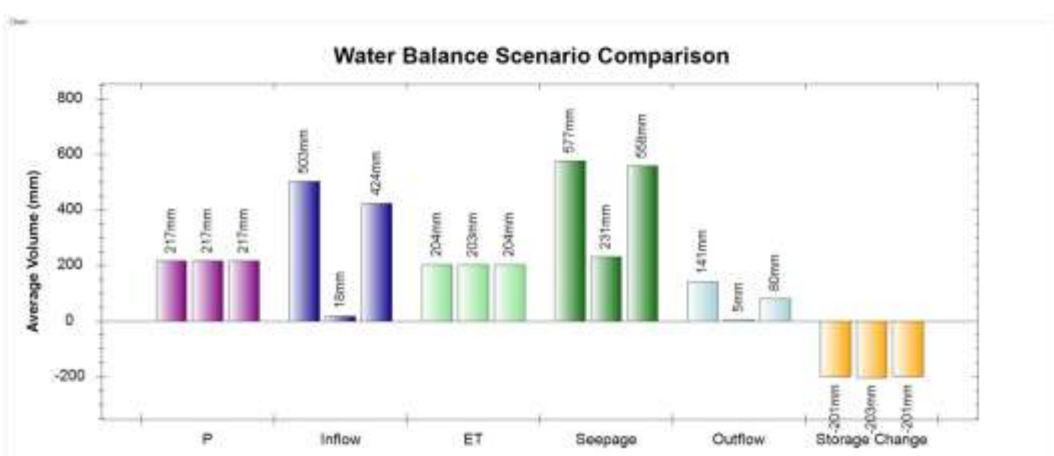
Figure 51: Average Weekly Depth in Sideline 26 Wetland

3.4.6 VO5: Long-term Simulation, Proposed Conditions with Mitigation

In order to simulate the mitigation scenario, a catchment was added to represent roof tops being directed to the wetland. A depression storage value of 10mm was used on the roof to catchment to mimic retention in a rain garden or bioretention cell upstream of the wetland, and a route reservoir was added to mimic the detention component of an LID. Using this methodology, the area of roofs and size of an upstream LID could be estimated in order to mitigate the impacts of the upstream development. The results of this mitigation are shown on Figure 49 - Figure 51. Comparing the maximum water levels over the long-term scenario shows that the maximum water depth in the wetland, which drop from 0.553m to 0.520m with development and no mitigation increase to 0.525m with mitigation. The average water level, which dropped from 0.330m to 0.327m in the scenario with no mitigation, is restored to 0.330m with mitigation.

Figure 52 summarizes the components of the wetland water balance on an annual, seasonal and monthly basis.

Figure 52: Sample water balance graph



3.4.7 VO5: Benefits, Challenges, Recommendations and References

Benefits

- Simple to use, generates defendable results. Having a command designed to represent a wetland makes modelling and calibration simpler than some other models, where different components are modeled separately (and potentially in multiple models).
- Having groundwater elevations as a model input simplifies building and calibrating the model. Although the impact of the wetland on the groundwater is not modeled, this model does use groundwater elevations to calculate soil saturation levels, changes in infiltration rates and groundwater seepage into the wetland.

Challenges

- As this is a hydrology model and does not model impact of the wetland on the local aquifer, it is only suitable for wetlands which do not have a large impact on the ground water. The model does not predict groundwater elevations and shows a water level of zero once the water level is below ground.
- Not having LIDs in the model made modelling mitigation a bit more challenging; however, VO developers intend to add LIDs functions to VO5 by the end of 2018.

Recommendations

- Discuss the use of this model with your local conservation authority prior to starting a water balance project as it is not suitable for use in wetlands which are primarily groundwater fed or for wetlands which may impact groundwater elevations. In most cases small wetlands will not have a noticeable impact on groundwater elevations as aquifers tend to have large catchments of which the wetland is only a small component.
- It is important when setting up a wetland model in VO that the groundwater, depth area curve and stage discharge curve are all generated relative to the lowest point in the wetland. If ground water elevations are not measured at the lowest point in the wetland, it may be necessary to adjust these elevations, in consultation with a hydrogeologist or geotechnical engineer, to represent groundwater levels at the lowest point in the wetland.

References

Visual OTTHYMO User Manual, Civica infrastructure Inc, August 2017 - http://visualotthymo.com/downloads/v5.0_usermanual.pdf

Visual OTTHYMO Reference Manual, Civica infrastructure Inc, March 2017 http://visualotthymo.com/downloads/Reference%20Manual%20-%20VO5.pdf

3.5 Storm Water Management Model (SWMM)

3.5.1 SWMM: Background

First developed in 1971 by the United States Environmental Protection Agency (EPA), the Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model that allows for both single event and continuous (long-term) simulation of runoff quantity and quality. It is geared towards analysis of urban and urbanizing catchments. The current version (SWMM 5) provides an integrated modelling environment for editing the properties of subcatchments and flow routing networks, running hydrologic, hydraulic, and water quality simulations, and viewing simulation results. The runoff component of SWMM simulates generation of runoff and pollutant loads from various subcatchment areas, while the routing component simulates the transport of runoff and pollutants through both natural and engineered flow networks. Model capabilities are summarized below in Table 13.

Table 13: SWMM model features summary

Model Features	SWMM
Model Type	Physically-based lumped parameter
Simulation Type	Single-event/continuous
Precipitation	Multiple/single hyetograph
Snow Melt	Heat budget equation, areal depletion curves, and modified degree-day
Evapotranspiration	Evaporation from water stored at surface and in soil; PET input as timeseries or computed from temperature using Hargreaves method
Infiltration	Horton infiltration
	Modified Horton infiltration
	Green-Ampt infiltration
	Modified Green-Ampt infiltration
	Curve Number infiltration
Overland Flow	Nonlinear reservoir routing
Subsurface Soil Water Flow	Vertical exchanges within 2-zone groundwater layer (saturated/unsaturated)
Channel/Reservoir	1D dynamic wave approximation
	1D kinematic wave flow
Groundwater Flow	Vertical exchange within 2-zone groundwater layer; lateral exchange with drainage network nodes (but not between subcatchments)
GIS interface	Accept GIS format data including point/contour/polygon /polyline/ASCII

EPA-SWMM is provided free of charge and is available for download at https://www.epa.gov. Various proprietary graphical user interfaces have been developed using the SWMM 5 engine (e.g. PC-SWMM, XP-SWMM), and can facilitate the editing of subcatchment and flow network properties and the viewing and exporting of data, but the underlying fundamental representation of hydrologic processes remains the same. See Rossman (2015) for a detailed description of model representation of hydrologic processes.

3.5.2 SWMM: Model Setup, Existing Conditions

The SWMM engine (using the PC-SWMM graphical user interface) was used to model two different wetland catchments, both of which are to the north of Taunton Road in Pickering, Ontario. The sites are referred to as Sideline 22 and Sideline 26; detailed descriptions and of both sites are provided in sections 3.1.2, 3.2.2, 3.3.2, and 3.4.2, with accompanying figures.

The data used to determine the conceptual water balance and in model set-up is outlined in Table 14 below, along with the data source.

Table 14: SWMM data types and sources

Data Type	Data Sources
Topography	10-m DEM; sub-centimeter resolution field topographic/bathymetric survey of wetland basins used to derive stage-storage curves
Climate data	5-min precipitation and temperature from nearby Brock West Landfill station (~3.0 km from study sites)
Land use	TRCA land use data; hypothetical post-development land use and catchment parameters
Soil data	Data from existing geotechnical reports and hand-augured soil samples; slug test-derived hydraulic conductivity estimates
Channel	TRCA DEM-derived drainage lines
Groundwater	Static groundwater level measurements from consultant hydrogeological reports ; slug test-derived hydraulic conductivity estimates
Water Level Monitoring	1-hr surface water and groundwater level data from piezometers at multiple depths within wetland; data covers growing season of 2013 and 2014; 2013 data used to calibrate models and 2014 to validate

Prior to calibration and validation of the models, a conceptual water balance model for each site was created based on the water transfer mechanisms known to exist or suspected of being present at each site. Conceptual models considered data on wetland hydrogeomorphic and hydrogeological setting, known spillway elevations, and ecological indicators of hydrological conditions. The conceptual water balance models for the two sites consisted of the following terms:

a. Sideline 22: $P + RO + GW_{in} - ET - GW_{out,L} = \Delta S + residual$

b. Sideline 26:

i. Basin 1: $P + RO + GW_{in,L} - ET - GW/SW_{out\,(to\,Basin\,2)} = \Delta S + residual$

ii. Basin 2: $P + RO + GW/SW_{in\,(from\,Basin\,1)} - ET - GW_{out,V} - GW/SW_{out,L} - SW_{out} = \Delta S + residual$

where P is precipitation, RO is overland runoff, GW_{in} is groundwater inflow (both vertical and lateral components, unless specified by subscript), ET is evapotranspiration, GW_{out} is groundwater outflow (both vertical and lateral components, unless specified by subscript), SW_{out} is channelized surface water outflow, ΔS is the change in volumetric storage, and *residual* is the residual error term. Where surface water and groundwater terms are showed together in combination, it indicates that subsurface volumetric storage above the water table (i.e. interflow) was included together with overland flow.

After determining the terms of the wetland water balance equations for each, the following general approach was used in the calibration and validation process for the models under existing conditions:

1. Where possible, independently estimate known inputs, outputs, and storage changes along with their corresponding uncertainties;
2. Determine the terms of the water balance associated with the greatest amount of error based on analysis of wetland storage response monthly water balance analysis;
3. Evaluate the relative contribution of water transfer mechanisms and the temporal variability of these contributions to the water balance.

3.5.3 SWMM: Calibration, Existing Conditions

The simulation settings used for both the calibration and validation of the model are summarized in Table 15.

Table 15: SWMM simulation settings for calibration and validation

Climatology and simulation options	1-hr dry weather time step, 5-min wet-weather time step, 30-s routing time step; *ET* calculated using Hargreaves method and inputs of daily precipitation totals, maximum and minimum temperatures
Wetland parameterization	Wetland represented as dynamic storage feature; detailed stage-storage curve was defined to account for open water, bank storage, and subsurface storage; calibration focused on wetland storage response to precipitation events
Catchment and aquifer parameterization	Multiple upstream catchments defined for both wetlands based on shared land use and soil drainage properties; one aquifer unit defined for all upstream catchments for both wetlands; aquifer properties defined using combination of local and regional geological data
Groundwater interaction	Wetlands received groundwater flow from upstream aquifer units; for Sideline 26, observed vertical losses simulated using seepage parameters; for Sideline 22, wetland lateral losses to groundwater were simulated using a downstream catchment and aquifer unit
Sensitivity, calibration and validation	Parameter sensitivity analysis performed; calibration and validation assessed using both visual and statistical (e.g. Nash-Sutcliffe efficiency) measures

Monitored surface water and groundwater level data collected at both Sideline 22 and Sideline 26 in the growing seasons of 2013 and 2014 was used to calibrate the model. An iterative process was followed to simulate wetland storage dynamics, whereby water transfer mechanisms were added one at a time to an initial simple water balance equation to try and mimic wetland storage dynamics under both wet and dry conditions. The following summarizes the general process that was followed to calibrate the wetland hydrology models for a) Sideline 22 and b) Sideline 26:

a. Sideline 22
    i. Parameterize catchment and perform sensitivity analysis
    ii. Incorporate wetland and stage-storage curve
    iii. Compare simulation results to observed surface water levels (monitoring data)
    iv. Refine stage-storage curve to include subsurface (extend curve to reflect depth-dependent specific yield of soils)
    v. Compare simulation results to observed groundwater levels (monitoring data)
    vi. Incorporate groundwater inflow
    vii. Compare simulation results to observed groundwater levels (monitoring data)
    viii. Investigate options for simulating groundwater outflow (orifice loss versus DS catchment)
    ix. Calibrate and validate model for both groundwater outflow scenarios

b. Sideline 26
    i. Parameterize catchment and perform sensitivity analysis
    ii. Incorporate two wetland basins and stage-storage curve
    iii. Compare simulation results to observed surface water levels (monitoring data)
    iv. Refine stage-storage curve to include subsurface (extend curve to reflect depth-dependent specific yield of soils)
    v. Compare simulation results to observed groundwater levels (monitoring data)
    vi. Incorporate estimated groundwater inflow
    vii. Compare simulation results to observed groundwater levels (monitoring data)
    viii. Add spillover overland flow connection from Basin 1 to Basin 2
    ix. Compare simulation results to observed groundwater levels (monitoring data)
    x. Add subsurface outflow pathways from Basins 1 and 2
    xi. Calibrate and validate model

The stage storage curves for both wetlands were defined using a combination of high resolution topographic/bathymetric survey data and estimates of soil specific yield (S_y) to account for changes in volumetric storage occurring in the subsurface zone. Different specific yield values were used for Areas 1 and 2; initial estimates of the specific yield terms were derived from Gasca and Ross (2009). Figure 53 depicts the process that was used to determine ΔS (volumetric storage, i.e. the wetland hydroperiod) for the model calibration and validation.

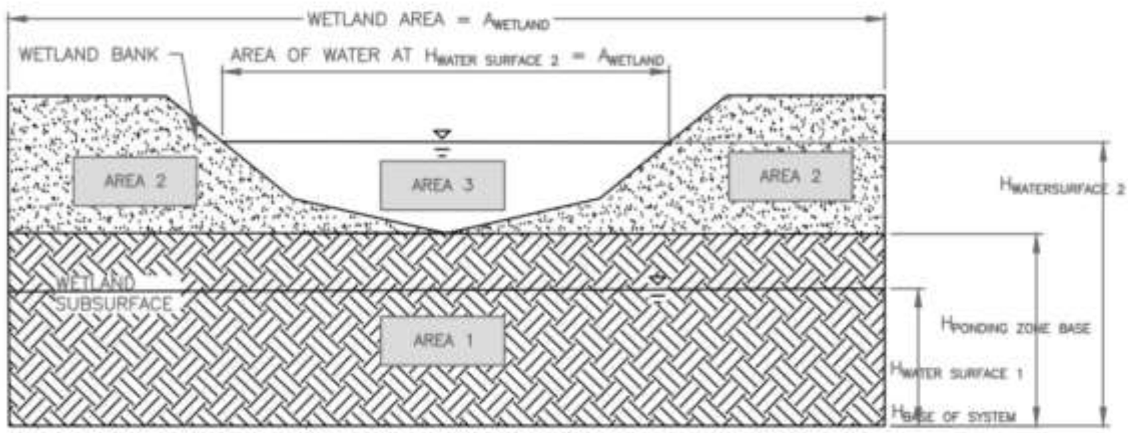


Figure 53: Calculation of total volumetric storage, incorporating specific yield (from Charbonneau, 2016)

The volumes for the respective reservoirs outlined in Figure 53 were calculated as follows:

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

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

$$V_{Area\ 3} = Surveyed\ wetland\ basin\ volume$$

$$\Delta S \begin{cases} \text{If water level < ponding zone base} = V_{Area\ 1} \\ \text{If water level > ponding zone base} = V_{Area\ 1} + V_{Area\ 2} + V_{Area\ 3} \end{cases}$$

An analysis of diurnal water level variations during several dry periods (periods with minimal 7-day antecedent rainfall during which no events >2 mm occurred) was used to isolate ET and vertical groundwater inflow fluxes following the method of McLaughlin and Cohen (2014). This method allowed the magnitude of these two terms to be estimated independently. For Sideline 26, owing to the relatively low conductivity soils within the catchment, it was assumed that there was no groundwater entering the wetland, and a small vertical outflow of groundwater from Basin 2 was identified through the monitored vertical hydraulic gradients. For Sideline 22, only vertical groundwater inflow was considered, while lateral groundwater outflow was identified as an important water transfer mechanism. Two methods were explored to replicate this water transfer mechanism in SWMM: 1) groundwater interactions within a downstream subcatchment aquifer unit, and; 2) outflow from the storage unit via an orifice. For the first method, an additional subcatchment with an aquifer unit associated with it was added to the model, and negative groundwater coefficients were added to the model to simulate groundwater outflow. For the second method, a circular orifice was added to the base of the wetland storage unit, and the coefficient and area were adjusted to attempt to replicate the lateral groundwater outflow.

The results of the model calibration are shown visually in Figure 54 and Figure 54 below; numerical results of the calibration as well as the validation of both models are shown in the subsequent section.

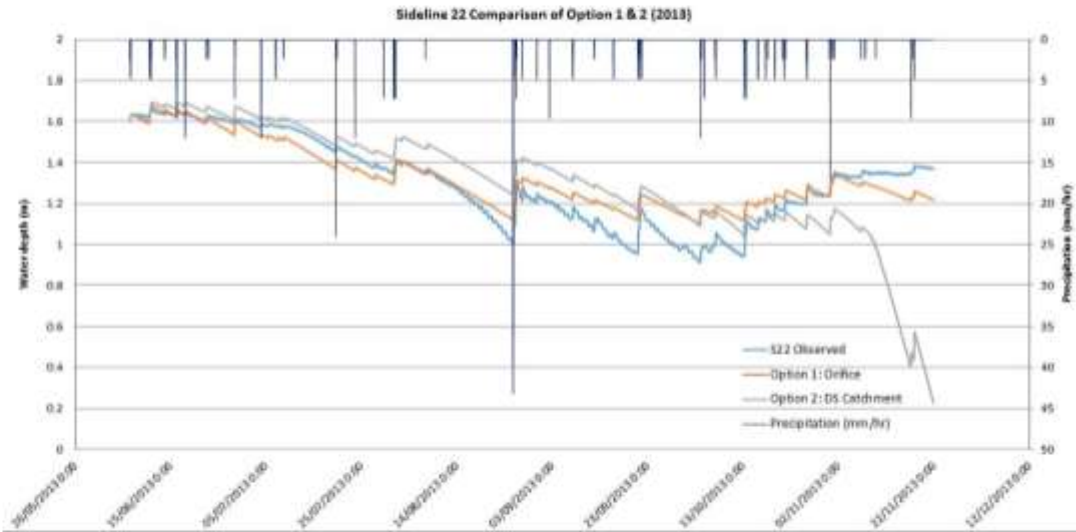


Figure 54: Results of calibration for Sideline 22, showing the representation of lateral groundwater outflow using both option 1 (orifice) and option 2 (catchment-aquifer unit), as described in text (from Charbonneau, 2016)

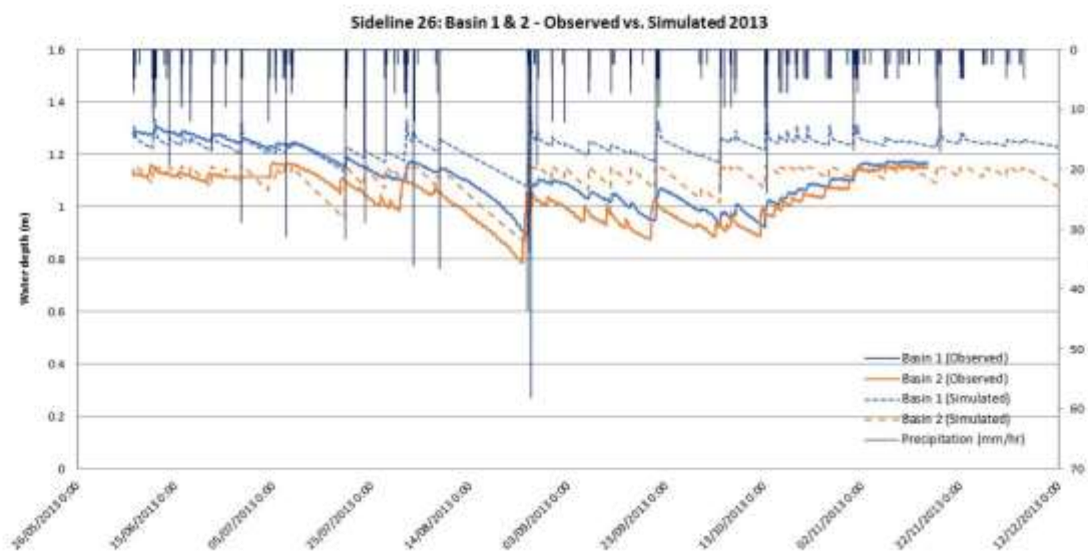


Figure 55: Results of calibration for Sideline 26, showing monitored and calibrated water levels for both Basin 1 and Basin 2 (from Charbonneau, 2016)

3.5.4 SWMM: Validation, Existing Conditions

Following calibration of the water balance models for Sideline 22 and Sideline 26 using monitoring data from the growing season of 2013, monitoring data for the year 2014 was used to validate the models. The results of the model performance for both the calibration and validation are shown in Table 16 and Table 17.

Table 16: Statistical performance measures for model calibration and validation for Sideline 22 (from Charbonneau, 2016)

Evaluation Functions	Value of Perfect Measure	Option 1: Orifice			Option 2: Downstream Catchment		
		2013 (189 days)	2013 (144 days)	2014 (246 days)	2013 (189 days)	2013 (110 days)	2014 (246 days)
Nash-Sutcliffe efficiency (NSE)	1	-0.037	0.862	-1.04	0.794	0.694	-1.01
Coefficient of determination	1	0.306	0.908	0.110	0.91	0.857	0.147
Standard error of estimate (SEE)	0	0.215	0.0804	0.418	0.127	0.126	0.142
Simple least squares (LSE)	0	190	17.8	940	53.3	55.4	109
Root mean square error (RMSE)	1	6.22	3.16	21.9	6.03	6.19	5.19

Table 17: Statistical performance measures for calibration and validation for Sideline 26 (from Charbonneau, 2016)

Evaluation Functions	Value of Perfect Measure	Basin 1		Basin 2	
		2013	2014	2013	2014
Nash-Sutcliffe efficiency (NSE)	1	0.502	-82.3	-11.2	-3.79
Coefficient of determination (R2)	1	0.12	0.01	0.03	0.06
Standard error of estimate (SEE)	0	0.362	0.291	0.312	0.231
Simple least squares (LSE)	0	538	461	398	291
Root mean square error (RMSE)	1	12.7	10.5	10.1	10

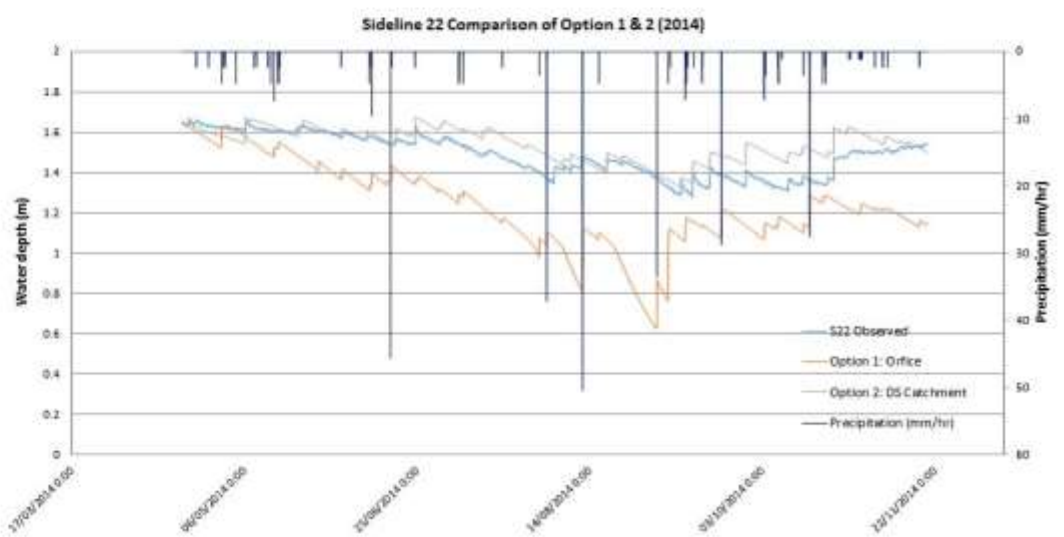


Figure 56: Results of validation for Sideline 22, showing difference between showing the representation of lateral groundwater outflow using both option 1 (orifice) and option 2 (catchment-aquifer unit) (from Charbonneau, 2016)

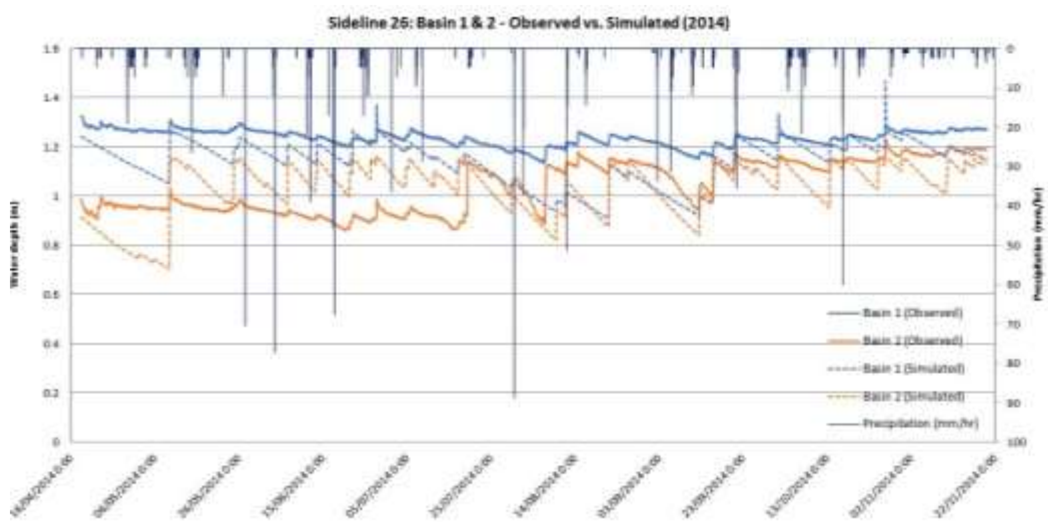


Figure 57: Results of validation for Sideline 26, showing monitored and calibrated water levels for both Basin 1 and Basin 2 (from Charbonneau, 2016)

For Sideline 26, the model showed a reasonable agreement between monitored and simulated wetland storage dynamics in both Basin 1 and Basin 2. The increase in storage in response to precipitation was occasionally overestimated in Basin 1, and a hypothesized subsurface flow path from Basin 1 to Basin 2 was not replicated but nonetheless the model represents wetland storage dynamics reasonably well.

At Sideline 22, there was a greater discrepancy between the modeled and monitored water levels, particularly in the late fall period. Lateral groundwater loss from the catchment needed to be simulated to account for the fact that no channelized surface water outflow existed at the site. Neither of the two methods used to simulate this water transfer mechanism (i.e., the downstream catchment-aquifer unit and circular orifice approaches, as described in Section 3.5.3) were fully satisfactory in replicating wetland storage dynamics, with the downstream catchment approach underestimating wetland water storage in 2013 while the orifice method underestimated storage in 2014. This shortcoming of the model speaks to the importance of using models that are capable of more explicitly representing groundwater-surface water interactions in settings characterized by a high degree of groundwater interaction such as the Sideline 22 wetland.

3.5.5 SWMM: Proposed Conditions without Mitigation

A post-development scenario was developed for Sideline 22 (only) by consulting preliminary draft subdivision plans for the area of the wetland catchment, which is zoned for residential development with some small commercial lots. The hypothetical development scenario was created based on the preliminary extent of development in the catchment and the proposed lot layout. To simulate the development, the degree of imperviousness in the upstream catchment area was increased from 3.5% to 50% and changing maximum flow path length to 30 m.

Table 18 shows the effect of development on each of the major terms in the water balance equation for Sideline 22. As would be expected for a large increase in the degree of catchment imperviousness, the proportion of water leaving the system as groundwater recharge decreases by nearly 50% (from 192.9 mm to 100.8 mm) while the proportion of precipitation entering the wetland as runoff increases from 12.9

mm to 187.0 mm. A relatively large decrease in total catchment evapotranspiration can also be observed (from 229.7 mm to 144.6 mm). Alterations to the wetland water balance of this magnitude clearly have the potential to lead to degradation or loss of wetland ecological functions as well as potential erosion issues, in the absence of a well-designed water balance mitigation strategy.

Table 18: Comparison of pre- to post-development water balance terms at Sideline 22 (from Charbonneau, 2016)

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

3.5.6 SWMM: Proposed Conditions with Mitigation

A number of scenarios were explored to determine the effect of different mitigation strategies. For the purposes of this review, the two scenarios that best demonstrated the capacity of SWMM to represent LID practices are reported here. These scenarios, referred to as Scenario 6 and Scenario 7, are described below. Both scenarios utilized bioretention cells to detain and infiltrate excess runoff from impervious surfaces. These cells are represented in SWMM as a three layer system (surface vegetated area, engineered soil, and storage layer), with an option to include an underdrain that was not used in this evaluation. The bioretention cells were sized to a 1-hr, 25 mm event. The parameters used to represent the bioretention cells are shown below in Table 19. An analysis of the sensitivity of total catchment infiltration, evapotranspiration, and runoff volume to the bioretention cell design parameters (soil depth, storage layer thickness, vegetation volume, berm height, cell area, and soil hydraulic conductivity) showed that only cell area had a significant effect on the volume of water infiltrated by the cells. As ponded water was rarely present on the cells across a wide range of settings, infiltration volume was seldom limiting, but rather it was the volume of runoff reaching the cells that controlled total infiltration volume.

Table 19: Parameters used in representation of LID practices (bioretention cells) (from Charbonneau, 2016)

Surface Layer	Value
Berm height (mm)	300
Vegetative volume (fraction)	0.10
Surface roughness (-)	0.0
Surface slope (%)	0.0
Soil Layer	**Value**
Thickness (mm)	200
Porosity (-)	0.40
Field capacity (-)	0.105
Wilting point (-)	0.047
Conductivity (mm/hr)	60
Conductivity slope (%)	5.0
Suction head (mm)	60
Storage Layer	**Value**
Thickness (mm)	200
Void ratio (voids/solids)	0.7
Seepage rate (mm/hr)	5.5
Clogging factor	0.0

For Scenario 6, 88% of the impervious area in the catchment (driveways, roofs, and portion of right-of-way) was treated by bioretention cells. From this treated runoff volume, 40% of the roof area runoff was diverted from the bioretention cells to a rainwater harvesting system, represented as a "rain barrel" in SWMM. This scenario represented the maximum extent of infiltration practices that could be used without exceeding the pre-development groundwater recharge volume. The bioretention cells were insufficient to mitigate the full excess runoff volume generated, and additional stormwater LIDs in the form of rainwater harvesting were thus required. However, it was noted that SWMM underestimates the volume lost to ET from bioretention cells, as ET cannot occur from the subsurface storage layers. This is a shortcoming of SWMM in long term continuous simulations of LID performance.

For Scenario 7, additional bioretention cell area was added such that 95% of impervious areas were treated. As in Scenario 6, 40% of the roof area runoff was diverted to a rainwater harvesting practice. Scenario 7 represented an "enhanced" recharge scenario, with groundwater recharge exceeding pre-development levels. The authors of this review note that such an option should only be considered in the context of an integrated urban water management plan where enhanced recharge is needed to mitigate factors such as water table drawdown due to external water takings or diversion. As SWMM is not capable of simulating dynamic interaction with groundwater, it would not be an appropriate tool to assess the potential consequences of an enhanced recharge program such as that in Scenario 7. Nonetheless, catchment runoff was reduced by >50% relative to Scenario 6, which reduced total catchment runoff to levels approaching but not matching pre-development conditions; the rainwater harvesting system mitigated the remaining unmitigated runoff.

The differences in the surface, subsurface, and total catchment water balance terms between the pre-development condition and Scenarios 6 and 7 are summarized in Table 20 below.

Table 20: Comparison of mitigation scenarios with pre-development water balance terms (from Charbonneau, 2016)

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

3.5.7 SWMM: Benefits, Challenges, Recommendations and References

Benefits:

- The SWMM model is capable of representing many important hydrological processes without requiring excessive input data or highly specialized expertise to operate.
- Representing wetlands as storage units allows for stage-storage and stage-discharge relationships to be defined, and for subsurface flow from the catchment to be transferred to the wetland; storage relationships can also be extended to include shallow subsurface storage.
- The representation in SWMM of LID practices as discrete features within the flow network with variable properties allows for a more realistic simulation of LIDs than simply changing the lumped parameters of the wetland catchment.

Challenges:

- Limitations in the representation of certain groundwater exchange pathways (e.g. lateral outflows from catchment outlet, groundwater mounding beneath LIDs) limit the validity of simulations of wetland storage dynamics where these processes constitute a large proportion of the overall water balance.
- The inability of SWMM to simulate ET from the soil layer of LIDs means that the ability of LIDs such as bioretention cells to mitigate excess runoff via evapotranspiration is likely underestimated in long-term simulations.

Recommendations:

- Wetland water balance modelling is an iterative process, and additional water transfer mechanisms should be added to an initial simplified water balance equation as the monitoring data and calibration process reveal their existence.

- It is critical to have multiple years of monitoring data to be able to isolate hydrological processes that are associated with wet or dry conditions or that vary seasonally; data should always be analyzed at multiple timescales (annual, seasonal, monthly, weekly, diurnal) to help isolate these processes.
- Independent estimates of certain water balance terms (e.g. ET, vertical groundwater inflow) can help to isolate other processes occurring simultaneously, and methods exist that can be applied to monitoring data for this purpose.
- Detailed topographic information can reduce the uncertainty in the above ground stage-storage relationship for wetland; site-specific information is needed reduce the error associated with the specific yield estimates below ground.

References:

Charbonneau , C. 2016. Hydrologic Analysis for the Protection of Wetlands in Urban Development. Master of Applied Science in Engineering Thesis, University of Guelph. Retrieved from https://atrium.lib.uoguelph.ca

Gasca, D., Ross, D. 2009. The use of wetland water balances to link hydrogeological processes to ecological effects. Hydrogeology Journal 17: 115-133. doi:10.1007/s10040-008-0407-x

McLaughlin, D.L., Cohen, M.J. 2014. Ecosystem specific yield for estimating evapotranspiration and groundwater exchange from diel surface water variation. Hydrological Processes 28: 1495-1506.

Rossman, L. 2015. Storm Water Management Model User's Manual Version 5.1 - manual. US EPA Office of Research and Development, Washington, DC, EPA/600/R-14/413 (NTIS EPA/600/R-14/413b).

United States Environmental Protection Agency. 2015. Storm Water Management Model. https://www.epa.gov/water-research/storm-water-management-model-swmm