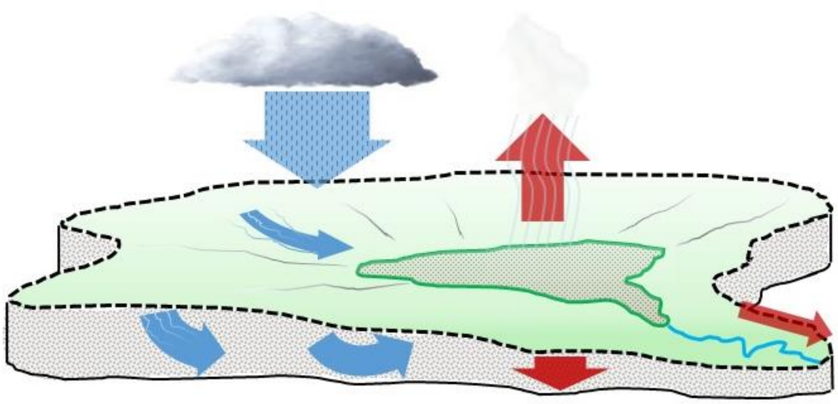

WETLAND WATER BALANCE MODELLING GUIDANCE DOCUMENT (DRAFT)

Toronto and Region Conservation Authority
June 2019

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Figures, Tables, and Equations

How to Read This Document

This *Wetland Water Balance Modelling Guidance Document* (hereafter *Modelling Document*) is intended to outline the approach and procedure for conducting a feature-based water balance modelling exercise for the protection of wetland hydrology, as outlined in the Stormwater Management Criteria Document (SWM Document; TRCA, 2012). The purpose of the modelling exercise is to inform the need for, and the design of, mitigation measures to ensure a minimal difference between the post-development and pre-development water balance of a wetland. This *Modelling Document* provides an overview of wetland hydrology modelling, the strengths and weaknesses of various hydrological models, and the information that needs to be included in a wetland feature-based water analysis report.

The sections of this *Modelling Document* correspond to the template format for a feature-based water balance analysis report, which is also outlined in Appendix A of this document. The intent is that the reader should refer to this document section by section to determine the information that is required in each corresponding section of the report (i.e. section 4 of the *Modelling Document*, outlining the development the conceptual model, corresponds to the information that should be included in the same section of the report).

Note that there is also a companion document to this *Modelling Document*, entitled *Wetland Water Balance Modelling Case Studies*, that outlines set-up, calibration, and validation of wetland water balance models within five commonly used continuous hydrology models (HEC-HMS, HSPF, SWMM, MIKE-SHE, and VO5). This collection of modelling case studies is not intended to be a definitive guide to application of these models, but rather illustrates potential approaches within each model, and the advantages or drawbacks to application of the models to specific scenarios. As model codes and modules change rapidly, other continuous hydrology models not listed in this document or the companion document may be acceptable; proponents are asked to verify alternative modelling approaches with TRCA staff prior to any submissions.

Finally, please note that this *Modelling Document* is intended to be a living document that TRCA staff intend to update periodically as new information and/or modelling approaches become available.

1 Introduction

This *Modelling Document* outlines the methods and procedures for conducting a feature-based water balance modelling exercise for the protection of wetland hydrology, as outlined in the Stormwater Management Criteria Document (*SWM Document*; TRCA, 2012) in *Appendix D: Water Balance for Protection of Natural Features.* The purpose of the modelling exercise is to inform the need for, and the design of, mitigation measures to ensure a minimal difference between the post-development and pre-development water balance of a wetland. Figure 1 below depicts an overview of the model development process, including critical steps for consultation with TRCA and/or the municipality.

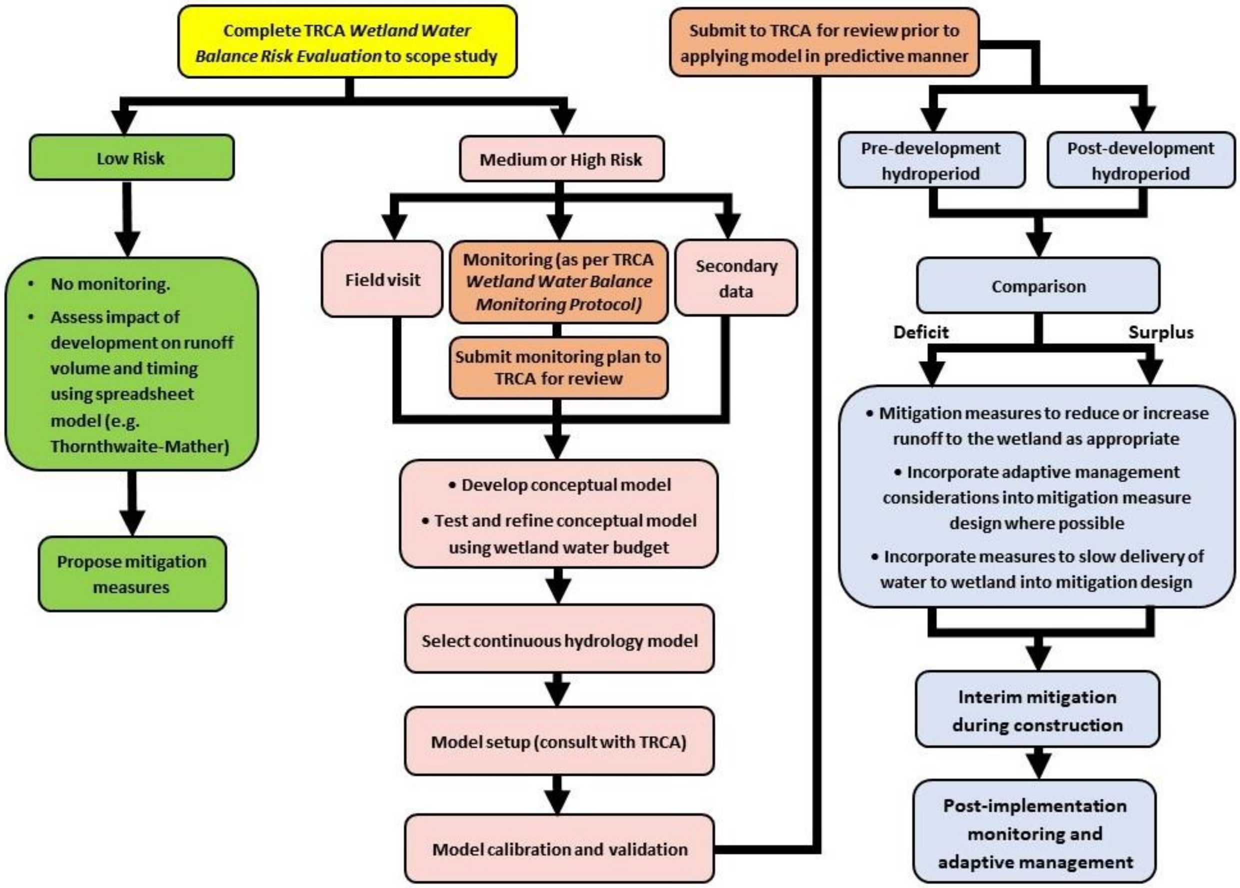


Figure 1: Steps for wetland modelling as part of a Feature-based Water Balance analysis

Proponents of development and infrastructure using this guidance document should refer to the *SWM Document* (TRCA, 2012) for guidance on the overall objectives of feature-based water balance analysis (also referred to as water balance for protection of natural features). The determination of which wetlands will be protected on the landscape is external to any application of this *Modelling Document* and will be made as part of a planning or infrastructure review and approval process. The *Wetland Water Balance Risk Evaluation* (*Risk Evaluation*; TRCA, 2017) should be completed in advance of any application of this guideline to determine the appropriate scope of analysis and type of model to be used. The Risk Evaluation considers the magnitude of potential hydrological change a proposal embodies relative to certain threshold values, as well as the sensitivity of the wetland in question in order to determine an appropriate scope of analysis. The *Modelling Document*, *Risk Evaluation*, and other tools supporting implementation of the *SWM Document* criteria are indicated in relation to the corresponding steps in the *SWM document* in Figure 2.

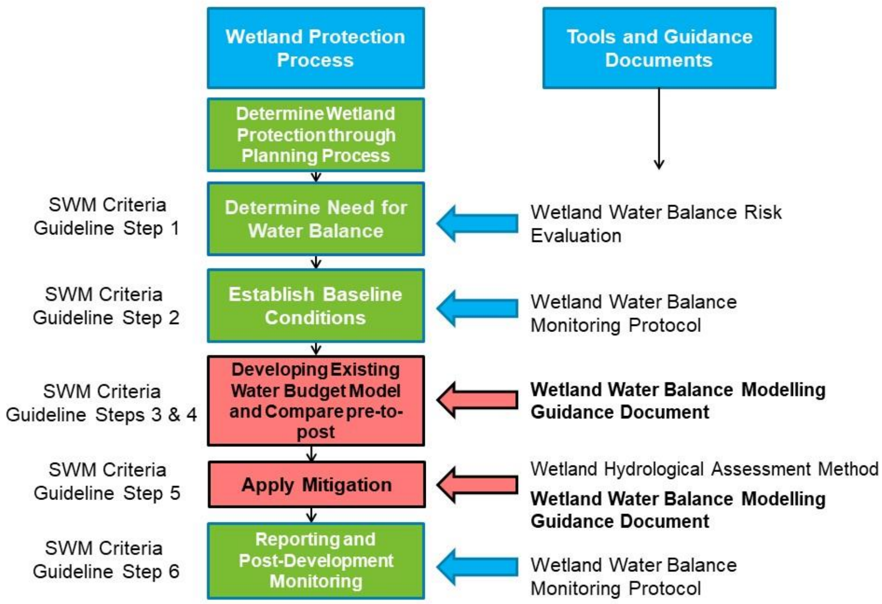


Figure 2: Wetland water balance tools and guidelines and their relation to steps in the SWM Document.

2 Understanding the Hydrological System

This section of the feature-based water balance (FBWB) report must include a discussion of the landscape and hydro(geo)logical contexts of the wetland(s) in question as they relate to the major hydrological processes operating within the wetland under natural (i.e. pre-development) conditions. This discussion should be informed by careful review of existing/secondary information, site surveys, and especially by wetland hydrology monitoring data collected on site.

The hydrology of a wetland directly determines many aspects of its physical, chemical, and ecological characteristics, and as such it is perhaps the most important variable influencing ecological function (Mitsch and Gosselink, 2007). Land development and infrastructure construction can affect the hydrology of a wetland in a number of ways, some of which may have a negative impact on the ecological function of a wetland. For example, water taking directly from a wetland or from an aquifer that discharges directly to a wetland has a clear potential to directly alter the wetland's water balance. Land use change within the surface water catchment of a wetland may alter the water balance by changing the ratio of surface runoff to infiltration within the catchment as well as the proportion of water lost to evapotranspiration. This is an issue particularly when there is a substantial increase in the proportion of impervious cover such as paved surfaces and roofs (Hicks and Larson, 1997; Reinelt and Taylor, 2001). Alteration to the size of the catchment area draining to a wetland due to land grading activities or stormwater management system design also has the potential to significantly change the water balance.

It is important to note that wetland hydrology encompasses much more than the average annual depth of water in a wetland. Aspects of wetland hydrology such as the proportion of total inflow derived from surface water or groundwater, the timing and duration of inflows, and the timing of water level drawdown over the growing season all contribute to the maintenance of a particular ecological function. For example, amphibian species may require water for breeding during spring but may also require habitat to be seasonally dry to prevent predatory fish from establishing in this habitat. Similarly, some obligate wetland plants will be outcompeted by facultative upland plants if a wetland dries out too early, leading to shifts in the ecological community. Significant differences in wetland ecology and associated ecosystem services can occur between relatively small differences in hydrological regime on the order of tens of centimeters (Baldwin *et al.*, 2001; Mitsch and Gosselink, 2007; Moor *et al.*, 2017).

The term *hydroperiod* is used to refer to the pattern of water level change within a wetland over time, both above and below ground, and is a measure of the net sum of interaction between the different water balance components (i.e. the change in storage). The *hydroperiod* is a key measure by which to track changes in the water balance over time, and is the primary focus of wetland hydrological monitoring, as outlined in the *Wetland Water Balance Monitoring Protocol* (TRCA, 2016).

Under increasing urbanization, ecosystem services provided by wetlands will be affected unless their hydroperiods are protected through implementation of water balance mitigation measures. The design of functioning wetland mitigation measures requires a proper understanding of the wetland hydrological system. A sound conceptual understanding of the wetland hydrological system is a prerequisite to assessment of the impact of any anthropogenic activities on the wetland hydrology. Also, lack of a proper conceptual understanding of how the wetland works will lead to selection of invalid models, which will then result in ineffective mitigation measures.

The hydrology of wetlands can be very complex. Some wetlands discharge to groundwater, while others are recharged by groundwater. Some will retain water year round while others may be dry for part of the year. Depending on the type and condition of vegetation and the amount of open water, evapotranspiration rates will vary greatly. Antecedent conditions of soil moisture and amount of water already stored in the wetland will affect how much storage is available for runoff. Hydrological models are tools that aid in understanding the interaction of the different components of the water balance by providing a simplified representation of these interactions. Provided that this simplified representation is sufficiently complete, good models allow different land use and stormwater management scenarios to be explored in a way that would not be otherwise possible, thereby helping engineers and other professionals come up with designs that minimize the difference between the pre- and post-development wetland hydroperiod.

In evaluating the hydro(geo)logic and landscape context of the wetland, proponents should start by reviewing available studies and datasets that conservation authorities and different levels of government have initiated. For example, regional groundwater studies, watershed and sub-watershed studies, geological and land cover maps, are all helpful in providing the landscape context for the FBWB study.

Following a review of existing/secondary information, the next information sources should be field inspections to verify existing conditions on the ground. Field visits can help confirm if overland drainage patterns inferred from secondary information reflect site conditions, or if features such as culverts or tile drains may cause conditions on the ground to differ from expectations. Field-based hydrology monitoring data on wetland storage dynamics and channelized surface flow is crucial to developing a better understanding of the wetland hydrological system, and can reveal a great deal about how the system functions.

In developing a better understanding of the wetland hydrological system through collected monitoring data and secondary sources, it may be helpful to consider the following questions:

1. What are the dominant water transfer mechanisms between the wetland and its surroundings?
2. How long does the wetland contain standing water?
3. Do the maximum depth and areal coverage of surface water change from year to year?
4. How quickly do water levels draw down during extended dry periods?
5. What is the wetland hydroperiod response to precipitation events?
6. Is the amount of surface water flowing into the wetland roughly equal to the amount flowing out?
7. What is the relationship between groundwater head and wetland water levels?
8. Is the hydraulic gradient in the wetland mostly upwards or downwards, and what is the hydraulic conductivity of the soil?
9. How do these observations relate to the observed distribution of wetland habitat?

The first step in attempting to answer these questions should be to construct simple time series plots of the wetland water levels and any data on nearby groundwater levels, surface water flows, etc., with all data displayed on the same plot. Trends should be visually analyzed at different time scales (hourly, daily, weekly, monthly) to identify periodicity and likely water sources and transfer mechanisms. Water sources and transfer mechanisms may vary throughout the year according to season.

3 Developing a Conceptual Model

This section of the FBWB report must include a conceptual diagram of the wetland showing all important hydrological sources, sinks, and transfer mechanisms, and the relationships between them. Any assumptions must be discussed and justified. For some wetlands, it will be necessary to have more than one conceptual diagram to describe its hydrology during different seasons or under different conditions.

After the practitioner has developed a conceptual understanding of the wetland hydrological system, a conceptual model should be developed to represent the important sources, sinks, and transfer mechanisms. A conceptual model should be in the form of a simplified diagram that provides a functional description of the hydrological system under pre-development conditions. The conceptual model needs to represent the main hydrological components and their interrelation, and needs to be suitable for implementation in a mathematical model. Figure 3 below illustrates two examples of conceptual diagrams for wetlands with slightly different hydrological components.

Conceptual models should always be written down and using an annotated diagram showing water transfer mechanisms, such as precipitation, evaporation, evapotranspiration, surface flow (overland flow, channelized flow and lateral flow in the unsaturated zone), over-bank flow and groundwater discharge and recharge, along with the structure of the underlying geologic strata. If water transfer mechanisms operate differently at different times (e.g. seasonally, or during dry and wet conditions) then different diagrams should be utilized to show variations of the water transfer mechanisms occurring in the wetland at those different times.

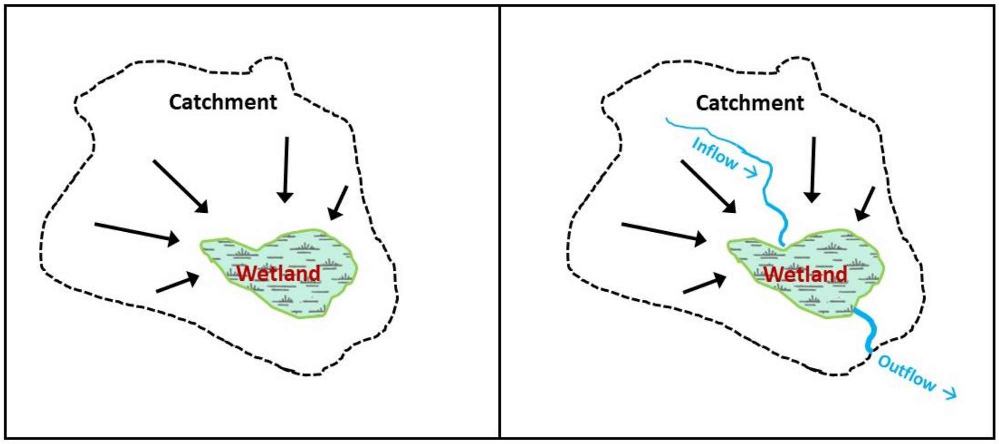


Figure 3: Conceptual diagram of a wetland with no channelized surface inflows or outflows (left) and a wetland with both channelized surface inflows and channelized outflows (right)

The FBWB report must discuss the conceptual model used to characterize the hydrology of the wetland under study. Conceptualization and characterization of the wetland will assist in selection of an appropriate hydrological model as it will help to define the significant water transfer mechanisms of the wetland hydrology and their interrelationships. The spatial boundary of the storage unit in the model representing the wetland and the temporal resolution requirements can be determined from the wetland characterization. Generally, the storage unit and its associated ratings curves (e.g. stage-storage curve) should be determined from the maximum observed water level. As the water transfer mechanisms in the wetland may vary seasonally, selection of the temporal resolution to be used in the computations must take into consideration the seasonal variability of the water transfer mechanisms of the wetlands. Conceptualization will also determine how lumped or detailed the modelled hydrological processes need to be. Any assumptions must be fully discussed and justified.

4 Testing and Refining the Conceptual Model Using a Water Budget Model

This section of the FBWB report must show the refinement of the conceptual model by quantifying rates of water transfer between model components via the transfer mechanisms previously identified in Section 3. A water budget model, as described below, should be used to determine if the components and transfer mechanisms identified in the conceptual model can adequately explain the observed wetland storage dynamics. If missing components or transfer mechanisms are identified, the water budget model should be refined as necessary. At this stage of the FBWB study, the model should be run using a monthly time-step.

The understanding of the wetland hydrological sources, sinks, and transfer mechanisms developed for the conceptual model next need to be tested, validated, and refined using a tool that allows quantification of water transfer rates through each transfer mechanism. A water budget model is a tool for quantifying the transfer of water in and out of the wetland via different pathways. This model can be a spreadsheet-based tool that uses appropriate equations to calculate the transfer rates and corresponding storage dynamics, or it can be any modelling software that allows quantification of water transfer rates through different transfer pathways over a given time period. The water budget model outputs should be on at least a monthly basis to enable comparison with the observed responses of the wetland hydroperiod, and to test the appropriateness of the conceptual understanding of the wetland water balance.

4.1 Water Budget Model

The approach (i.e. spreadsheet calculations, modelling software) for the water budget model should be selected based on the understanding of the conceptual model. It may be found that the modelling approach may need to be revised as the qualitative understanding of the conceptual modelling is refined based on the difference between observed and simulated wetland storage dynamics.

To assess the transfer of water into and out of the wetland, the wetland should be viewed as a single open system. The system boundary should be drawn around the wetland by projecting the spatial wetland boundary vertically upwards and downwards to horizontal planes at the top and bottom of the system. The establishment of boundaries allows for a balance approach representing the movement of water into and out of the wetland system to be applied. The water balance of any bounded environmental system follows the principle of conservation of mass, and represents a budget of inputs, outputs, and storage of water in the system. The movement of water within the wetland system can be expressed using a water balance, an equation that accounts for water inflows to and outflows from the system. The wetland water balance equation is basically a routing procedure that sums the water inputs into and out of the wetland area, and the storage in the wetland. The wetland water balance can be described in the general form as follows:

$$\text{INFLOWS} - \text{OUTFLOWS} = \Delta\text{STORAGE} \qquad \text{Equation 1}$$

A more specific form of the water balance equation, which decomposes inflows and outflows into their constituent elements, is given in along with a conceptual diagram in Figure 4 below.

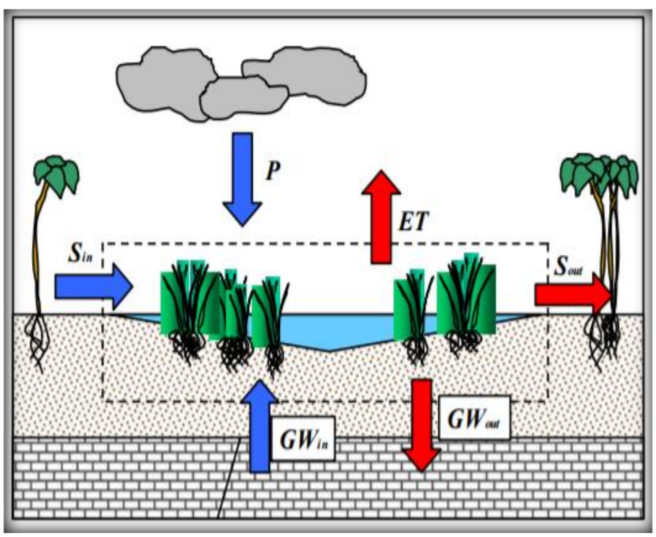


Figure 4: Conceptual representation of a wetland water balance

$$(P + S_{in} + GW_{in}) - (ET + S_{out} + GW_{out}) + \mu = \Delta S \qquad \text{Equation 2}$$

Where:

- P is precipitation in the form of rain or snow on the wetland catchment;
- S_{in} is the surface runoff into the wetland;
- S_{out} is the surface runoff out of the wetland;
- GW_{in} is the groundwater seepage into the wetland;
- GW_{out} is the groundwater seepage out of the wetland;
- ET is evapotranspiration from the wetland;
- μ is the residual; and
- ΔS is the change in water storage of the wetland.

In , the components on the left side represent the inputs (additions) and outputs (losses) to and from the wetland, while the right hand side represents the cumulative change in storage. An error term, µ, is added in order to account for some degree of measurement error. Each of the terms of the water budget can be expressed as depth of water per unit time (L/T) or as volume of water per unit time (L^3/T). The resultant equation quantifies the change in water storage over time as a function of water related inputs and outputs occurring in the wetland over the study period. Water balance analysis allows the conceptual understanding of the wetland hydrology to be refined by identifying gaps in understanding and missing inflows or outflows. A good strategy is to calculate the water balance for a single year representative of long-term average climate conditions, and then to calculate under years representative of relatively wet and relatively dry climatic conditions.

The water balance analysis should be undertaken for the wetland itself as a single hydrological unit. However, there are some complex wetlands which may be impossible to represent as one hydrological unit. For these complex wetlands it is appropriate to subdivide the wetland into two or more hydrologically distinct units, and the water budget should be calculated separately for each of the different hydrological units. Figure 5 below shows a wetland that has two features which are connected when the northern feature is filled and overtops the berm or the divide and flows into the southern feature. It should be noted that during more frequent events these two features may not be hydraulically connected on the surface. However, during major events they are hydraulically connected. In wetland systems such as this, it may be practical to divide the wetland into different hydrological storage units. For such complex wetland systems, calibration will likely be improved if monitoring data is available for each of the wetland hydrological storage units.

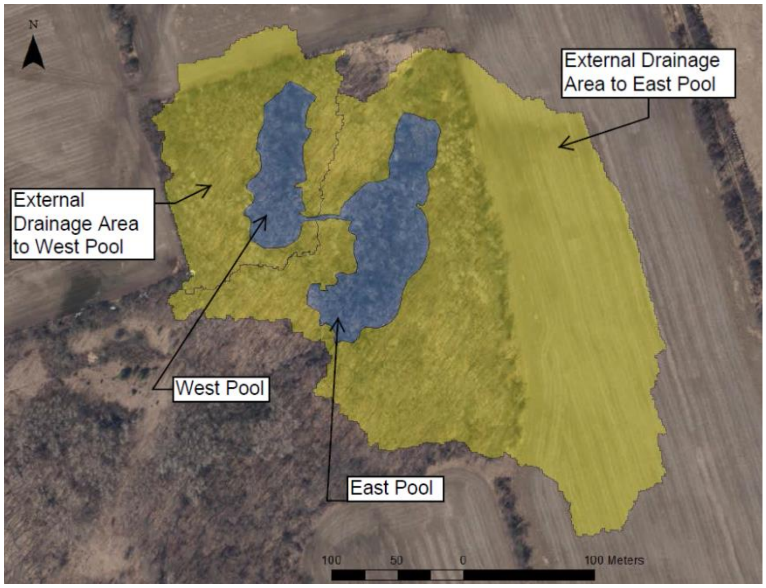


Figure 5: Example of wetland with two distinct hydrological units or pools

In the next sections, each of the water balance components will be discussed in terms of the common methods of estimation available. **For additional information, including governing equations for various water balance components and for potential data sources, the reader should refer to Appendix B**.

4.1.1 Precipitation

Precipitation, in the context of estimating a wetland water balance, refers to the quantity of direct precipitation received by the wetland and surrounding catchment area. Precipitation is most often estimated from the precipitation recorded by a network of gauges, such as those operated by provincial and federal agencies, conservation authorities, and municipalities. Interpolation of precipitation totals, on both an event and an annual basis, is preferable to estimates based on a single point of measurement, as spatial variability associated with precipitation can lead to substantial error and uncertainty. This may be a particular problem in cases where precipitation is a dominant input into the wetland system and a more precise precipitation estimate is needed. There are several methods available for estimating average precipitation from a network. The three most common methods for computing average precipitation within an area are the arithmetic mean, the Thiessen Polygon Method, and the Isohyetal method. There are abundant resources available to assist the proponent in applying each of these methods of calculation, and therefore they are not repeated here.

The steps used to quantify the precipitation component of a wetland water balance are outlined below in Figure 6.

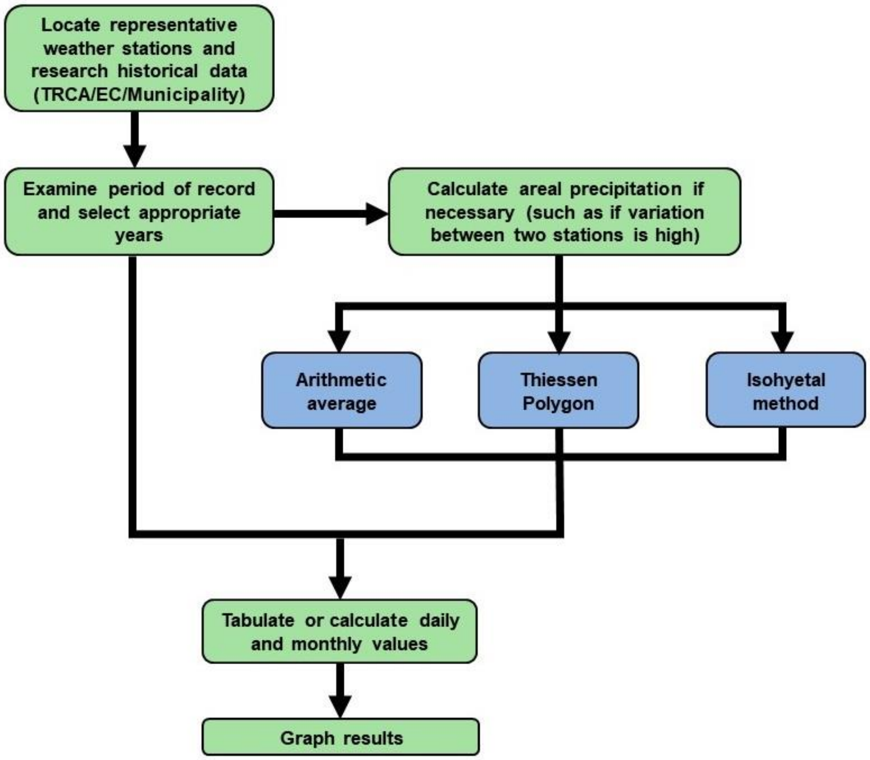


Figure 6: Flow chart for the calculation of the precipitation component of a wetland water budget.

4.1.2 Surface Flow

Surface flow into a wetland can be derived from channelized flow (streamflow), non-channelized flow, and seasonal or periodic inputs from lakes, ponds, and rivers during high water periods. Surface water outflows from wetlands that have precipitation as their dominant input are typically highest during the wet season. However, in wetlands which have major inputs of groundwater, surface water outflows may be more evenly distributed throughout the year. Presence of surface water within a wetland throughout the year depends on the temporal balance of inflows and outflows. Generally, in southern Ontario, runoff rates are highest during the spring due to the combination of abundant rainfall, saturated soils, low evapotranspiration rates, and snowmelt contributions. Runoff rates from May through October tend to be low as evapotranspiration is high and drier soils have greater capacity to infiltrate moderate- and low-intensity rainfall events. Runoff typically increases through fall as plants enter senescence and evapotranspiration decreases. Runoff rates are variable through winter depending on patterns of precipitation and air temperature.

The sections below outline methods that can be used to estimate non-channelized flow from the wetland catchment and channelized flow draining into the wetland.

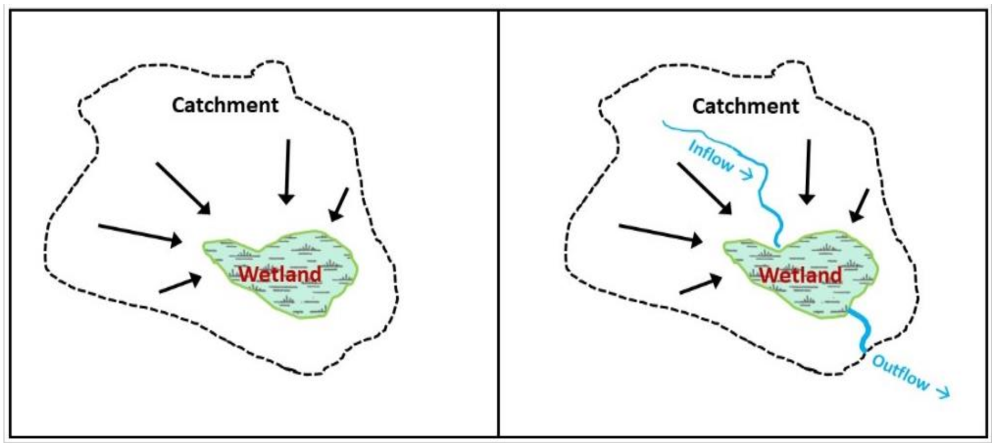


Figure 7: Wetland receiving non-channelized flow only (left) and wetland receiving both non-channelized and channelized flow (right)

Non- channelized Surface Flow

As field measurements of diffuse overland flow are quite challenging, generally a simple modelling approach is used to estimate the volume of overland flow generated by contributing catchment areas. The United States Department of Agriculture's Soil Conservation Service (SCS) developed the curve number (CN) method (SCS, 1972), a simple model to estimate surface runoff volumes generated by a catchment for a given precipitation event. The CN method is widely used and was developed initially for application in small- to medium-sized rural catchments across the United States. To apply the CN method, the contributing catchment area is first divided according to land-use types. An appropriate CN value for each land use type is determined from a lookup table (see Table B1, Appendix B) and a single CN value based on the weighted area of the individual CN values is used to determine the value of potential storage (S) in the CN equation (SCS, 1972).

For more information on the SCS curve number method, relevant equations, and CN lookup values, see section B1 in Appendix B.

Channelized Surface Flow

If the wetland receives surface water in the form of channelized flow, it may be possible to make direct measurements using weirs, flumes, and stage-gauging techniques. Accurate field-based streamflow measurements can provide valuable input data to inform wetland water balance analysis. By establishing the cross-sectional area of flow (A, m^2) associated with each stream or channel stage, the continuity equation can be used to calculate discharge (Q, m^3/s). The velocity component (V, m/s) of the continuity equation can be calculated using Manning's Formula (Manning, 1891). Appropriate values for Manning's roughness factor can be found in Table B2, Appendix B.

In circumstances in which direct discharge measurements using weirs and flumes cannot be made, or in which data is not available, hydrological models may be used to estimate channelized flows. Although models are simplified representations of natural hydrological systems, they are nonetheless valuable tools for quantifying different components of the water balance. Selection of the most appropriate model depends on the ultimate objective of the surface water study and the characteristics of the wetland catchment in question; see section 5.3 and section 5.4 for more information on selection criteria for continuous hydrology models.

The steps used to quantify the surface water portion of a wetland water budget are summarized in Figure 8. All non-channelized surface flow that enters the wetland from the surrounding catchment can be quantified using the runoff curve number or model another hydrological model with the capability to simulate surface runoff from the catchment area. Channelized flow can be estimated using the continuity equation in combination with measured stage-gauge data, or else by using a continuous hydrology model. Quantification of channelized flow using a hydrology model may minimize the need to collect data at a particular site for wetland water balance analysis, but field data may reduce some uncertainty introduced by the simplification of the wetland hydrological system in the model and the selection of model parameters. More information on field monitoring procedures and requirements can be found in the *Wetland Water Balance Monitoring Protocol* (TRCA, 2016).

The sum of channelized and non-channelized flow values constitutes the overall surface water input to the wetland system. An adequate assessment of surface water inputs is important for all wetlands, but for riverine and other surface-water-driven wetlands it is critical. Contributions of non-channelized and channelized flow must be quantified for all sites. Daily and monthly surface water flow values must be calculated for representative wet, dry, and average years. These values should be converted to units of depth per unit time and graphed alongside the other components of the water budget.

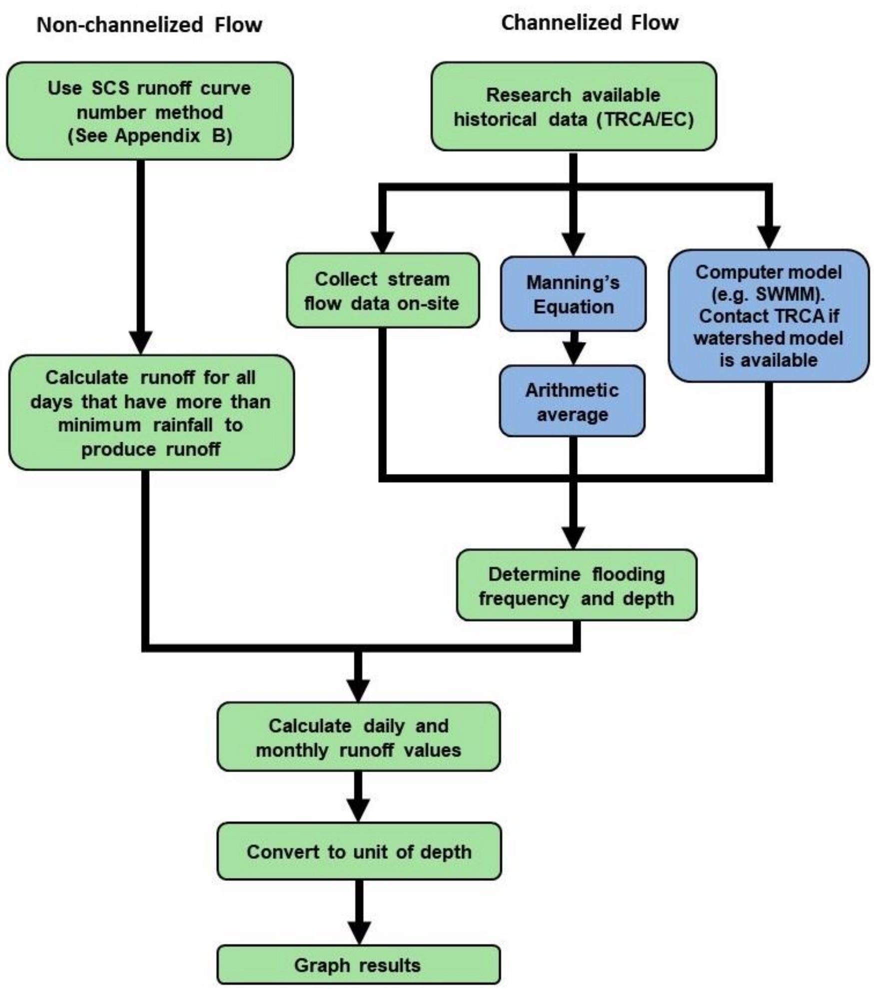


Figure 8: Steps used to quantify surface-flow

4.1.3 Evapotranspiration

Evapotranspiration refers to the loss of water to the atmosphere in the vapour phase from both evaporation (from surface water bodies and soil water) and transpiration (water passing through plants via transpiration). Evapotranspiration (ET) rates from a wetland are affected by several meteorological, physical, and biological variables, including solar radiation, surface temperature, wind speed, relative humidity, available soil moisture, and vegetation type and density. Evapotranspiration varies both seasonally and daily. The evapotranspiration rate is higher during periods when plants are actively growing and transpiring than during periods when they are dormant (Carter, 1996), and tends to be lower at night and on cool, cloudy days and higher on hot, sunny days.

Generally, empirical methods for estimating ET are used to calculate potential evapotranspiration (PET), which is subtracted from the available surface water or soil moisture in the wetland at a given time to calculate actual evapotranspiration (AET). PET rates assume that ET is not limited by water availability; if there is no water left for the atmosphere to extract from the wetland surface and soil, such as during exceptionally dry periods in summer or late fall, then no ET takes place, and AET is lower than PET. As a rule, AET will never exceed PET.

It should be noted that estimating evapotranspiration (ET) is one of the most challenging components of a wetland's water balance to calculate because of the complexity of monitoring this flux and its high variability in time and space. Evapotranspiration rates vary during different growth periods of vegetation communities. A variety of methods are available to estimate ET,

	Method					
Variable	Thorn-thwaite (1948)	Hargreaves *et al.* (1985)	Makkink (1957)	Turc (1961)	Priestley-Taylor (1972)	Penman-Monteith (1965)
Temperature	Required	Required	Required	Required	Required	Required
Humidity				Required		Required
Wind Speed						Required
Radiation		Required*	Required**	Required**	Required***	Required***
No. of daylight hours	Required					
Saturated Vapour pressure						Required
Ground Heat Flux					Required	Required
Resolution	Monthly	Daily	Daily or finer	Daily	Daily or finer	Daily or finer

*Daily radiation at top of atmosphere, as calculated using global solar constants according to latitude and Julian day
**Insolation, or incoming shortwave radiation (only)
***Net radiation, or incoming minus outgoing radiation

Table 1: Comparison of several ET estimation methods in terms of required parameters

including direct-measurement procedures and empirical formulas; however, it has always been a challenge to determine the accuracy and practicability of these methods. Generally, the Penman-Montieth method (Monteith, 1965) is considered the most accurate available empirical method, but requires a number of parameters that may be difficult and/or expensive to measure. For this reason, other estimation methods for ET, requiring a reduced set of input parameters, are more commonly used.

Table 1: Comparison of several ET estimation method below outlines the data requirements for a number of ET methods. More information on a number of empirical equations and their application is provided in Appendix B. The first step should be to establish what meteorological data are available within a reasonable vicinity of the study site, as the parameters available will dictate which methods may be applied. Alternatively, if no suitable data is available, proponents may wish either to collect direct measurement data, or to supplement existing station data with data collected on-site for use with empirical methods. Typically, Environment Canada stations have daily temperature and some have radiation data that can be used as input parameters to estimate ET; some conservation authorities and municipalities may have additional meteorological stations with data for relevant input parameters.

The steps used to quantify the ET portion of a wetland water budget are shown below in Figure 9.

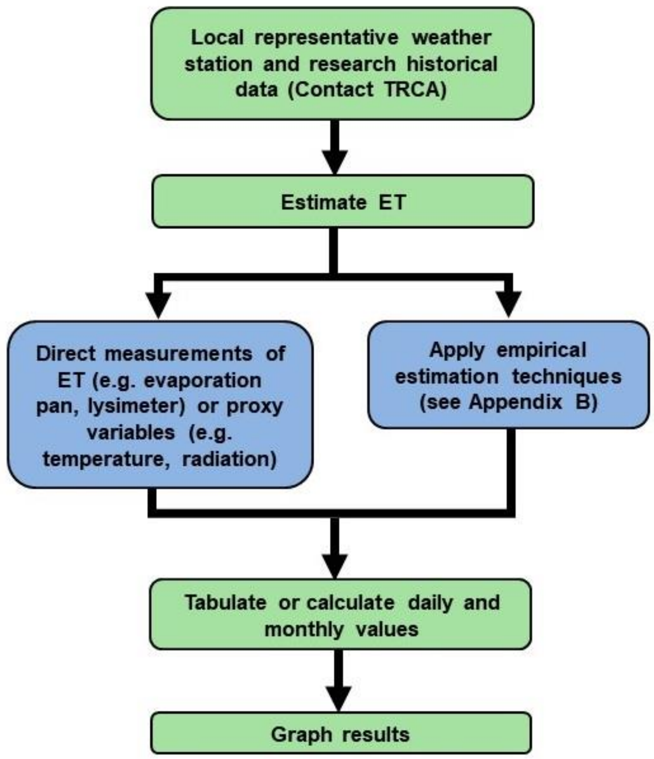


Figure 9: Steps used to quantify the ET component of a wetland water balance

4.1.4 Groundwater flow

Although accurate estimation of the groundwater component of the wetland water balance can be challenging due to the cost of subsurface investigations, estimates of the groundwater flux can be critical to the assessment of water budgets. TRCA advises applicants to begin by researching existing and historical groundwater information in the vicinity of the subject wetland. Regional groundwater datasets, such as that maintained by the Oak Ridges Moraine Groundwater Program, may be useful in this regard. Determining what is known about groundwater and the subsurface environment within the study area will help to determine the amount of data that needs to be collected on-site. Collection of on-site data is often essential to understanding groundwater exchange between the wetland and the surrounding area, as the hydrogeologic environment can vary dramatically over short distances. Collection of hydrological monitoring data, as per the TRCA *Wetland Water Balance Monitoring Protocol* (2016), can help to ascertain local conditions. Drive-point piezometers can be installed by hand within the wetland, including at multiple depth intervals to estimate vertical hydraulic gradients and hydraulic conductivity, and are a much cheaper alternative to drilled wells for investigating the local groundwater environment.

For some wetlands, it may be possible to find an analytical solution to Darcy's Law or various derived forms of Darcy's Law and thereby calculate flow across a series of two-dimensional planes or sections surrounding the wetland. However, for wetlands and aquifers with more complex geometries, or sites dominated by bedrock, an analytical solution using Darcy's Law may not be possible. Under these circumstances, a numerical groundwater flow model can be used to simulate groundwater flow. Numerical groundwater flow models are mathematical representation of an actual groundwater system that can be used to predict water levels as well as the direction and magnitude of flow. Models range from simple to very complex in terms of data-input requirements, calibration requirements, and data output. An internally drained wetland where the outflows from the wetland are only groundwater outflow and evapotranspiration will definitely require a complex numerical ground-water flow model to accurately estimate the groundwater flow exchange between the wetland and the surrounding areas. The applicant should consult with the local conservation authority to determine if there any existing calibrated numerical groundwater flow models.

For both the analytical and modeled solutions to estimating the groundwater component of the water balance, it is critical that wells are installed such that they can adequately characterize water table fluctuations and groundwater movement across the site. The hydraulic conductivity of local aquifers and aquitards must be determined from soil borings, wells, infiltrometers, permeameters, and/or aquifer tests. Daily and monthly groundwater flux rates should be tabulated and graphed for the monitored time period; multi-year data sets may be needed to adequately characterize groundwater interaction, particularly at sites where groundwater head is a dominant control on wetland water levels. Figure 10 outlines the steps used to quantify the groundwater component of a wetland water balance.

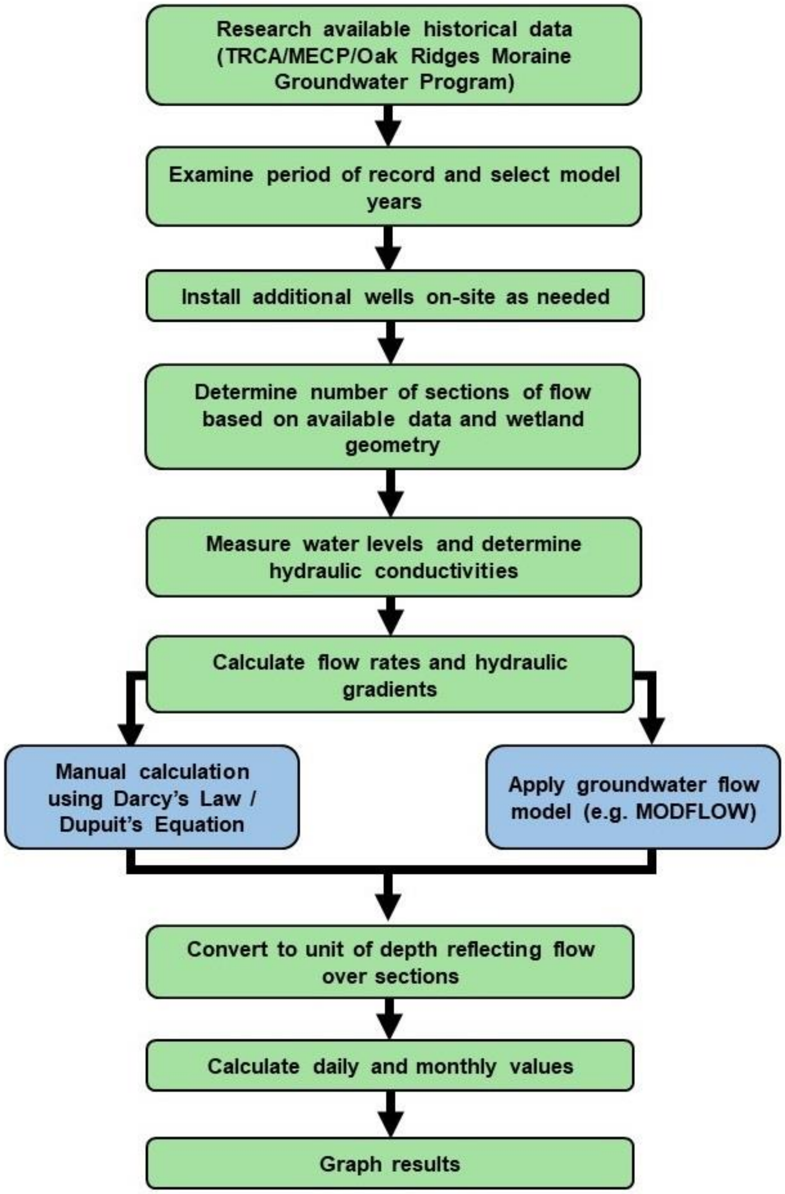


Figure 10: Steps used to quantify the groundwater component of a water balance

4.1.5 Change in Storage

Total storage in a wetland consists of the sum of surface water, soil moisture, and groundwater within the model-defined wetland boundary. The change in storage (ΔS) in a wetland over any period of time represents the difference between the inflows to and outflows from the feature; if the water balance calculation yields a negative ΔS value, more water is flowing out than in, and the opposite is true for a positive ΔS value. The change in storage is essentially equivalent to the *hydroperiod* of the wetland, or the rise and fall of water levels above and below ground within the wetland, as defined in the *Stormwater Management Criteria* (TRCA, 2012). The hydroperiod is the most important variable for monitoring to capture, as outlined in the *Wetland Water Balance Monitoring Protocol* (TRCA, 2016). Monitoring of the hydroperiod is generally most effective when instruments are installed such that the water levels within the lowest points of the wetland, and closest to the center, are captured.

For the standing water portion of a wetland's hydroperiod, ΔS (in units of depth) is equal to the change in water level (stage) multiplied by the area affected; these parameters are related via a stage-storage curve outlining the volume stored in the wetland at each stage. Various techniques with differing levels of accuracy can be used to develop a stage-storage curve, but are beyond the scope of this guideline. A stage gage can be used to help measure change in storage for the standing water portion of the hydroperiod, although important elements of the storage dynamics such as precipitation event response may be lost in the absence of a data logger.

For the below-ground surface portion of a wetland's hydroperiod, ΔS is equal to the change in measured water level multiplied by the specific yield of the sediment. Soils containing a high sand content tend to have a higher specific yield than soils with a higher proportion of silt and clay particles. Some residual storage water remains in the unsaturated zone above the water table when the water table elevation decreases; however, this quantity of storage may be negligible while the water table remains close to the ground surface. Some continuous hydrology models have the capacity to calculate the soil moisture component of ΔS.

Calculating ΔS from monitoring data using one or both of these data-based methods serves as a useful check against the value of ΔS calculated through the water balance approach. The difference between monitored and modeled ΔS can help to quantify the total error/uncertainty in the model, although it is less helpful in distinguishing between sources of error among individual components of the water balance.

4.1.6 Uncertainty/Errors

All water balance calculations have some inherent degree of uncertainty. This uncertainty results from both natural variability within the hydrological cycle and from errors in measurement and estimation. While uncertainty cannot be eliminated, application of appropriate methods can help to both reduce and quantify uncertainty. Calculating the water balance during representative wet, dry, and average climatological years can help to quantify some of the natural variability that may be expected at the site. A sensitivity analysis is a useful tool to help determine how the overall water balance is affected by changes to the magnitude of its individual components. By comparing the change in magnitude of the overall water balance resulting from changes to the magnitude of each individual parameter (e.g. magnitude of groundwater fluxes resulting under different hydraulic conductivity values), the practitioner can quantify the relative sensitivity of each parameter. Additional emphasis should be placed on parameters to which the water balance is especially sensitive in the refinement of the water balance model.

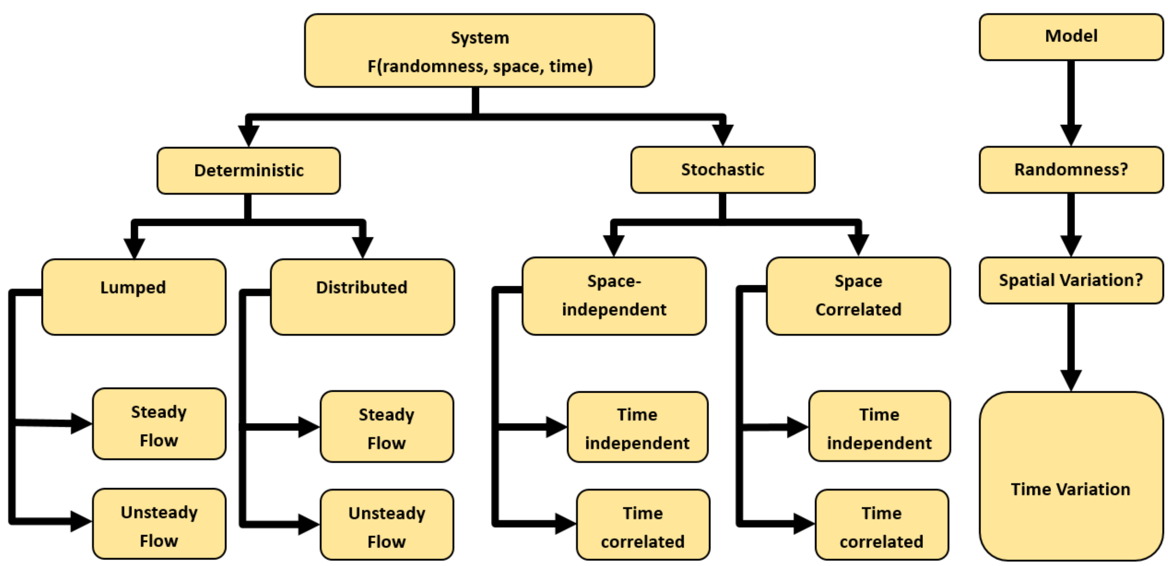
5 Continuous Hydrology Model Selection

This section of the FBWB report must describe the model set-up and the criteria that were used to select a continuous hydrology model as they relate to the objectives of the study. After model setup is complete, TRCA recommends that the applicant submit the model setup to TRCA to discuss before proceeding further to model calibration. This section should describe the procedure that was used to calibrate and validate the model using field monitoring data, including initial and final values of parameters, citing rationale and literature values, as appropriate. TRCA requires that the preliminary model calibration to existing conditions be documented and submitted for review and approval prior to proceeding to the application of the model in a predictive manner.

Continuous hydrology models are simplified representations of hydrological systems, and are the best tool available to practitioners for evaluating the current state of a system against many possible future states (e.g. different land use scenarios or different stormwater management techniques). Models can be broadly understood as a system of equations and logical statements that express relationships between variables and parameters (Clarke, 1973). Whereas parameters are generally assumed to be quantities that are constant in time and represent a fundamental property of the hydrological system (e.g. slope), variables may be measurable and generally assume different values at different times (e.g. storage in a pond) (Clarke, 1973).

Continuous hydrology models can be broadly classified into deterministic versus stochastic models (Chow *et al.* 1988; see Figure 11); deterministic simulation models do not have any random variables, and describe how a mass of water moves through a wetland catchment according to various physically-based hydrological processes. Stochastic models incorporate random variables described by probability distributions. All of the models referred to in this document are deterministic, including HEC-HMS, Hydrological Simulation Program – FORTRAN (HSPF), Precipitation-Runoff Modelling System (PRMS), EPA Storm Water Management Model (SWMM), PCSWMM, VH Otthymo Continuous, MIKE SHE and GSFLOW.

Figure 11: Classification of models, after Chow *et al.* (1988)



Another major distinction within the conceptual framework of Chow *et al.* (1988) is between lumped and distributed hydrological models. Lumped models ignore spatial variability of input variables and catchment parameters, instead subdividing the catchment(s) being represented into hydrologically homogenous units. By contrast, distributed models account for spatial variability of hydrological processes, input data, boundary conditions, and catchment characteristics, representing the catchment as a collection of cells of uniform size. Runoff volumes, determined from hydrological processes occurring within each cell, are routed to adjacent cells based on the direction of slope, down to the catchment outlet.

Hydrological models can be event-based or continuous in their simulation capacity. Event-based simulations represent the catchment hydrological response to an individual rainfall event in terms of runoff quantity, peak, timing, detention etc. In these simulations, which run on timescales of an hour to several days, infiltrating precipitation is omitted from the water balance calculation, "disappearing" into the soil with no further accounting for processes such as interflow or dynamic interaction with groundwater. This is due to the emphasis of these models on characterizing peak flow, to which the contribution of interflow and groundwater is generally believed to be negligible. Event simulation models similarly do not account for evapotranspiration or changes in soil moisture, for the same reason. Continuous models operate over extended periods of time (months to years) and determine fluxes of water via various processes including during periods with no precipitation or runoff. Continuous models also account for infiltrating water, generally routing it into soil moisture storage, groundwater flow, unsaturated flow, and evapotranspiration.

5.1 Why Continuous Simulation for Wetland Hydrology Modelling?

The water input to a wetland catchment reaches and then leaves the wetland on a variety of timescales, producing the seasonal patterns of fluctuations in hydroperiod that are the primary determinant of distinct wetland flora and fauna communities present at a site. Continuous simulation over a longer time period is needed to account for antecedent moisture conditions and the inter-event hydrology of the wetland catchment, and to explore how changes in land use and drainage may affect the hydroperiod of the wetland under the full range of natural conditions that could be expected at a given location. Continuous hydrology models offer a much more detailed representation of the wetland hydrological response under both natural (pre-development) and post-development scenarios, if the model is well conceptualized, calibrated, and validated. Simulation using these types of models therefore provides a more robust basis on which to make decisions about the potential impacts a proposal may have on a wetland and the potential measures to mitigate those impacts.

5.2 Criteria for Selection of Continuous Hydrology Models

Deciding on the right model to simulate wetland hydrology has always been a challenge due to the many factors that must be considered. Hydrological models vary widely in their capabilities, complexity, strengths and weaknesses, making selection of an appropriate model for a specific application difficult (Golmohammadi *et al.*, 2014). Many criteria for model selection will be project-dependent and user-dependent, and therefore somewhat subjective. For example, preferences concerning the graphical user interface (GUI), computer operation system, input-output management and structure, or add-on expansibility, are subject to individual modeler preference and experience.

The following are some of the project-dependent considerations that should be considered in selecting a continuous hydrology model. It might not be possible to be address all concerns in all four areas outlined below, and so selection criteria should be considered iteratively, recognizing that limitations in any of the four areas may restrict choices and thus require re-evaluation of the personnel involved, cost of the exercise, and so on.

A) Objectives of the overall modelling exercise

This consideration is at the very core of a successful modelling exercise. Key questions that need to be answered include:

- Is the broader context of the modelling clear?
- How are the results of the modelling going to be used?
- What specific outputs are needed?
- Where will the model be applied?
- What are the proposed actions that need to be represented in the model?
- Who will be interpreting the results and what decisions will they be making?

Answers to these questions will provide an outline of the basic capabilities required of the models under consideration. Defining the required model outputs defines what the model must be able to represent, and the appropriate scales of time and space for the model exercise. It is very important to consider the main hydrological processes operating in the wetland's pre-development condition, and that may be operating in the post-development condition, based on the best available information about the wetland and the proposed development at the start of the modelling exercise. Generally, the main hydrological processes that need to be considered for inclusion in a continuous wetland hydrology model include precipitation, interception, depression storage, infiltration, overland flow, lateral flow, base (subsurface) flow, stream flow, evapotranspiration, channel routing and reservoir routing.

Other key questions that may help to define model objectives and selection of an appropriate model include:

- Land use: can the model represent existing land use conditions?
- Intended use: is the intended use for planning purposes, engineering/design, or operational performance?
- Model complexity: is a less complex model sufficient?
- Modeler experience: what is the model-specific expertise of current staff? Is there budget to hire an expert?
- Green Infrastructure/LID: does the model has the capability of integrating green infrastructure/LID

When defining the modelling objectives, the modelers and decision-makers should also consider whether the model is required for regulatory compliance, and which models are accepted by the regulatory agency, by consulting with the conservation authority.

B) Availability of input data

The selection of an initial modelling platform based on the identified modelling objectives will define the general data needs. Data limitations are the single biggest constraint to model choice and confidence in results. Without reliable data, there is no reliable way to evaluate the relationship between the simulation results and the conditions in reality.

Some key questions regarding the availability of input data include:

- Are data at the right spatial and temporal resolution available?
- Is there a good understanding of the data accuracy?
- Are the input data collected at the right location, so as to be representative of conditions in the wetland?
- Can all the inputs required by the model be provided within the time and cost constraints of the project?

- How much work is needed to make the data usable in a model?
- If certain data are not available, can they easily be collected?

Failure to consider these questions will likely lead to model results in which there is little confidence.

C) Availability of modelling expertise

Different models require different levels and types of skill to apply and interpret. Important considerations with respect to appropriate expertise include: understanding of the physical processes and catchment behavior involved (e.g. surface water vs. groundwater processes); interpretive and technical understanding concerning models and algorithms; numerical and data manipulation skills; and communication skills (particularly if the modelling is part of a broader development design process). An honest assessment of the capabilities of the team early on will identify major gaps and may limit the type of model the modeler chooses. The overall confidence in a modelling exercise is in general highly dependent on the quality of the modelling team in addition to the model itself.

D) Availability of resources (time and money)

Modelling, data collection, and data manipulation are time consuming. Data are of little use without the expertise for interpretation, and expertise (both technical and non-technical) can be expensive. There will be constraints on total time and money available, possibly limiting the extent to which the original objectives can be met. There will invariably be a trade-off between resources and the extent to which all objectives can be met, and this trade-off needs to be discussed. The modelling team needs to be able to clearly articulate what is reasonable to expect given the available resources, and how an increase or decrease in resources would affect the scope and utility of the modelling exercise.

5.3 Review of Available Continuous Hydrology Models.

Surface hydrology models such as HEC-HMS, HSPF, PRMS, SWMM, Visual OttoHymo, and integrated hydrology models such as MIKE SHE and GSFLOW, have been successfully applied to simulating wetland hydrology and assessing the effect of land use changes on the wetland. A brief description of each of these continuous hydrology models is provided below. As mentioned previously, other continuous hydrology models not listed in this document or the associated case studies companion document may be acceptable, but proponents are asked to verify alternative modelling approaches with TRCA staff prior to any submissions.

HEC-HMS

The US Army Corps of Engineers (US-ACE) Hydrologic Engineering Center HEC-HMS (Hydrologic Modelling System) model is designed to simulate the complete hydrological processes of watershed systems. Hydrological analysis procedures such as event infiltration, unit hydrographs, and hydrological routing are included in HEC-HMS. The model also includes procedures necessary for continuous simulation including evapotranspiration, snowmelt, and soil moisture accounting. Advanced capabilities are also provided for gridded runoff simulation using the linear quasi-distributed runoff transform (ModClark). Supplemental analysis tools are provided for model optimization, forecasting streamflow, depth-area reduction, assessing model uncertainty, erosion and sediment transport, and water quality. HEC-HMS is comprised of a graphical user interface, integrated hydrological analysis components, data storage and management capabilities, and graphics and reporting facilities. Infiltration losses can be simulated for event modelling by initial and constant, SCS curve, gridded SCS curve number, and Green & Ampt methods. The five-layer soil moisture accounting model can be used for continuous modelling of complex infiltration and evapotranspiration environments. Excess precipitation can be transformed into surface runoff by unit hydrograph methods, Clark, ModClark, Snyder, and SCS technique. A variety of hydrological routing methods are included for simulating flow in open channels (lag method, Muskingum method, modified Puls method, kinematic wave or Muskingum-Cunge method). Most parameters for methods included in subbasin and reach elements can be estimated automatically using the optimization manager. Wetland in HEC-HMS can be represented in reservoir routing. HEC-HMS does not simulate groundwater movement explicitly. However, the groundwater recharge and discharge can be calculated externally and the calculated value can be included in the model as point sources.

HSPF

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). Hydrocomp, Inc. developed its present form. HSPF is a comprehensive, conceptual, continuous watershed simulation model designed to simulate all water quantity and quality processes that occur in a watershed, including sediment transport and movement of contaminants (Bicknell et al., 1997). 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. Routing is done using a modified version of the kinematic wave equation. HSPF includes an internal database management system for input and output.

PRMS

The US Geological Survey (USGS) PRMS (Precipitation-Runoff Modelling System) model is a modular-design, deterministic modelling system developed to evaluate the impacts of various combinations of precipitation, climate, and land use on streamflow, sediment yields, and general basin hydrology (Leavesley et al., 1983). In PRMS a watershed can be divided into subunits based on basin characteristics (slope, aspect, elevation, vegetation type, soil type, land use, and precipitation distribution). Two levels of partitioning are available (USGS, 2000). The first divides the basin into homogeneous response units (HRU) based on the basin characteristics. The sum of the responses of all HRU's, weighted on a unit-area basis, produces the daily system response and streamflow for a basin. A second level of partitioning is available for storm hydrograph simulation. The watershed is conceptualized as a series of interconnected flow planes and channel segments. Surface runoff is routed over the flow planes into the channel segments; channel flow is routed through the watershed channel system. Output options include observed (if available) and predicted mean daily discharge, annual and monthly summaries of precipitation, interception, potential and actual evapotranspiration, and inflows and outflows of the ground water and subsurface reservoirs. Parameter-optimization and sensitivity analysis capabilities are provided to fit selected model parameters and evaluate their individual and joint effects on model output.

SWMM

The US-EPA Storm Water Management Model (SWMM) is a comprehensive dynamic hydrological simulation model for analysis of quantity and quality problems associated with urban runoff (CHI, 2003). Both single-event and continuous simulation can be performed on urban basins. Modeller can simulate all aspects of the urban hydrological and quality cycles, including rainfall, snowmelt, surface and subsurface runoff, flow routing through drainage network, storage and treatment. Flow routing can be performed in the Runoff, Transport and Extran blocks, in increasing order of sophistication. Extran block solves complete dynamic flow routing equations for accurate simulation of backwater, looped connections, surcharging, and pressure flow. The hydrological simulation in the Runoff block uses the Horton or Green & Ampt equations where the data requirements include area, imperviousness, slope, roughness, width (a shape factor), depression storage, and infiltration values for either the Horton or Green & Ampt equations for up to 100 subbasins. The program is driven by precipitation for up to ten gages (distributed spatially), and evaporation. Basic SWMM output consists of hydrographs and pollutographs at any desired location in the drainage system. The model performs best in urbanized areas with impervious drainage. The model lacks GUI, but various vendors have developed user-friendly GUIs (OSU-CE, 2003): (PCSWMM – a menu-driven interface developed by Computational Hydraulics International, XP-SWMM or Visual SWMM by XP Software, the Danish Hydraulic Institute GUI for the Runoff and Extran Blocks, MIKE-SWMM).

Visual OttoHymo

Visual OTTHYMO (VO) is a hydrological 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 wetland command is a new feature added to VO 5.0 in 2018. This command is designed to model all the hydrological 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.

MIKE SHE

MIKE SHE is a commercial engineering software package developed at the Danish Hydraulic Institute (DHI). MIKESHE, integrated, physically based, fully distributed, modular, dynamic modelling system, the DHI version of the original SHI (Systeme Hydrologique Europeen) program developed through a joint project of CEH Wallingford, Danish Hydraulics Institute and SOGREAH (France). The model is applicable on spatial scales ranging from single soil profiles (for infiltration studies) to regional watershed studies. MIKESHE includes all of the processes in the land phase of the hydrological cycle: precipitation (rain or snow), evapotranspiration, interception, overland sheet flow, channel flow, unsaturated sub-surface flow and saturated groundwater flow. Evapotranspiration is calculated using the Kristensen and Jensen method. MIKESHE's overland-flow component includes a 2D finite difference diffusive wave approach using the same 2D mesh as the groundwater component. MIKESHE includes a traditional 2D or 3D finite-difference groundwater model. There are three options in MIKESHE for calculating vertical flow in the unsaturated zone: the full Richards equation, a simplified gravity flow procedure, and a simple two-layer water balance method for shallow water tables (DHI, 2000b).

GSFLOW

GSFLOW is the USGS modelling system that integrates the surface and groundwater components of the hydrological cycle. GSFLOW is based on two USGS models namely PRMS and MODFLOW. With GSFLOW, the user has the option to run the codes together in a fully fashion or to run each of the models independently. Within GSFLOW, both codes are fully coupled and capable of providing the feedbacks from surface water to groundwater resources vice versa. It is essential to include such feedbacks within GSFLOW for they affect the timing and rates of evapotranspiration, surface runoff, soil-zone flow, and groundwater interactions (Markstrom et al., 2008). GSFLOW is capable modelling system with potential applications to a variety of research questions, such as (i) how surface water processes affect recharge and water table responses, (ii) how climate change is likely to impact groundwater and surface water, and (iii) surface and groundwater effects on the behavior of springs, wetlands, and ecological systems (Markstrom et al., 2008).

Model Features	SWMM	HEC-HMS	HSPF	VH Ottohymo	PRMS
Model Type	Lumped-parameter	Lumped-parameter	Lumped-parameter	Lumped-parameter	Lumped-parameter
Simulation Type	Single-event/continuous	Single-event	Continuous	Single-event/continuous	Continuous
Watershed subdivision unit	Subbasins	Subbasins	subbasins	NasHyds/StandHyds	Hydrologic Response Units
Precipitation	Single/multiple hyetographs	single hyetograph	multiple hyetographs	Multiple hyetographs	Multiple hyetographs
Snow Melt	Snow accumulation Snow redistribution by areal depletion and removal operations Snow melt via heat budget accounting	Yes	Yes	Yes	Yes
Evapotranspiration	Yes (Modified Hargreaves using temperature, or timeseries input)	No	Yes	Yes	Yes
Infiltration	Green-Ampt Infiltration Curve Number infiltration Horton Infiltration	SCS curve number Initial and uniform loss Exponential loss rate Holtan loss rate Green-Ampt loss rate	Empirical equation based on soil type and available storage	SCS curve number	Green-Ampt during storm mode
Rainfall Excess to Runoff	Physically based, nonlinear reservoir model Kinematic Wave	SCS unit hydrograph Clark unit hydrograph Snyder unit hydrograph Kinematic wave	Manning's equation based on the depth of surface detention of excess precipitation	Nash unit hydrograph Standard unit hydrograph	Kinematic wave
Reservoir storage and routing	Excess volume Under Steady and Kinematic Wave flow routing. In Dynamic Wave routing, the excess volume is assumed to pond over the node with a constant surface area.	Modified-Puls routing Level pool routing	Outflow can be volume or time dependent or user-specified	Modified-Puls routing	Modified-Puls routing Linear-storage routing

Subsurface Soil Water Flow	Computing the water fluxes during given time step using infiltration, evapotranspiration, percolation, seepage, lateral groundwater interflow	Baseflow quantity can be specified	Yes	No	Yes
Channel Routing	Steady flow routing Kinematic wave routing Dynamic wave routing	Muskingum Weighted Inflow Kinematic Wave Muskingum-Cunge Modified Puls Normal Depth Working R and D	Kinematic wave	Variable Storage Coefficient Muskingum-Cunge	Kinematic wave
Reservoir Routing	Steady flow routing Kinematic wave routing Dynamic wave routing	Storage-outflow, Elevation-storage-outflow, elevation area-outflow	Surface area- volume and wind speed	Modified-Puls routing	Puls Linear routing
GIS interface	Interface with GRASS	WMS, Geo-STORM, GISIWAM	no specific interface	Interface with ArcGIS	In development as a component of MMS

Table 2: Comparison of surface hydrological model capabilities

Model Features	MIKE SHE	GSFLOW
Model Type	Lumped-parameter	Lumped-parameter
Simulation Type	Single-event	Continuous
Watershed subdivision unit	Sub-basins	Hydrologic Response Units
Precipitation	Single hyetograph	Multiple hyetographs
Snow Melt	Yes	Yes
Evapotranspiration	Kristensen & Jensen method	Yes
Infiltration	SCS curve number; Initial and uniform loss; Exponential loss rate; Holtan loss rate; Green-Ampt loss rate	Green-Ampt (during storm mode)
Rainfall Excess to Runoff	SCS unit hydrograph Clark unit hydrograph Snyder unit hydrograph Kinematic wave	Kinematic wave
Reservoir storage and routing	Modified-Puls routing Level pool routing	Modified-Puls routing Linear-storage routing
Subsurface Soil Water Flow	Baseflow quantity can be specified	Yes
Channel Routing	Muskingum Weighted Inflow Kinematic Wave Muskingum-Cunge Modified Puls Normal Depth Working R and D	Kinematic wave
GIS interface	WMS, Geo-STORM, GISIWAM	In development as a component of MMS

Table 3: Comparison of integrated hydrological model capabilities

5.4 Model Setup

After going through the steps listed above for scoping the project and selecting an appropriate continuous hydrology model based on the study parameters, model setup can begin. Model setup describes the process of preparing the input data in the correct format, creating the model input files, and undertaking initial simulations. Setup is greatly dependent upon the availability of good quality data and field observations to characterize the study area. Hydrological data must be cleaned from random and systematic errors, otherwise a model may be erroneously rejected, or its calibration otherwise compromised so as to reduce the utility of the model.

In the model setup, there are some differences in the steps required to parameterize hydrological processes in different models. The preparation of inputs for some lumped catchment models is not complex, however data preparation for distributed, physically-based models is typically more complex. That being said, many parameters can be estimated for catchment properties, and therefore during model setup and parameterization, respective model manuals should be consulted and referenced.

Typically, the following input data will be needed for modelling the relevant hydrological processes in most continuous hydrology models:

- High resolution Digital Elevation Model (DEM)
- Land use / land cover
- Soil type and other basin physiographic data (e.g. depression storage coefficients)
- Precipitation and temperature data
- Channel and reservoir hydraulic data
- Stage-storage and stage-discharge data
- Actual or potential evapotranspiration data, or sufficient input data for one of the empirical estimation equations.

The FBWB report must discuss the rationale for model setup, and include a description of the input data preparation and model input files. The report must describe sources of data that are used in the estimation of the parameters for the model and the assumptions that are used in the process. To the greatest extent possible, model parameters should be derived from site-specific observations. The topographic features onsite should be represented at the finest resolution possible and can be derived from digital elevation models or site surveys. Infiltration and recharge parameters, soil zone parameters, and hydraulic conductivities should ideally be obtained from onsite soils analysis or borehole drilling. Land cover mapping should be revised for consistency with the existing site conditions, if required.

As the FBWB methodology outlined in this report requires continuous hydrology modelling, long-term climate data inputs should be prepared for the model simulations. TRCA's *SWM Document* (2012) suggests using climate data from as close as possible to the target site to determine the target (i.e. pre-development baseline) long-term hydroperiod and assessing and mitigating the impact of development. At a minimum, the period from 1991 to 2008, considered to be representative, should be used. This is considered to be a representative period containing wet, average, and dry years. TRCA staff can provide a forcing dataset for the representative period upon request. Model output should be set to daily resolution, which will be used to create weekly, monthly, and annual summaries.

After model setup is complete, TRCA recommends that the applicant submit the model setup to TRCA and discuss with TRCA before proceeding further to model calibration.

5.5 Model Calibration

Watershed models contain many parameters; these parameters are classified into two groups: physical and process parameters**.** A physical parameter represents physically measurable properties of the catchment (e.g. areas of the catchment, fraction of impervious area and surface area of water bodies, surface slope etc.). Process parameters represents properties of the catchment which are not directly measurable e.g. average or effective depth of surface soil moisture storage, the effective lateral inflow rate, the coefficient of non-linearity controlling the rate of percolation to the groundwater. (Sorooshian, and Gupta 1995). Hence in order to utilize any predictive catchment model for estimating the effectiveness of future potential management practices one needs to select values for the model parameters so that the model closely simulates the behavior of the study site. The process by which the parameters are selected is called model calibration. There are two parts to this process: parameter specification and parameter estimation.

Assigning of initial estimates parameters of the model using prior knowledge about the catchment properties and behaviors is called parameter specification. For "physical" parameters, estimates are made using measurements obtained from maps in the field. The parameters are then typically fixed at these measured values and not adjusted further unless determined to be in error. For "process parameters", estimates of the range (minimum and maximum values) of possible values for these parameters are determined based on judgment and understanding of the hydrology of the catchment. The process of parameter estimation described below then reduces this uncertainty in the parameter estimates.

Parameter estimation is various techniques designed to reduce the uncertainty in the estimates of the process parameters. A typical approach is to first select an initial estimate for the parameters, somewhere inside the ranges previously specified. The parameter values are then adjusted to more closely match the model behavior to that of the catchment. The process of adjustment can be done "manually" or using computer-based "automatic" methods.

As it is mentioned above, the objective of a calibration procedure is the estimation of values for those parameters, which cannot be assessed directly from field data. According to Refsgaard and Storm (1996), three types of calibration procedures can be differentiated:

1. Trial-and-error, manual parameter adjustment;

2. Automatic, numerical parameter optimization;

3. A combination of (1) and (2).

Refsgaard and Storm (1996) argued that the first method is the most common, and especially recommended for the application of more complicated models in which a good graphical representation is a prerequisite. Alternatively, an automatic calibration involves the use of a numerical algorithm, which finds the optimum of a given numerical objective function. This is carried out by applying the model to numerous combinations and permutations of parameter levels, in order to find the best parameter set in terms of satisfying the criterion of accuracy. The combination means that the manual method is placed at the beginning of the procedure in order to delineate rough orders of magnitude, which is followed by the automatic calibration for fine adjustment. The reverse procedure is also possible, whereby the automatic method is used as a kind of sensitivity analysis to find the most important parameters, which are afterwards manually calibrated.

Gan (1988) has recommended that a combination of manual and automatic procedure be adopted for the model calibration. Manual calibration alone is very tedious, time consuming, and requires the experience of the modeler. Because of the time-consuming nature of the manual model calibration, there have been a number of researches towards development of automated calibration methods. Automatic calibration on the other hand relies heavily on the optimization algorithm and the specified objective function.

Model outputs should be calibrated to fall within a percentage of average measured values and then model performance statistics (r^2 and E_{NS}) were evaluated. If measured and simulated means met the calibration criteria and daily, weekly and monthly r^2 and E_{NS} did not, and then additional checking was performed to ensure that rainfall variability and evapotranspiration seasonal variability were properly simulated over time. If all parameters were pushed to the limit of their ranges for a model output (i.e., flow or water level) and the calibration criteria were still not met, then calibration should be stopped for that output and the modeler should do further investigation on the input parameters.

5.6 Validation

In order to utilize any predictive catchment model for estimating the effectiveness of future potential management practices the model must be first calibrated to measured data and should then be tested (without further parameter adjustment) against an independent set of measured data. This testing of a model on an independent data set is commonly referred to as model validation. Model calibration determines the best, or at least a reasonable, parameter set while validation ensures that the calibrated parameters set performs reasonably well under an independent data set. Provided the model predictive capability is demonstrated as being reasonable in both the calibration and validation phase, the model can be used with some confidence for future predictions under somewhat different management scenarios.

5.7 Model Performance Assessment

In order to assess the ability of the calibrated model in mimicking the hydrological processes within the wetland catchment, model performance assessment measures must be applied. Model performance assessment can usually be done by comparing both simulated and observed hydrographs graphically and using statistical measures.

5.7.1 Graphical Comparison of Observed and Calibrated Hydrographs

Graphical display of calibrated and observed flows is very important because the traditional method of evaluating model performance by statistical measures has limitations. Statistical indices are not effective in communicating qualitative information such as trends, types of errors and distribution patterns. In fact, one should not depend on only single statistical measures of model performance. These are sometimes misleading because of the high possibility of compensation of errors from season to season or over years in long-term calibration. In both calibration and validation processes both observed and simulated hydrographs must be compared graphically. Figure 12 and Figure 13 below demonstrate graphical comparisons.

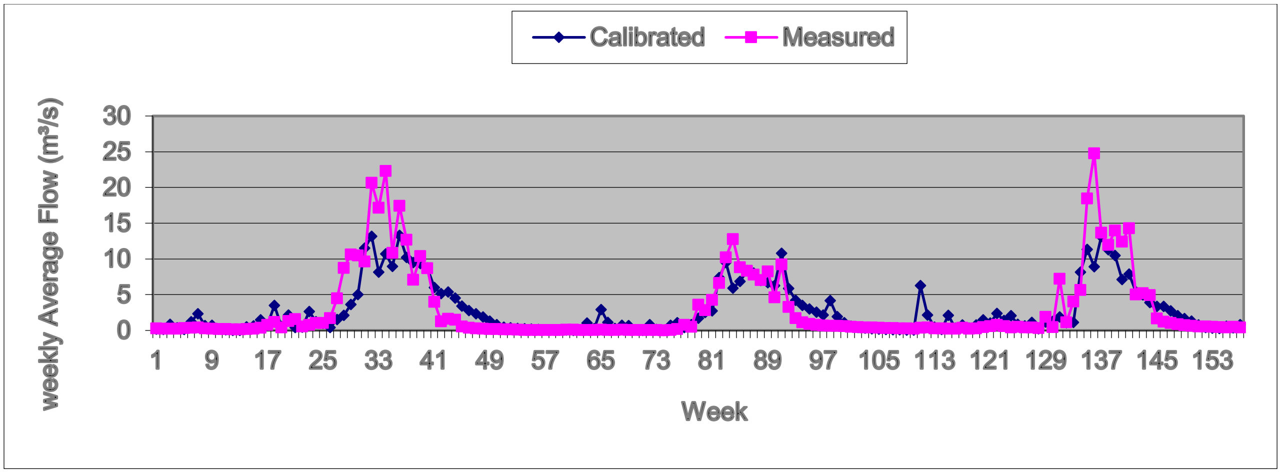


Figure 12: Observed vs. calibrated weekly flow

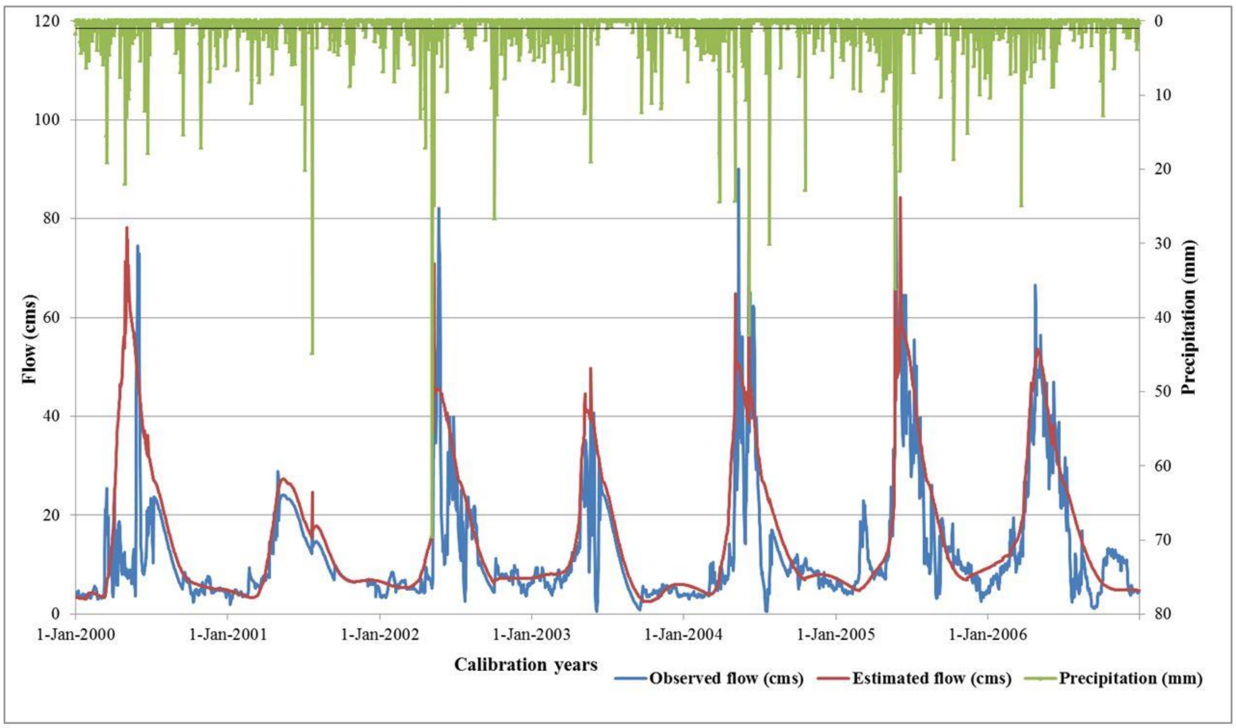


Figure 13: Observed vs calibrated daily flow and rainfall

5.7.2 Statistical Measures

Three methods for goodness-of-fit measures of model predictions can be utilized during the calibration and validation periods, these three numerical model performance measures are the percent difference (D), coefficient of determination (r^2 coefficient) and the Nash-Suttcliffe simulation efficiency (E_{NS}) (Nash and Sutcliffe 1970).

Percent Difference (D)

The percent difference measures the average tendency of the modeled values to be higher or smaller than the measured values for a given quantity over a specified period (usually the entire calibration or validation period in the study). (Gupta et al., 1999). The percent difference for a quantity (D) over a specified period with total days is calculated from measured and simulated values of the quantity in each model time step as:

$$D = 100 \cdot \left[\frac{\left(\sum_{i=1}^{n} q_{si} - \sum_{i=1}^{n} q_{oi} \right)}{\sum_{i=1}^{n} q_{oi}} \right] \qquad \text{Equation 3}$$

Where:

- *q_{si} is the simulated values of the quantity in each model time step*
- *q_{oi} is the measured values of the quantity in each model time step*

A value close to 0% is optimal value of D which means the model is simulating accurately. Positive values of D show that the model underestimates whereas negative values show that the model overestimates. . (Legates and McCabe, 1999)

Coefficient of Determination (r^2 coefficient)

The r^2 coefficient is a measure of how well trends in the measured data are reproduced by the simulated results over a specified time period and for a specified time step. The range of values for r^2 is 1.0 (best) to 0.0. The r^2 coefficient measures the fraction of the variation in the measured data that is replicated in the simulated model results. A value of 0.0 for r^2 means that none of the variance in the measured data is replicated by the model predictions. On the other hand, a value of 1.0 indicates that all of the variance in the measured data is replicated by the model predictions.

The r^2 coefficient for n time steps is calculated as:

$$r^2 = \frac{\left[\sum_{i=1}^{n} (q_{si} - \overline{q}_s)(q_{oi} - \overline{q}_o) \right]^2}{\sum_{i=1}^{n} (q_{si} - \overline{q}_s)^2 \sum_{i=1}^{n} (q_{oi} - \overline{q}_o)^2} \qquad \text{Equation 4}$$

Where:

- *q_{si} is the simulated values of the quantity in each model time step*
- *q_{oi} is the measured values of the quantity in each model time step*
- *$\overline{q}_s$ is the average simulated value of the quantity in each model time step*
- *$\overline{q}_o$ is the average measured value of the quantity in each model time step*

Nash-Sutcliffe Simulation Efficiency (E_{NS})

The E_{NS} simulation efficiency is a normalized statistic that demonstrates the relative magnitude of the residual variance compared to the variance of the measured data (Nash and Sutcliffe 1970).

The E_{NS} simulation efficiency for n time steps is calculated as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(q_{oi} - q_{si})^2}{\sum_{i=1}^{n}(q_{oi} - \overline{q}_o)^2} \qquad \text{Equation 5}$$

Where:

- *q_{si} is the simulated values of the quantity in each model time step (in this case, daily, weekly and monthly)*
- q_{oi} is the measured values of the quantity in each model time step (in this case, daily, weekly and monthly)

The statistical index of modelling efficiency (E_{NS}) values range from 1.0(best) to negative infinity. E_{NS} measures how well the simulated results predict the measured data relative to simply predicting the quantity of interest by using the average of the measured data over the period of comparison. E_{NS} is a more stringent test of performance than r^2 and is never larger than r^2. A value of 0.0 for E_{NS} means that the model predictions are just as accurate as using the measured data average to predict the measured data. E_{NS} values range negative infinite and positive 1. When the E_{NS} values are less than 0.0 indicate the measured data average is a better predictor of the measured data than the model predictions while a value greater than 0.0 indicates the model is a better predictor of the measured data than the measured data average. E_{NS} values equalis to 1 is the optimal value. Servat and Dezetter (1991), the ASCE (1993), and by Legates and McCabe (1999) recommended this model performance evaluation technique. The E_{NS} simulation efficiency shows how well a graph of observed versus simulated values fits a 1:1 line

Figure 14 shows an example scatter diagram that demonstrates r^2 coefficient and E_{NS} simulation efficiency measures.

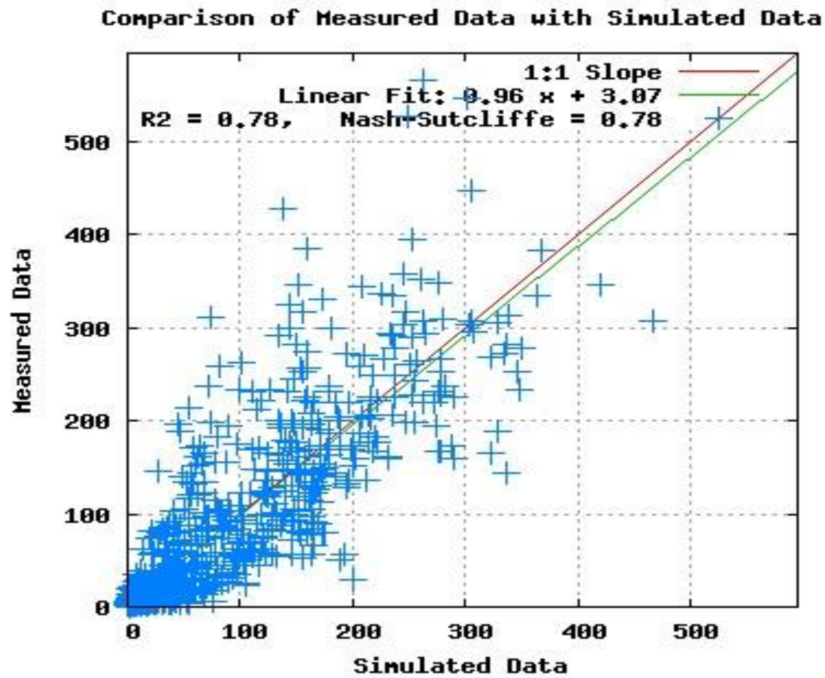


Figure 14: Scatter diagram of simulated vs. measured flow

The established continuous hydrologic model needs to be calibrated with measured data. The parameters in the hydrology model should be adjusted until the model performance statistics fall within D<15%, r^2 >0.75 and ENS >0.65 for daily values. The time step in the continuous hydrologic analysis needs to be daily values and the daily values can be used to generate weekly results.

TRCA requires that the preliminary model calibration to existing conditions be documented and submitted for review and approval prior to proceeding to the application of the model in a predictive manner.

6 Establishing Target Hydroperiod Using Existing Condition

This section of the FBWB report must establish the target hydroperiod by running the calibrated pre-development model using a long-term dataset as described in this section of the guidance document. The calibrated model should be approved by TRCA staff to ensure satisfactory performance prior to being applied in a predictive manner. Results should be presented for each year both graphically and in tabular format as outlined in Section 8.

The *Stormwater Management Criteria Document* (TRCA, 2012) states that the overall objective of FBWB analysis is to “manage the water balance with the intent to maintain the quantity (i.e. volume, timing, and spatial distribution) of surface water and groundwater contributions that ensures the pre-development hydroperiod (seasonal pattern of water level fluctuation) of the wetland is protected" (p.27). The proposed development must not cause significant changes to the hydroperiod that negatively impact the ecological and hydrological functions of the feature, as discussed in Section 8.

To produce the target hydroperiod, the calibrated model (reviewed and approved by TRCA staff) should be run under pre-development baseline conditions using a forcing dataset consisting of precipitation and temperature covering a period of 1991 to 2008. This is considered to be a representative period containing wet, average, and dry years. TRCA staff can provide a forcing dataset for the representative period upon request. Model output should be set to daily resolution, which will be used to create weekly, monthly, and annual summaries.

Following the pre-development model run, the average storage depth for each Julian day (e.g. February 19 = Day 50) during the modelled pre-development period should be calculated and used to create upper and lower boundaries for the 95 percent confidence interval boundaries.

7 Post-development Unmitigated Hydroperiod

This section of the FBWB report must provide the results from running the model using the same forcing data under post-development conditions without stormwater management mitigation practices. The representation of the developed areas of the wetland catchment in the model should be discussed and changes to the parameters of hydrologic response units outlined. The model output should be presented for each year both graphically and in tabular format as outlined in Section 8.

After establishing the target hydroperiod, the calibrated continuous hydrological model needs to be reconfigured to reflect the post-development land use and land cover condition. The configuration and parameterization of sub-catchments should be based on the best available knowledge about the development form and servicing requirements at the time of the analysis. The parameters assigned to the post-development sub-catchments and any changes to the configuration of the model should be reported in this section.

A graphical representation of the pre- to post-development comparison is shown below in Figures 15 and 16. In Figure 15, the proposed development has greatly increased the runoff volume going to the wetland while infiltration is simultaneously reduced, resulting in a significant increase in the wetland storage volume. Figure 16 shows an alternative example where the proposed development diverts most of the runoff volume away from the wetland while also reducing infiltration, resulting in a significant decrease in wetland storage volume.

To produce the post-development unmitigated hydroperiod, the calibrated pre-development model approved by TRCA staff should be run in post-development mode using the same 1991 to 2008 forcing dataset. Model output should be set to daily resolution, which will be used to create weekly, monthly, and annual summaries.

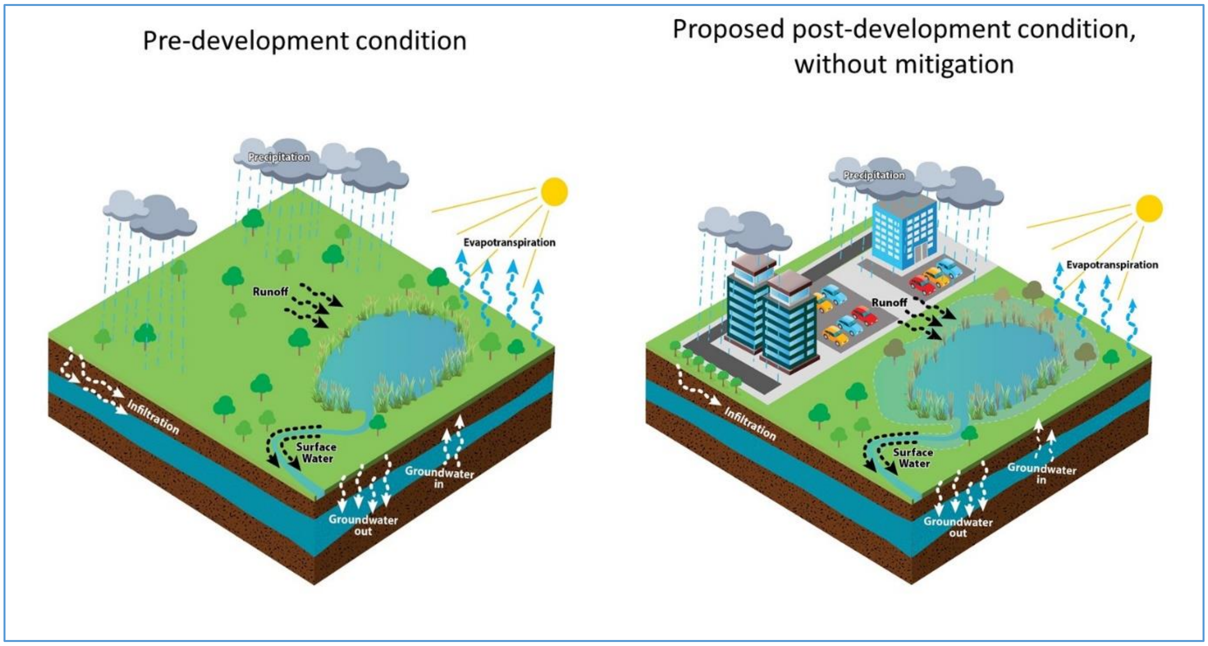


Figure 15: Development increased runoff volume to the wetland and reduced infiltration

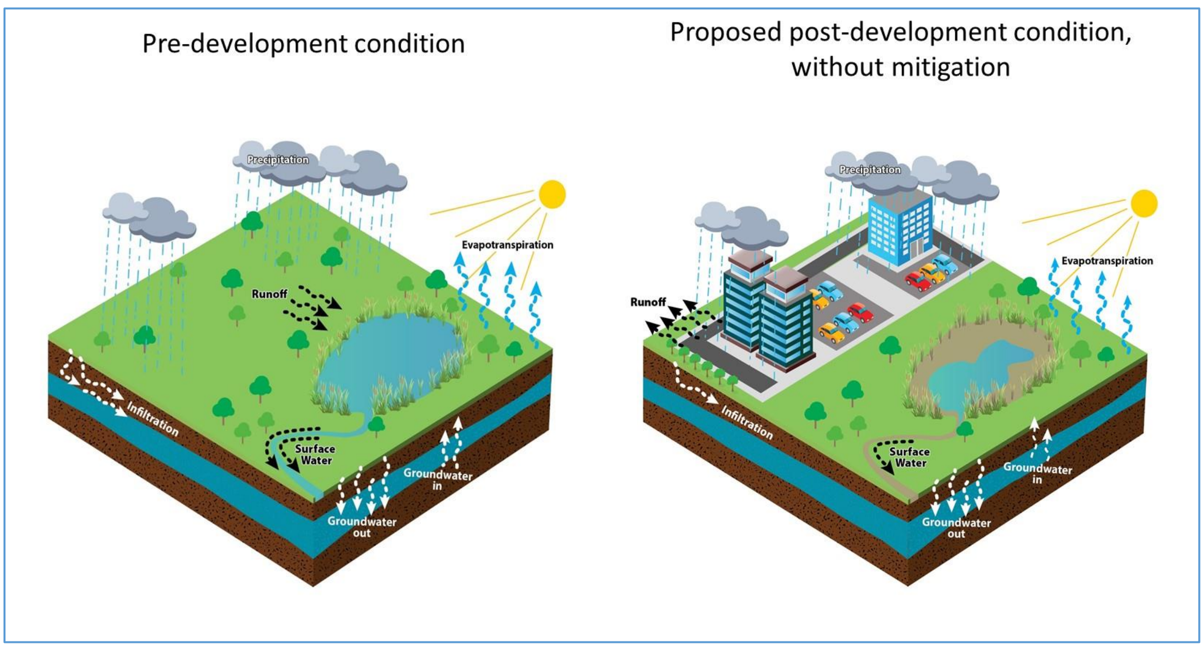


Figure 16: Development decreased runoff volume to the wetland and reduced infiltration

8 Comparison of the Pre-development Target Hydroperiod with the Unmitigated Post-development Hydroperiod

This section of the FBWB report should compare the simulated target hydroperiod with the post-development unmitigated hydroperiod, both graphically and in tabular format, for each model simulation year. A discussion of the potential ecological significance of differences detected between the target and post-development hydroperiod should also be included.

For each simulation year, create a hydrograph showing the modelled pre-development and post-development unmitigated wetland storage levels. The average storage depth for each Julian day (e.g. February 19 = Day 50) during the modelled pre-development period should be calculated and used to create upper and lower 95 percent confidence interval boundaries, to be plotted on each hydrograph alongside modelled wetland storage. The confidence intervals will be the same for each year. An example of this for one year of data is shown below in Figure 17**.**

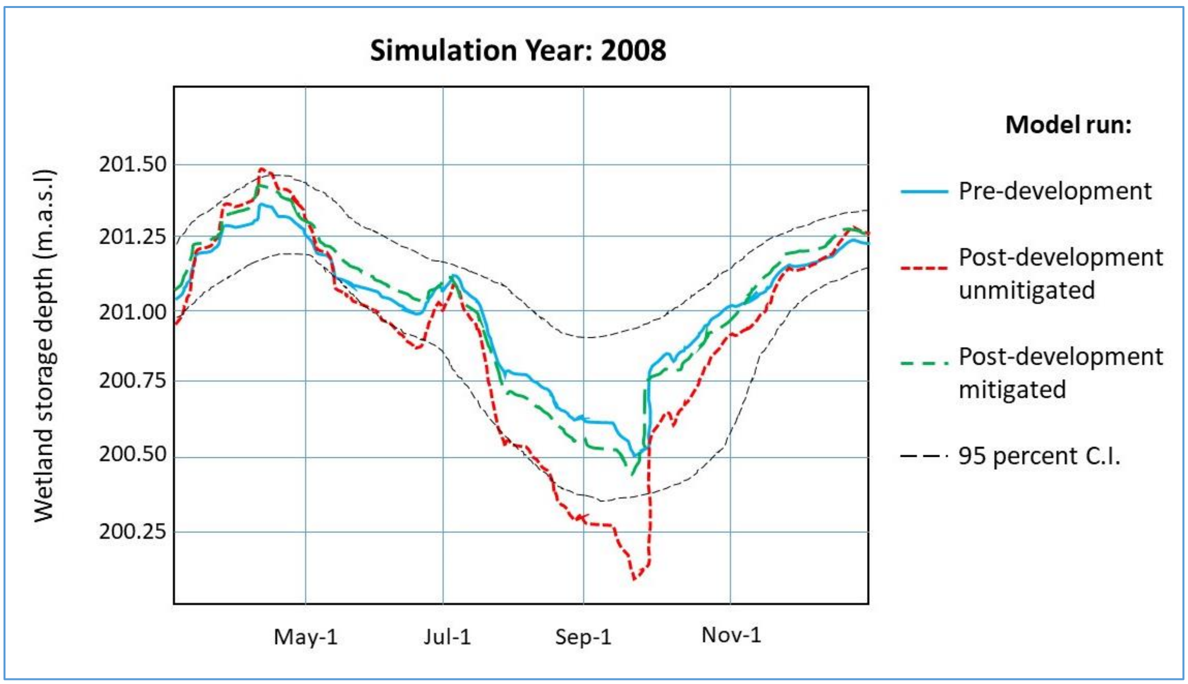


Figure 17: Hypothetical hydrograph for one simulation year comparing pre- and post-development

For tabular presentation of results, the storage depth and the inflow and outflow volumes to and from the wetland storage unit should be reported for each year. Inflow and outflow volumes should be further subdivided into their major constituents (e.g. output broken down into overland flow, ET, and infiltration). Each of these values should be summed over weekly, monthly, and annual intervals within the table, with differences between the pre- and post-development scenario calculated at each time interval as percentage of pre-development volume.

The report should include an assessment of the potential impact of changes on the wetland flora and fauna communities. An ecologist will provide an analysis of the model outputs to determine whether the risk to the wetland's ecological and hydrological functions can be considered acceptable. This assessment should be placed in the context of the model performance and uncertainty under different conditions and times of year.

TRCA staff recognizes that in most cases it will not be possible to achieve a post-development hydroperiod that matches exactly the pre-development hydroperiod. Instead the proponent should focus on minimizing the difference in hydroperiod timing and magnitude in order to minimize negative impacts to the wetland. TRCA is conducting research to support more robust decision making around levels of ecological risk, based on the natural range of observed variation within and among different wetland communities. However, it will continue to be necessary to consult with planning ecologists and other technical review staff to determine the scope of required mitigation.

9 Prepare Mitigation Measures

This section of the FBWB report should outline the design of mitigation measures, where required, and evaluate their performance by running the model using the same forcing data under mitigated post-development conditions. Performance evaluation should be measured against the target hydroperiod using the same graphical and tabular comparison as was used for the previous section. The event-based performance of any proposed stormwater management infrastructure involved in a mitigation solution also needs to be demonstrated.

The modeler should work collaboratively with an ecologist to understand the sensitivity of the wetland and to develop appropriate mitigation measures, where required, to ensure maintenance of the pre-development wetland hydroperiod. Once proposed measures have been identified, the modeler should modify the parameters and structure of the post-development unmitigated model to reflect the proposed changes to the development design, and re-run the model using the same long-term forcing dataset. Note that use of "mitigation measures" does not refer exclusively to stormwater management infrastructure, but rather could include solutions such as increased natural buffer widths or incorporation of more permeable surfaces like parklands within the development area of the wetland catchment.

A detailed description of proposed mitigation measures such as clean roof drainage collector systems directed to bioswales, infiltration galleries, third pipe systems, etc. should be included in the FBWB report. The locations and extents of the proposed mitigation measures and any stormwater management facilities should be clearly indicated in relation to the wetland on a map, including a description of how water will be conveyed to the wetland. Note that clean runoff from greenspace and roof areas is preferred to feed wetlands as necessary, as runoff from roads or paved surfaces as sources of supplemental water should only be considered as a last resort owing to the accumulation of sediment, salt, and hydrocarbons in stormwater runoff from roads and walkways.

Uncertainty in prediction is an issue in hydrological modelling due to uncertainty in input data, errors in measured data used for calibration, model structure uncertainty, and numerical error such as truncation error or roundoff error. There are different methods to estimate uncertainty in hydrological modelling analysis. Assessment of uncertainties of the prediction of the wetland hydrology model can be onerous exercise. However, uncertainty of impact prediction in the design of mitigation measures can be accounted for by expanding proposed mitigation measure by a given factor. In TRCA jurisdiction, it is recommended that a Factor of Safety by implemented for wetland mitigation measures by increasing the catchment area for the measures by 30%.

For development scenarios in which it is necessary to supply additional water to the wetland to maintain the water balance, the mitigation measures should be designed to collect runoff from an area that is 30 percent larger than the calculated area required wherever possible. For example, if a roof drain collector system is being used to supply additional runoff volume to the wetland, and calculations suggest that a total of 1 ha of roof runoff is necessary to replace the volume of water lost, the system should be designed to collect runoff from 1.3 ha of roof area. Additionally, adjustable orifices should be incorporated into the conveyance system, such that the orifice can be reduced or enlarged if monitoring and adaptive management identifies a surplus or a deficit of runoff reaching the wetland, and any excess runoff volume is conveyed via an overflow to the main storm sewer system. The requirement of 30 percent additional contributing area is meant to address the fact that it is much more difficult to add extra contributing roof area to a drain collector system than it is to re-route already connected contributing roof area to a different outlet (e.g. a stormwater management pond). The 30 percent additional contributing area recognizes the inherent uncertainty of modelling input data, output data, and mitigation system performance. The use of an adjustable orifice and overflow system allows for a mitigation system that is both adaptive and that functions in a completely passive manner, once it has been demonstrated to successfully maintain the wetland water balance.

The timing of release of runoff into the wetland resulting from the proposed mitigation design should be evaluated to ensure that there are no concerns around peak flow and localized erosion impacts. To confirm the timing of runoff entering the wetland, provide five (5) hydrograph of distinct storm events of precipitation volumes 15 mm or greater, showing existing and proposed timing of the hydrologic input. A table for each hydrograph should be provided demonstrating the time to the peak inflow rate, the peak inflow rate, and total time of hydrologic input demonstrating the proposed timing matches the existing condition as closely as possible. Further, an additional five (5) hydrographs of distinct storm events should be provided to verify the design, showing the same level of information and comparison. While it will not be possible to precisely match the pre-development timing of inflows to the wetland in the post-development condition, measures to slow the delivery of runoff to the wetland will help reduce the risk of ecological degradation owing to sudden changes in water level and to associated erosion and sediment control impacts.

The model output from the post-development mitigated scenario should be compared for each year against the target hydroperiod and post-development unmitigated hydroperiod using the exact same graphical and tabular presentation formats outlined in Section 8. The difference between the proposed post-development mitigation scenario and the target pre-development should be scenario calculated at each time interval as percentage of pre-development volume, as in Section 8.

Finally, this section should include a discussion about the potential residual negative impacts to the wetland ecological processes resulting from altered hydroperiod, after all mitigation measures have been incorporated. An ecologist should ensure that the mitigated hydroperiod is consistent with the wetland community.

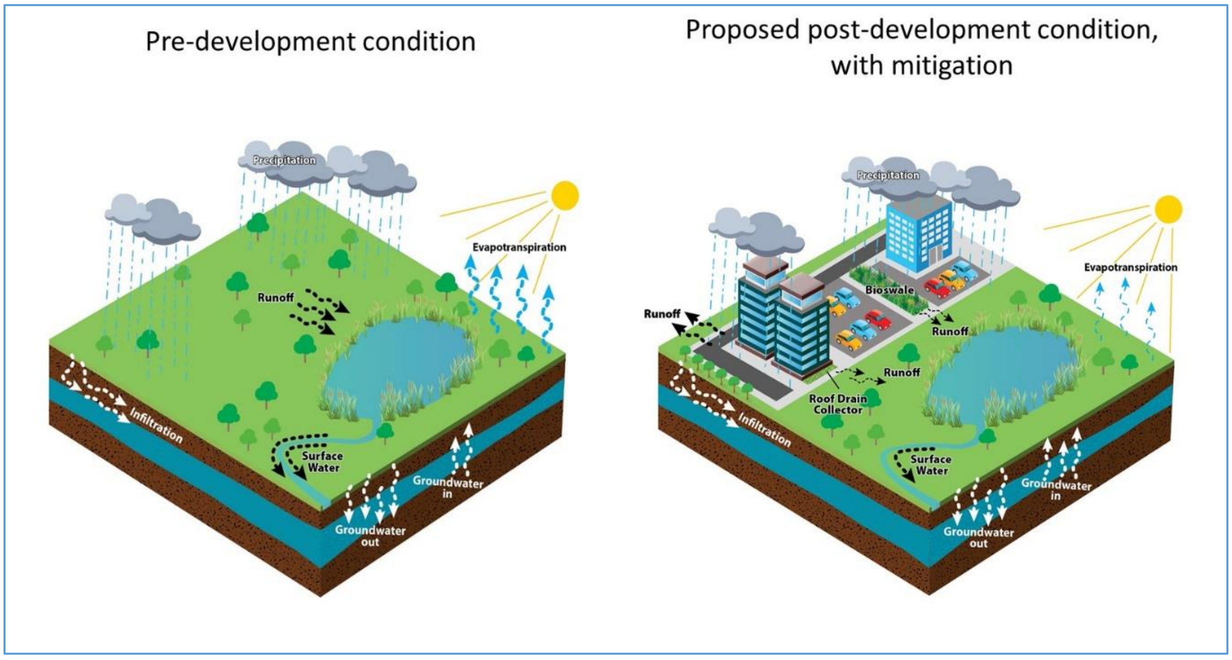


Figure 18: Development incorporated mitigation measures to maintain the pre-development hydroperiod in the post-development condition

10 Interim Mitigation Plan during Construction of the Project

This section of the FBWB report should outline an interim mitigation plan to protect the wetland during the construction phase, where a plan has been deemed necessary through consultation with the conservation authority. The mitigation plan should outline triggers for action and define the corresponding actions to take.

An interim mitigation plan may be required for developments where there is a risk of negative effects to the wetland resulting from the delay between alterations to the wetland catchment (typically during earthworks) and the implementation of mitigation measures (typically during building construction). The need for a mitigation plan will be determined in consultation with TRCA and municipal staff. A mitigation plan should outline active management measures for supplementing the water balance during construction and define triggers for when action is required (e.g. low and high water level thresholds for a specified duration and/or time of year, as deemed appropriate by ecologists). Such measures may be necessary to protect the ecological and hydrological functions of the wetland from multi-year disturbances which degrade the wetland to a point where these functions cannot be restored. In the case where supplemental water is needed to augment the interim water balance, clean sources of water are preferred (e.g. roof runoff, runoff from greenspace, or unchlorinated water from a water truck). Interim mitigation plans may include, for example, phasing soil stripping or grading activities within the wetland catchment, or having an interim grading plan that is designed to compensate for an anticipated surplus or deficit of water during the construction phase.

11 Monitoring and Adaptive Management Plan

This section of the FBWB report should outline the post-implementation monitoring plan where this has been identified as a requirement. The plan should outline the triggers for action and the associated adaptive management options, should post-implementation monitoring identify an excess or deficit in wetland water storage.

For proposals that have been determined to be medium or high risk as per the TRCA *Wetland Water Balance Risk Evaluation* (TRCA, 2017), post-implementation water balance monitoring is required to characterize the new wetland hydrology following construction and to understand any changes to the wetland's ecological function. The TRCA Wetland Water Balance Monitoring Protocol (TRCA, 2016) should be consulted for more detailed guidance. The hydrological monitoring instrumentation should remain in place post-development for a period agreed upon with the agencies, and continuous hydrological data should be collected during these years. The first year of post-development data collection may begin at 80-85% build-out as long as all mitigation measures designed to protect wetland hydrology have been implemented. As the purpose of post-development monitoring is to capture the passive operation of the mitigation system, this phase of the monitoring may not begin until these measures have been fully implemented.

In the FBWB report, the proponent should clearly outline the methods that will be used to evaluate the effectiveness of the mitigation measures in maintaining the pre-development wetland hydroperiod. For example, the modelled long-term hydroperiod can be used as a basis for comparison by plotting the monitored post-development water levels by Julian day-of-year (i.e. day 1-365) against the statistical distribution of long-term annual water levels over the same period. TRCA can provide tools and scripts upon request that can be used to facilitate these analyses and other numerical and graphical comparisons between different scenarios; two such tools are currently available in beta form.

An adaptive management plan should outline potential mitigation actions, should post-implementation monitoring identify an excess or a deficit in wetland water storage. The specifics of the adaptive management plan will necessarily depend strongly on local conditions and constraints, but may include, for example, designs that incorporate adjustable orifices, flow splitters, and similar devices that allow for the post-development area contributing runoff volume to be adjusted to some degree. The benefit of such designs is that they can operate passively without requiring active intervention, once a suitable post-development hydrological regime has been settled on. The feature-based water balance analysis report should identify opportunities to incorporate such designs so that the opportunity to integrate them into servicing and infrastructure is not missed. Consult with the conservation authority regarding appropriate adaptive management plan objectives and hydroperiod targets.

12 Conclusions and Recommendations

This final section of the FBWB report should summarize the original objectives of the modelling exercise and the main outcomes for each objective. The results of the comparison between the pre-development hydroperiod and the post-development hydroperiod should also be summarized. Finally, the design recommendations and supporting rationale with regard to any water balance mitigation measures that have been determined to be necessary through consultation with TRCA staff should be summarized.

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Appendix A: Feature-based Water Balance Analysis Report Template

The following structure is suggested as a standard format for the modelling part of feature based water balance analysis study report. Depending on the characteristics of impacts of the proposed development on the wetland, some sections may not be necessary, while additional sections may be required. The suggested report format and main section headings are listed below.

Suggested Report Format

1. **Introduction**
    a. Determine the scope of analysis applicable to the proposal using TRCA's *Wetland Water Balance Risk Evaluation* and establish the need for a continuous modelling exercise
2. **Understanding the wetland water balance based on monitored and secondary data**
    a. Analyze the monitored hydrological time series data to help answer the following questions:
        i. What are the dominant water transfer mechanisms between the wetland and its surroundings?
        ii. How long does the wetland contain standing water?
        iii. Do the maximum depth and areal coverage of surface water change from year to year?
        iv. How quickly do water levels draw down during extended dry periods?
        v. What is the wetland hydroperiod response to precipitation events?
        vi. Is the amount of surface water flowing into the wetland roughly equal to the amount flowing out?
        vii. What is the relationship between groundwater head and wetland water levels?
        viii. Is the hydraulic gradient in the wetland mostly upwards or downwards, and what is the hydraulic conductivity of the soil?
        ix. How do these observations relate to the observed distribution of wetland habitat?
    b. Identify wetland water sources
    c. Identify water transfer mechanisms
    d. Determine significant hydrological processes
3. **Developing the conceptual model**
4. **Testing and refining the conceptual model**
    a. The conceptual model should be tested using a tool that quantifies the terms of the wetland water balance
5. **Continuous hydrological model**
    a. Describe the selected software for the continuous hydrological model
    b. Provide technical justification for the suitability of the selected model or the criteria applied in selecting the model, referring to list of significant hydrological processes

   c. Model setup
      i. Data requirements (data sources, any shortcomings, any data gap filling techniques employed, etc.)
      ii. Parameterization (limitations)
      iii. Representation of the wetland in the model
   d. Model calibration
      i. Identify all parameters that were changed during calibration
      ii. Develop a table comparing all initial parameter values vs. all calibrated parameter values
      iii. Provide description and justification of calibrated values
   e. Model performance assessment
      i. Graphical
      ii. Statistical – $D<15\%$, $r^2 >0.75$ and ENS >0.65 for daily values
   f. Model validation

6. **Establishing a pre-development target hydroperiod**
   a. Run a long-term analysis using forcing dataset from nearest available climate station (minimum 1991-2008)
   b. Save model output at daily timestep
7. **Unmitigated post-development scenario hydroperiod**
   a. Modify the parameters of the calibrated model to reflect post-development land use conditions and run the model using the same long-term forcing dataset (minimum 1991-2008)
   b. Save model output at daily timestep
8. **Comparison of the pre-development target hydroperiod with the unmitigated post-development hydroperiod**
   a. Comparisons should be made summarizing daily outputs at weekly, monthly, and annual intervals in a table
   b. Quantify changes in the water budget components at the same intervals
   c. Create a hydrograph for each model year showing the target (pre-development) hydroperiod, post-development hydroperiod, and the 95 percent upper and lower confidence interval boundaries of the target hydroperiod for each Julian day
   d. Assess the impacts of these changes on the wetland flora and fauna communities; an ecologist should analyze model outputs to determine potential ecological impacts
   e. If the pre-to-post development comparison shows that there will be a negative impact to the wetland, mitigation measures will be required to ensure maintenance of the pre-development wetland hydroperiod
9. **Prepare mitigation measures**
   a. Work collaboratively with an ecologist to understand the sensitivity of the wetland and to develop appropriate mitigation measures to ensure maintenance of the pre-development wetland hydroperiod
   b. Modify the parameters of the calibrated model to reflect post-development land use conditions including proposed mitigation measures and run the model using the same long-term forcing dataset (minimum 1991- 2008)

   i. Provide a description of proposed mitigation measures such as clean roof drainage collector directed to bioswales, infiltration galleries, third pipe, etc.

   c. Comparisons between the target (pre-development) hydroperiod and post-development mitigated hydroperiod should be made summarizing daily outputs at weekly, monthly, and annual intervals in a table
   d. Quantify changes in the water budget components at the same intervals
   e. Create a hydrograph for each model year showing the target (pre-development) hydroperiod, post-development hydroperiod, and the 95 percent upper and lower confidence interval boundaries of the target hydroperiod for each Julian day
   f. Discuss the comparison results, deviations from the pre-development condition, and their implications on the ability of the wetland to sustain ecological processes; check with the ecologist to ensure the mitigated hydroperiod is consistent with the wetland community
   g. Describe the design of the proposed mitigation and how it conveys water to the wetland and demonstrate event-based performance

10. **Interim mitigation plan during construction of the project**
    a. Discuss the period of construction and its potential impact on the wetland
    b. Outline interim mitigation measures and triggers for action
11. **Monitoring and adaptive management plan**
    a. Discuss the post-implementation monitoring plan and reporting
    b. Suggest methods to evaluate the effectiveness of the mitigation measures in maintaining the pre-development hydroperiod
    c. Recommend actions for cases where a deficit or excess of water is observed and what adaptive management will be required
    d. Discuss how the design of proposed mitigation measures can be modified to accommodate future adaptive management recommendations
12. **Conclusions and recommendations**
    a. Summarize original objectives of the modelling exercise and the main outcomes for each objective
    b. Summarize the results of the comparison between the pre-development hydroperiod and the post-development unmitigated hydroperiod as determined through the modelling exercise
    c. Summarize the design recommendations and supporting rationale with regard to any water balance mitigation measures that have been determined to be necessary

Appendix B: Hydrological Processes: Governing Equations, Input Data Sources, and References

B1: Precipitation

Environment Canada, conservation authorities, and local municipalities own and operate local weather stations and can provide local precipitation data for these stations. Depending on the instrumentation at a particular station as well as the availability of data summaries, precipitation data can be retrieved at yearly, monthly, daily, or hourly time intervals, and in some cases as real-time data. The proponent should investigate if precipitation values from these weather stations can be utilized for the wetland water balance analysis.

Precipitation events are recorded by gauges at specific locations. If the location of available gauges is not in close proximity with the wetland study area, then the applicant should discuss with the local conservation authority to determine if there is a need for site-specific gauging. Depending the location of the wetland in relation to the gauges' locations, examining data from a nearby representative weather station is the method that is most often used to estimate precipitation input into a wetland system. Precipitation estimates that are based on a single data point, however, may be subject to substantial error and uncertainty because of the spatial variability associated with precipitation. This may cause discrepancies between the estimated total precipitation received by the catchment and the actual amount received, as well as the timing of rainfall at a sub-daily scale. To achieve a more accurate representation of the areal precipitation distribution, data from a network of stations can be used. There are several methods available for estimating average precipitation. The three most common methods for computing average rainfall in a catchment are the arithmetic mean, the Thiessen Polygon Method, and the Isohyetal Method. The steps used to quantify the precipitation amount of the wetland water balance are outlined in Figure 6.

B2: Surface Flow

Surface water inflow to a wetland is derived from channelized streamflow, non-channelized (i.e. overland) flow, and seasonal or periodic flooding of lakes, ponds, and rivers. Surface water outflow results when the storage capacity of a depressional area such as a wetland is exceeded. Outflows from a wetland may be concentrated into a channelized watercourse or may be more diffuse. Surface water inflows and outflows vary seasonally and generally correspond to variations in precipitation and spring thaw. In wetlands where groundwater is a major source to the wetland, surface water outflow may be more evenly distributed throughout the year.

Non-channelized Surface Flows

Non-channelized surface water flows entering a wetland are difficult to quantify using on-site measurements, and so are generally estimated using simple modelling approaches. The runoff curve number (CN) method developed by the United States Department of Agriculture's Soil Conservation Service (SCS) is widely used for estimating runoff from rainfall events in small- to medium-sized watersheds under varying land use and soil types (SCS, 1972). The CN method describes the production of runoff during a rain event, considering the initial depth of rainfall that is "abstracted" as storage in soil moisture in the upper soil horizons and in surface depressions.

Once this initial abstraction depth has been exceeded, all subsequent "excess" rainfall is converted directly to runoff.

The CN value for each combination of land use, land cover, and soil type is determined using a lookup table such as Table B1. The source for all CN values used should be cited. The catchment of the wetland is divided up into as many unique combinations of land use, land cover, and soil type as may be present, and a CN value assigned to each unique combination. A single CN value is then determined based on the areally weighted average for all CN values within the wetland catchment.

The SCS CN equation is (SCS, 1972):

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$$

Equation B-1

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

Equation B-2

Where:

- Q_{surf} is rainfall excess (mm),
- R_{day} is daily total rainfall(mm),
- I_a is initial abstraction (sum of surface storage, interception, and infiltration) (mm),
- CN is the curve number determined for the catchment as a whole using lookup tables and the procedure described above (unitless), and
- S is the retention or storage parameter (mm), determined using the *CN* value for the catchment as a whole. The value of S may vary spatially and over time as a function of soil moisture content. The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content.

A common approach is to approximate initial abstraction I_a as 0.2 S, which substituted into Equation B1 then becomes:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)}$$

Equation B-3

The SCS CN method was originally developed for single rainfall event analysis. To adapt this method for continuous modelling, use Equation B3 to determine the minimum daily total rainfall necessary to produce runoff, then determine runoff for each day where rainfall exceeds this minimum depth.

Landuse (TRCACode)	TIMP	Cover Type	Hydrologic Soil Group			
			A	B	C	D
Cemetery	35	**35% Impervious + 65% Lawns**	71	81	88	90
Commercial	95	**95% Impervious + 5% Lawns**	98	99	99	99
Conservation Lands	0	**80% Woods + 20% Meadows**	38	61	74	80
Estate Residential	40	**40% Impervious + 60% Lawns**	74	83	89	91
Farm	0	**Cultivated**	66	74	82	86
Golf Course	0	**Lawns**	56	71	81	85
Hydro Corridor	10	**10% Impervious + 90% Meadows**	51	69	79	84
Industrial	95	**95% Impervious + 5% Lawns**	98	99	99	99
Institutional	80	**80% Impervious + 20% Lawns**	91	94	96	97
Open Space	0	**50% Woods + 50% Meadows**	41	63	75	81
Park	10	**10% Impervious + 45% Woods + 45% Meadows**	47	67	78	82
Recreational	20	**20% Impervious + 80% Lawns**	65	77	85	88
Residential High	80	**80% Impervious + 20% Lawns**	91	94	96	97
Residential LowMed	60	**60% Impervious + 40% Lawns**	82	88	92	94
Road (ROW)	90	**90% Impervious + 10% Lawns**	96	97	98	99
Rural Residential	20	**20% Impervious + 80% Lawns**	65	77	85	88
Transportation	60	**60% Impervious + 40% Lawns**	82	88	92	94
Water	100	**Impervious**	100	100	100	100
Natural	0	**50% Woods + 50% Meadows**	41	63	75	81

Table B1: Updated lookup table for Curve Number (CN) based on total imperviousness

Channelized Surface Flows

All wetlands will receive some non-channelized surface water input, but some wetlands may receive equivalent or greater volumes of water from channelized flow as well. To quantify channelized surface water flows, direct on-site measurements made using weirs, flumes, and stage-gauging techniques are the preferred source of data. TRCA's *Wetland Water Balance Monitoring Protocol* (2016) outlines basic procedures for estimate channelized flow at concentrated inflow or outflow locations. Accurate on-site measurements are invaluable as input data for water balance analysis. If the wetland is on a higher order stream, it may be prudent to see if Environment Canada or the local conservation authority operates a stream gauge nearby. Techniques exist for transferring flow data from a watercourse in one basin to another nearby basin with similar characteristics; however, caution should be used before applying these techniques to ensure all underlying assumptions are met.

If direct discharge measurements are not available the next best option is to approximate channelized flows based on the shape of the inflow and/or outflow channel using the continuity equation:

$$Q = VA$$

Equation B-4

Where:

- Q is discharge (m^3/s)
- V is velocity (m/s)

- A is cross-sectional area of flow (m^2).

To calculate the velocity term, Manning's equation can be used:

$$V = \left(\frac{1}{n}\right) R^{2/3} S^{1/2}$$

Equation B-5

Where:

- V is velocity (m/s);
- n is Manning's roughness coefficient, based on lookup table;
- R is hydraulic radius(m), equivalent to the cross-sectional area of flow (A) divided by the wetted perimeter (W_p) such that $R = A/W_p$; and
- S is slope (m/m).

Manning's roughness coefficient values based on the type of material lining the channel are listed in Table B2.

The steps used to quantify the surface water portion of a wetland water budget are outlined in Figure 8. An adequate assessment of surface water inputs is important for all wetlands, but for riverine and other surface-water-driven wetlands it is critical. Contribution of non-channelized and channelized flow must be quantified for all sites. The sum of channelized and non-channelized flow values constitutes the overall surface water input to the wetland system. Daily and monthly surface-water flow values should be calculated for representative wet, dry, and average years, expressed in units of depth per unit time and plotted along with the other components of the water budget.

Some continuous hydrological models may have routines that use alternative methods for simulating surface water inputs from the catchment area. All methods and assumptions used in the calculation of the surface water component of the water budget should be listed in the relevant section of the report.

Surface Material	Manning's Roughness Coefficient (*n*)	Surface Material	Manning's Roughness Coefficient (*n*)
Asbestos cement	0.011	Glass	0.010
Asphalt	0.016	Gravel, firm	0.023
Brass	0.011	Lead	0.011
Brick	0.015	Masonry	0.025
Canvas	0.012	Metal, corrugated	0.022
Cast-iron, new	0.012	Natural streams – clean & straight	0.030
Clay tile	0.014	Natural streams – major river	0.035
Concrete – steel forms	0.011	Natural streams – sluggish, deep pools	0.040
Concrete (cement) – finished	0.012	Natural channels – very poor condition	0.060
Concrete – wooden forms	0.015	Plastic	0.009
Concrete – centrifugally spun	0.013	Polyethylene PE – corrugated with smooth inner walls	0.009 - 0.015
Copper	0.011	Polyethylene PE – corrugated inner walls	0.018 - 0.025
Corrugated metal	0.022	PVC – smooth inner walls	0.009 - 0.011
Earth, smooth	0.018	Rubble masonry	0.017
Earth channel – clean	0.022	Steel – Coal-tar enamel	0.010
Earth channel – gravelly	0.025	Steel – smooth	0.012
Earth channel – weedy	0.030	Steel – new, unlined	0.011
Earth channel – stony, cobbles	0.035	Steep – riveted	0.019
Floodplains – pasture, farmland	0.035	Vitrified sewer	0.013 - 0.015
Floodplains – light brush	0.050	Wood – planed	0.012
Floodplains – heavy brush	0.075	Wood – unplaned	0.013
Floodplains – trees	0.150	Wood stove pipe, small diameter	0.011 - 0.012
Galvanized iron	0.016	Wood stove pipe, small diameter	0.012 - 0.013

Table B24: Manning's Roughness Coefficient Values

B3: Evapotranspiration

Evapotranspiration (ET) is one of the most challenging components of a wetland water budget to estimate because of its high variability in time and space and the complexity of monitoring atmospheric water vapour fluxes. ET varies according to both meteorological variables as well as phases of vegetation growth. While the Penman-Montieth method (Monteith, 1965) is often considered the most accurate available empirical method, it requires a number of parameters that may be difficult and/or expensive to measure. For this reason, other estimation methods for ET, requiring a reduced set of input parameters, are more commonly used.

The steps involved in quantifying the ET portion of a wetland water budget are shown in Figure 9. A good first step for any modelling study is to determine the availability of meteorological data in proximity to the study site for the period of interest, and then to determine the necessity of collecting any additional required input data at the study site in order to apply the desired ET estimation method.

Direct Measurement Techniques

An evaporation pan is one example of a direct measurement technique to estimate evapotranspiration. The evaporative water loss from a standard class “A” pan is determined by measuring the decrease in water level or mass over time, or the volume or mass required to maintain a specified water level in the pan. A monthly variable crop coefficient (*k*) is generally used to convert pan evaporation (E_{pan}) into potential ET (*PET*) such that PET = $k \cdot E_{pan}$ (Mao *et al.*, 2002). If using a pan evaporation approach, it is important to use local crop coefficients that account for local climate conditions. Conservation authorities and universities can provide appropriate local crop coefficients. The calculated PET is the subtracted from available water held in storage on the surface and in soils at each calculation timestep.

Thornthwaite Method

The Thornthwaite method (Thornthwaite, 1948) calculates PET at monthly resolution using only monthly temperature as an input:

$$PET = 16 * \left(\frac{10 \cdot Ti}{I}\right)^{a} \left(\frac{N}{12}\right)\left(\frac{d}{30}\right)$$

Equation B-6

$$I = \sum_{i=1}^{12} \left(\frac{Ti}{5}\right)^{1.514}$$

Equation B-7

$$a = (492390 + (17920 \cdot I) - (771 \cdot I^2) + (0.675 \cdot I^3)) * 10^{-6}$$

Equation B-8

Where:

- PET is monthly potential evapotranspiration (mm/month)
- T_i is monthly average temperature (°C)
- N is the number of monthly daylight hours for a given latitude, from a lookup table (Thornthwaite, 1948)

- d is the number of days in the given month
- I is the annual heat index for the given year (Equation B6)
- a is a function of I (Equation B7)

While the Thornthwaite method is useful for estimating PET as part of a conceptual water balance model or coarse scale exercise, its monthly output resolution means it may not be appropriate for continuous modelling exercises. Locally calibrated monthly adjustment coefficients to further refine PET estimates from the Thornthwaite method are available (see Metcalfe *et al.,* 2019) and generally show the method to underestimate PET in the spring and fall while slightly overestimating PET in the summer. For any month where T_i is ≤0, estimated PET will be zero.

Hargreaves / Hargreaves-Samani Method

The method of Hargreaves *et al.* (1985), sometimes referred to as the “Hargreaves-Samani 1982” method, is also widely applied because it requires as input only the daily maximum and minimum air temperature. The radiation term does not require site-scale data but rather is calculated for a given latitude and day of year using solar radiation theory (see for example Allen *et al.,* 1998). The equation is given as:

$$\lambda(PET) = 0.0023(T_m + 17.8)\left(\sqrt{T_{max} - T_{min}}\right)R_a$$

Equation B-9

Where:

- λ is the latent heat of vapouration (J/kg)
- PET is daily potential evapotranspiration (mm/day)
- T_m is daily mean air temperature (°C),
- T_{max} is daily maximum air temperature (°C),
- T_{min} is daily minimum air temperature (°C), and
- R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}).

Metcalfe *et al.* (2019) recommend replacing the coefficient of 0.0023 with a monthly variable coefficient calibrated to regional climate conditions. For example, for southwestern Ontario, the locally-calibrated coefficients range from a high of 0.0025 in April to a low of 0.0020 over June through September (Metcalfe *et al.*, 2019).

Makkink Method

The Makkink (1957) method was developed for use in the Netherlands and has been found by TRCA staff to perform well in the Toronto region. The method requires incoming solar radiation at the site or regional scale as well as air temperature as inputs, and can be calculated at variable timesteps:

$$\lambda(PET) = 0.61\, R_s \frac{\Delta}{\Delta + \gamma} - 0.12$$

Equation B-10

Where:

- PET is potential evapotranspiration (mm),
- Δ is the slope of the saturation vapour pressure vs. temperature curve (kPa/K) for the average air temperature over each time interval,

- R_s is incoming solar radiation (W/m^2),
- Υ is the Psychrometric Constant (kPa/K), and
- 0.61 and 0.12 are empirical fitting parameters

Turc Method

The Turc (1961) method was developed for western Europe and requires the same inputs as the Makkink (1957) method, as well as a correction factor for when relative humidity is <50%. TRCA staff have found that this method performs well in the Toronto region.

$$\lambda(PET) = 0.013\ C_{RH} \frac{T}{T + 15}(R_s + 50)$$

Equation B-11

Where:

- PET is daily potential evapotranspiration (mm),
- C_{RH} is an adjustment factor for relative humidity, equal to 1 when RH≥50% and to (1+((50-RH)/70)) when RH<50%, where RH is relative humidity expressed in percent,
- T is daily average air temperature (°C), and
- 0.013 and 50 are empirical fitting parameters

For any day where T is ≤0, estimated PET will be zero.

Priestley Taylor Method

The Priestley-Taylor (1972) method was developed as a simplified form of the Penman-Montieth equation. While it has ben applied in a variety of different settings, it requires site-scale data or appropriate downscaling techniques for the net radiation, ground heat flux, and alpha terms, and as such may be challenging to apply in the absence of site-scale data.

$$\lambda(PET) = \alpha \frac{\Delta}{\Delta + \gamma}(R - G)$$

Equation B-12

Where:

- *PET* is potential evapotranspiration (mm),
- *α* is an empirical coefficient that varies based on land cover and regional climate, generally set to a default value of 1.26,
- *R* is net radiation (W/m^2), and
- G is ground heat flux, (W/m^2; positive in the downwards direction).

Penman-Monteith Method

The Penman-Monteith (Monteith, 1965) method was developed as a modification of Penman's formula for evaporation from open water surfaces to account for the atmospheric resistance of the vegetation canopy. It considers all major factors contributing to PET, meaning that it is appropriate for use without calibration to local conditions but is also very data intensive.

$$\lambda(PET) = \frac{\Delta(R - G) + \rho_a c_p \frac{(e_s - e)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

Equation B-13

Where:
- r_a is aerodynamic resistance (s/m)
- r_s is stomatal or canopy resistance (s/m)
- e is the vapour pressure (kPa)
- e_s is the saturated vapour pressure (kPa)
- ρ_a is the density of air (g/m³)
- c_p is the specific heat capacity of air (≈1.004 J/g/K)

B4: Groundwater Flow

Groundwater is taken to be all subsurface water in the saturated zone below the water table. Although the cost and complexity of subsurface investigations makes accurate quantification challenging, some assessment of the groundwater flux is critical to assessing the water balance of a wetland. TRCA advises applicants to begin with obtaining historical groundwater information in the vicinity of the subject wetland. The Ontario Ministry of Environment, Conservation, and Parks (MECP) well records database and the Oak Ridges Moraine Groundwater Program database are good starting places to help determine the amount and types of data that need to be collected on-site to fully understand groundwater fluctuations and groundwater movement between the wetland and the surrounding area. Because the groundwater environment is hidden from view and can vary dramatically over short distances, it is essential to collect data on-site in order to ascertain local hydrogeologic conditions. Drive point piezometers can be a relatively inexpensive way to assess the subsurface environment of wetlands, for example by determining the presence or absence of vertical hydraulic gradients within the study wetland. Once on-site data have been collected using the *Wetland Water Balance Monitoring Protocol* (TRCA, 2016), the following calculations and models can be used to estimate ground-water inputs to and outputs from the wetland system.

Darcy's Law describes the movement of water through a porous medium from areas of high pressure to low pressure, with the rate of flow being proportional to the difference in hydraulic head between two points and inversely proportional to the length of flow path between two points (Fetter, 2001):

$$Q = KA\left(\frac{\Delta \mathrm{h}}{\mathrm{L}}\right)$$

Equation B-14

Where:
- Q is volumetric discharge (L^3/T; m^3/d),
- K is hydraulic conductivity (L/T; m/d), a proportionality constant,
- A is the cross-sectional area of flow (L^2; m^2),
- L is the flow length (L; m), and
- Δh is the difference in hydraulic head along the flow length L

Using this equation, the rate of flow of ground water into or out of a wetland can be estimated from measurements made on-site, because a number of the above parameters can be measured in the field following installation of wells. The difference in hydraulic head, Δh, can be determined from water-level measurements made in two different wells, where L represents the distance between the wells. The cross-sectional area, A, is calculated as the confined aquifer's saturated thickness, multiplied by the aquifer width. The hydraulic conductivity, K, must be estimated using either on-site tests (e.g. slug tests or bail tests, such as the Hvorslev (1951) method) or existing information about the hydrogeological properties of geological strata. . Note that the hydraulic conductivity is typically greater in the horizontal direction than in the vertical direction as a consequence of bedding planes, laminae, and other sedimentary structures. This information can then be used to estimate the rate and quantity of ground-water inflow to and outflow from a wetland.

A form of Darcy's Law that is used to quantify flow through unconfined aquifers is Dupuit's Equation (Fetter, 2001):

$$q' = \frac{1}{2}K\left(\frac{h_1^2 - h_2^2}{L}\right)$$

Equation B-15

Where:

- q' is flow per unit width (L^2/T; m^2/d)
- K is hydraulic conductivity (L/T; m/d)
- h_1 is head at the origin (L; m)
- h_2 is head at flow length (L; m)
- L is flow length (L; m).

For more complex wetlands, an analytical solution using Darcy's Law may not be practical and not all bedrock-dominated flow systems can be characterized using Darcy's Law. Under these circumstances, a numerical groundwater flow model can be used to simulate groundwater flow. Numerical groundwater flow models are mathematical representation of an actual groundwater system that can be used to predict water levels as well as the direction and magnitude of flow. Models range from simple to very complex in terms of data input requirements, calibration requirements, and data output. An internally drained wetland where the outflows from the wetland are only in the form of groundwater outflow and evapotranspiration will almost certainly require a complex numerical groundwater flow model to accurately estimate the groundwater flow exchange between the wetland and the surrounding areas. The applicant should consult with the local Conservation Authority to determine if there any existing calibrated numerical ground-water flow models in the vicinity of the study site.

The steps used to quantify the groundwater portion of a wetland water budget are outlined in Figure 10. In summary, historical data should be evaluated to identify data gaps and determine the data needs for feature-based water balance analysis. Historical groundwater data also may be used to generate a long term record from shorter-term measurements and to determine representative wet, dry, and average conditions. Available data on the site's topography, soil type, surficial geology, and hydrography should be examined to determine the number of sections of groundwater flow at a site.

Wells must be installed to adequately characterize water table fluctuations and groundwater movement across the site, both vertically and horizontally. The hydraulic conductivity of both aquifers and aquitards also must be determined from soil borings, wells, infiltrometers, permeameters, and/or aquifer tests. The monitored data should be used to calculate groundwater flow using Darcy's Law and/or outputs from numerical ground-water flow models (e.g. MODFLOW). The results of the analysis can be used to determine groundwater inputs to and outputs from the wetland system. Daily and monthly groundwater flux values can then be tabulated and graphed for the monitoring time period.