

Chapter 6

Development and Initial Refinement of a Water Balance Model as a Planning Tool for Stormwater Management Application

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Water balance models can be very useful when establishing the long-term water budget components of an area prior to urban development and the changes in the hydrologic cycle after development. In this case, the water budget components considered include: precipitation; snowmelt and rainfall runoff; evapotranspiration; and surficial and deeper groundwater recharge. Continuous review and refinements of the model component routines and future calibration work allows for expansion of applicability. The model discussed here has been applied to compute the effects of urbanization on the water balance in a high recharge area and to assess specific control measures for mitigating recharge reductions. As part of the first refinement, the evapotranspiration (ET) relation has been enhanced and compared to the original simulation results.

This chapter describes the first phase of the development, refinement, and application of a planning-level water balance model.

6.1 Introduction

The importance of understanding how the surface and groundwater regimes react to land use change or management options it is now well recognized. This is particularly true in head-water areas where groundwater recharge provides

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baseflow to downstream cold water spawning tributaries or water quality dilution zones. As indicated in the Stormwater Management Practices (SWMP) Planning and Design Manual in Ontario (MOEE, 1994), there is no convenient approach to predict the interaction between surface water and groundwater systems before and after urban development, and to determine the relative proportions of groundwater and surface water inputs, other than in a very broad way. Linking surface water models which can simulate surface runoff on a continuous basis with groundwater modeling packages requires substantial effort and can usually be accomplished only if significant groundwater data is available.

This chapter summarizes some of the development features and provides results of an application of the Stormwater Management Practices Water Balance Model (Version 1) produced as an attempt to bridge the gap in the availability of suitable analysis tools. The modeling approach involves the continuous determination of the daily hydrologic budget components of an area as they occur in the hydrologic cycle and as they are modified by urban development and the incorporation of specific stormwater controls. A brief example of its application is given, describing the input and results showing relative changes between different land-uses and control measures. Calibration and validation, or even rigorous comparison of results with other established and detailed models, is left for upcoming development phases. Further review and incorporation of alternative theories and routines is also on-going.

6.2 Methodology

The water budget determination implies quantification of the volumes of storage and rates of water movement from one physical state and location to another. An accounting is made of water entering, leaving, and remaining in storage during a specified time period over a study area which can be defined by topographic, political, or other arbitrary criteria. The water components considered in this modeling approach include precipitation in the form of rainfall or snowfall, rainfall runoff, snowmelt, upper soil infiltration, evapotranspiration, groundwater recharge, and SWMP input to groundwater as a way of controlling reductions in infiltration after development (e.g. infiltration trenches, perforated sewer pipes, reduced lot grading, etc.).

The theories used in the model to compute each of these individual components have been adopted from previously published equations. The model brings the concepts and equations together to simulate their interaction in an attempt to approximate their occurrence. The surface water inputs of rain and snow are applied on a daily basis and calculations made of outputs of runoff, abstraction to surface storage and infiltration to soilwater storage. However, in developing this approach it was recognized that daily time steps are not particularly

suited when determining surficial soil infiltration during specific event data due to the tendency to overestimate the infiltration capacity. However, in the interim, for planning purposes, this approach would still compare favourably with other presently-used modeling approaches also applying daily values (Johnstone et al., undated).

The general balance equation used to account for the surface and ground water storage and for the surface abstraction storage for a given time interval is:

$$\Delta S = I - O \quad (6.1)$$

where:

$$\begin{aligned} \Delta S &= \text{change in storage,} \\ I &= \text{inflow,} \\ O &= \text{outflow.} \end{aligned}$$

The water budget over the surface (other than initial abstraction storage) is:

$$\Delta S = R + SM - SI - RO \quad (6.2)$$

where:

$$\begin{aligned} \Delta S &= \text{change in surface water storage (mm),} \\ R &= \text{rainfall (mm),} \\ SM &= \text{snowmelt (mm),} \\ SI &= \text{upper soil infiltration (mm),} \\ RO &= \text{surface runoff (mm).} \end{aligned}$$

For the purpose of this analysis, no significant evapotranspiration is assumed to occur during rainfall or snowmelt periods (however, this approach may be revised to account for evapotranspiration).

6.2.1 Snowmelt, (SM)

Precipitation occurs as rain or snow. The model algorithm uses the average daily temperature as a base temperature to determine the form of precipitation: if the temperature is above the base (e.g. 0° C), the precipitation occurs as rain. If the temperature is below the base temperature, the precipitation occurs as snow and accumulates in the snowpack.

Snowmelt is calculated using degree-day equations as defined by Environment Canada's Atmospheric Environment Service (AES). The AES defined five different models for several regions in Canada. The Southern Ontario model is given by (Bruce and Clark, 1966):

$$SM = 0.02(Tx - 32) \quad (6.3)$$

where:

$$\begin{aligned} SM &= \text{snowmelt (inches/day),} \\ T_x &= \text{maximum daily air temperature (}^{\circ}\text{F).} \end{aligned}$$

A form of Equation 6.3 converted to metric units is used in the model as described by the AES to accumulate snow on the snowpack and to deplete the storage during days with average daily temperature above the base temperature. The algorithm ends when the snowpack is reduced to zero. Evaporation (sublimation) from snow is ignored.

6.2.2 Surface Runoff, (RO)

Similar to other water balance planning approaches (Harbor, 1994) and for this first phase of development, the surface runoff is computed using a modified Soil Conservation Service (SCS) form of the rainfall-runoff equation:

$$RO = \frac{(R + SM + IA)^2}{(R + SM - IA) + SS} \quad (6.4)$$

where:

$$\begin{aligned} R &= \text{rainfall (mm),} \\ SM &= \text{snowmelt (mm/day),} \\ IA &= \text{maximum surface abstraction available (mm),} \\ SS &= \text{available upper soil storage (mm).} \end{aligned}$$

6.2.3 Maximum Surface Abstractions, (IA)

The surface abstractions are accounted separately for pervious and impervious areas. During a precipitation event, the available surface abstractions are filled first, before runoff. The storage is re-established during inter-event dry periods at the rate of evaporation and, for pervious areas, at the added user-defined upper soil infiltration rate.

6.2.4 Available Upper Soil Storage, (SS)

A separate water balance computation is conducted for the amount of storage available in the upper soil layer (upper soil storage). The change in storage is expressed as:

$$\Delta SS = SI - SET - RGI \quad (6.5)$$

where:

$$\begin{aligned} \Delta SS &= \text{change in upper soil storage (mm),} \\ SI &= \text{infiltration (from surface to upper soil storage) (mm),} \end{aligned}$$

SET = upper soil evapotranspiration (mm),
 RGI = recharge (seepage) to groundwater (mm).

The maximum amount of storage available in the upper layer at any one time corresponds to antecedent soilwater condition I (AMC I) in the Soil Conservation Service (SCS) relation. The equivalent depth below the surface which defines the upper soil layer is determined from maximum storage divided by the soil porosity value as listed in Table 6.1.

Table 6.1 Hydrologic capacities of soil texture classes (after Viessmann *et al.*, 1977).

Texture Class	S [%]	G [%]	AWC
Coarse Sand	24.4	17.7	6.7
Coarse Sandy Loam	24.5	15.8	8.7
Sand	32.3	19.0	13.3
Loamy Sand	37.0	26.9	10.1
Loamy Fine Sand	32.6	27.2	5.4
Sandy Loam	30.9	18.6	12.3
Fine Sandy Loam	36.6	23.5	13.1
Very Fine Sandy Loam	32.7	21.0	11.7
Loam	30.0	14.4	15.6
Silt Loam	31.3	11.4	19.9
Sand Clay Loam	25.3	13.4	11.9
Clay Loam	25.7	13.0	12.7
Silty Clay Loam	23.3	8.4	14.9
Sand Clay	19.4	11.6	7.8
Silty Clay	21.4	9.1	12.3
Clay	18.8	7.3	11.5

where: S = total porosity - 15 bar soilwater %,

G = total porosity - 0.3 bar soilwater %

AWC = S - G = porosity drainable only by evapotranspiration.

6.2.5 Upper Soil Infiltration, (SI)

The upper soil infiltration accounts for the water movement between the surface and the upper soil storage. The rate and volume of water moving into ground storage depends on the available storage in the soil. The upper soil infiltration is calculated directly from Equation 6.2 by adding any residual surface water storage (after depletion by evapotranspiration), to the difference (R+SM-RO).

6.2.6 Evapotranspiration, (ET)

Water leaving the watershed through evaporation and transpiration can be very significant over time and continuous modeling requires that estimates of this be incorporated. In most cases, potential evapotranspiration and soilwater conditions are the predominant factors used in calculating evapotranspiration. The potential evapotranspiration (PET) is defined as the amount of “water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation” (Viessman et. al. 1977). In this case the PET is taken from AES estimates of daily lake evaporation. The actual ET from the soilwater layer is calculated using a slightly modified version of an equation developed by the U.S. Agricultural Research Service (ARS) which accounts for the vegetation characteristics and soilwater (Viessman, p. 58). The modified ARS form of equation is as follows:

$$ET = GI \times k \times PE \left(\frac{S - SA}{S} \right)^n \quad (6.6)$$

where:

- ET = actual evapotranspiration (mm/day),
- GI = growth index of vegetation as proportion of maturity,
- k = the ratio of ET to potential evapotranspiration at full canopy with freely-available water,
- PE = lake evaporation taken as the potential (mm/day),
- S = as identified in Table 6.1,
- SA = available porosity (unfilled by water),
- n = an exponent that varies with soil type in the range of 0.1 to 0.25.

In this case after contacting the ARS, the denominator inside the brackets has been modified from ‘AWC’ (porosity drainable only by evapotranspiration) in the original form of the equation to ‘S’, and the exponent from ‘x’ (x=AWC/G, where AWC is the porosity drainable only by evapotranspiration and G being the moisture freely drained by gravity).

In this application, the growth index (GI) is simplified by a sinusoidal distribution over the summer growing season. Evapotranspiration from surface storage (interception and depression storage) is assumed to occur at the potential rate.

The model calculates actual evapotranspiration ET from the vegetation growth index as a function of the time of year, lake evaporation as PET, and the underlying soil conditions. The resulting ET is a measure of the water loss from surficial soil storage largely through diffusion of water vapour from plant leaves to the atmosphere (transpiration). It should be noted that evapotranspiration below an air temperature of 4.4°C (40°F) was considered to be negligible in these calculations, consistent with other applications (Viessman et. al., 1977).

The algorithm selected first depletes surficial abstraction or interception storage at the potential rate. The PET remaining and ‘evapotranspiration opportunity’ are used to quantify and extend the water loss from the upper soil storage to the root zone. Evapotranspiration opportunity is defined as the maximum amount of water available for evapotranspiration at a particular location during a prescribed period.

6.3 Example

6.3.1 Meteorologic Data

Depending on the site, meteorologic input data are available through Environment Canada Atmospheric Environment Service (AES) in either hourly or daily format. For this purpose, twenty years of daily precipitation, mean daily dry-bulb temperature, and lake evaporation components have been obtained from the AES from several gauging stations in Ontario.

6.3.2 Site Data

Site data includes all the measured pervious and impervious area parameters such as tributary areas and land uses, percent imperviousness, and measured surface and subsurface hydrologic parameters such as hydraulic conductivities, and porosity. Additional data includes soil cover, vegetation growth indices, base temperatures for snowmelt, and snowmelt factor. For this purpose, these have been selected based on site-specific conditions and professional judgement.

6.3.3 Analysis Approach

A water balance model was applied to assess the impacts of a proposed residential development on the water budget components in a high recharge area.

The study approach first determined water balance components under present, undeveloped conditions. These results provide target values for groundwater recharge after development. The hydrologic and hydrogeologic model parameters affected by the urbanization were then updated to reflect the proposed development conditions without SWMPs. The difference between pre and post-development infiltration volume corresponds to the SWMP infiltration required. Lot-level controls in the form of roof-runoff soakaway pits were introduced and their size sequentially increased up to the maximum recommended size (15 mm of roof runoff). The storage volume is equal to the product of the roof depth sizing criteria (e.g. 5 or 15 mm) and the total roof area.

A perforated pipe system was also incorporated into the model as a reservoir receiving runoff from the roads and its effects evaluated. The perforated pipe storage is implemented by intercepting the excess runoff from the area and discharging only when the storage provided by the pipes is exceeded. The storage volume is set equal to the product of the depth sizing criteria (e.g. 2 mm) and the tributary area. For example, a 2 mm perforated pipe storage (net trench storage below the perforated pipe) corresponds to the product of 2 mm over the 82.5 hectare study area, or 1650 m³.

6.3.4 Results

The following water balance results are presented in Table 6.2 as average yearly values over the study area. The following assumptions and comments are applicable to the results in Table 6.2:

- Post-development vegetation cover type is assumed to remain as under pre-development conditions. Therefore, changes (reductions) in evapotranspiration between development conditions are due to reduction in vegetated and pervious areas after urbanization.
- Initial abstractions have been decreased to reflect uniform lot grading.
- Although the SWMP sizing criteria recommends a one day drainage time, the model conservatively considers uniform discharge over three days. The two additional days account for decreased infiltration rates resulting from lower overall hydraulic gradient in the confining soil around and beneath infiltration facilities after a wet-weather event (i.e. increase in soilwater content).
- The average runoff coefficient obtained is consistent with typical values expected from similar land-uses and soil conditions.
- The reduction in surficial soil infiltration with soakaway pits and perforated pipes occurs because SWMP infiltration contributes directly to deeper soils. SWMP infiltration has direct benefits for removing surface runoff.

- Computed post-development groundwater recharge decreases about 22% compared to pre-development conditions. This reduction is consistent with the increased imperviousness after development. In comparison, allowing roof areas to drain to pervious surfaces yields a computed 15% reduction in recharge as compared with pre-development levels.
- Soakaway pits sized to infiltrate 5 mm of roof runoff are computed to provide a marginal improvement in total infiltration volume compared to attenuating the roof runoff by dispersing it over the pervious area.
- The perforated pipe system is computed to provide significant improvements to the total groundwater recharge volumes.
- The evapotranspiration values are low in comparison with other sites, particularly those with average infiltration capacity. The values shown in Scenario 8 correspond to an earlier version of the evapotranspiration Equation 6.6 shown previously. However, as in this study area, evapotranspiration values can be affected (reduced) by sands with low soilwater retention capacity (lower irreducible water saturation).
- The refined evapotranspiration relation in Equation 6.6 yields higher average annual ET totals depicted in Table 6.2 (Scenario 9). Further testing with additional model parameters such as the watershed cover factor, resulted in further increases in total evapotranspiration. However, monitoring and calibration will be required to justify and establish more precise values and results.

6.4 Conclusions

The SWMP water balance model produced useful results when establishing relative proportions of pre-development and post-development water budget components. The model provides great flexibility when assessing different development configurations and control measures to achieve specific recharge targets. Additional work is required to refine the water budget routines and extend the applicability of the model.

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Table 6.2 Typical water balance results in a high recharge area (units in mm/year).

Selected Surface and Subsurface Water Budget Components	Pre-Develop	Post-Development Scenarios								
		(1) No SWMPs (*)	(2) No SWMPs (**)	(3) 5 mm Roof Storage in Soak-Away Pits	(4) 15 mm Roof Storage in Soak-Away Pits	(5) 2 mm Perforated Pipe Storage (***)	(6) 5 mm Perforated Pipe Storage (***)	(7) 15 mm Perforated Pipe Storage (***)	(8) Combined (4) and (6)	(9) (4) & (6) with ET Refined
Runoff	57	228	201	220	198	108	54	8	51	51
Surface Abstractions	191	92	97	90	90	91	91	91	90	90
Surficial Soil Infiltration	659	518	556	544	529	557	557	557	529	529
Groundwater Recharge	557	436	476	478	481	555	610	655	613	575
Evapo-Transpiration	177	119	120	120	120	120	120	120	120	158
Runoff Coefficient	0.07	0.29	0.26	0.28	0.25	0.14	0.07	0.01	0.06	0.06

Notes to Table 6.2

Average yearly precipitation = 785 mm

For checks on water balance (runoff + evapotranspiration + groundwater recharge) = yearly precipitation of 785 mm +/- year to year changes in soilwater storage.

Evapotranspiration amounts in scenarios 1 to 8 have been made with an earlier version of Equation 6.6 and are generally low. Comparative performance of alternative SWMP alternatives is the objective of their presentation.

* Roof runoff discharged directly to sewers (ie. directly connected).

** Roof runoff discharged to pervious areas (ie. not directly connected) - this also applicable to remaining scenarios (3 to 9).

***SWMP sufficient to maintain the ground water recharge rates at pre-development levels.

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