OAK RIDGES MORAINE CONSERVATION PLAN
Technical Paper Series

10 - Water Budgets

1   Purpose and Overview

This technical paper provides guidance for implementing Section 25 of the Oak Ridges Moraine Conservation Plan (ORMCP) pertaining to water budgets. The main audience for this technical paper is the municipalities and conservation authorities who are concerned with developing and implementing the water budget and watershed plan requirements of the ORMCP. Guidance pertaining to watershed plans and water conservation plans is available in separate technical papers.

Section 3 of this technical paper outlines the ORMCP requirements pertaining to the preparation of water budgets. Section 4 outlines the rationale for the requirements, as well as the anticipated uses of the water budgets that are to be prepared. Section 5 describes other relevant initiatives related to water budgets in Ontario and the Oak Ridges Moraine (ORM). Section 6 describes water budgets and their components. Section 7 outlines a six-step process for developing and applying a water budget to fulfill the requirements of the ORMCP. Pertinent references are listed in Section 8.

2   Related Considerations

When preparing Water Budgets, it is suggested that the reader also review the highlighted, associated topic areas as discussed in the ORMCP, as shown in Figure 1 below.

Clean Water Act, 2006

The *Clean Water Act, 2006* was passed on October 19, 2006. Associated regulations, Director's Rules and technical modules are currently being developed. Readers of this technical paper should take note that the requirements of the *Clean Water Act, 2006* may have implications to initiatives undertaken to implement the ORMCP. Information concerning the *Clean Water Act, 2006* is available at: www.ene.gov.on.ca/en/water/ .

Further Reading

Please also refer to the additional list of resources and references listed at the end of this technical paper.

Figure 1 ORMCP Topic Areas and Linkages with Technical Paper 10 - Water Budgets
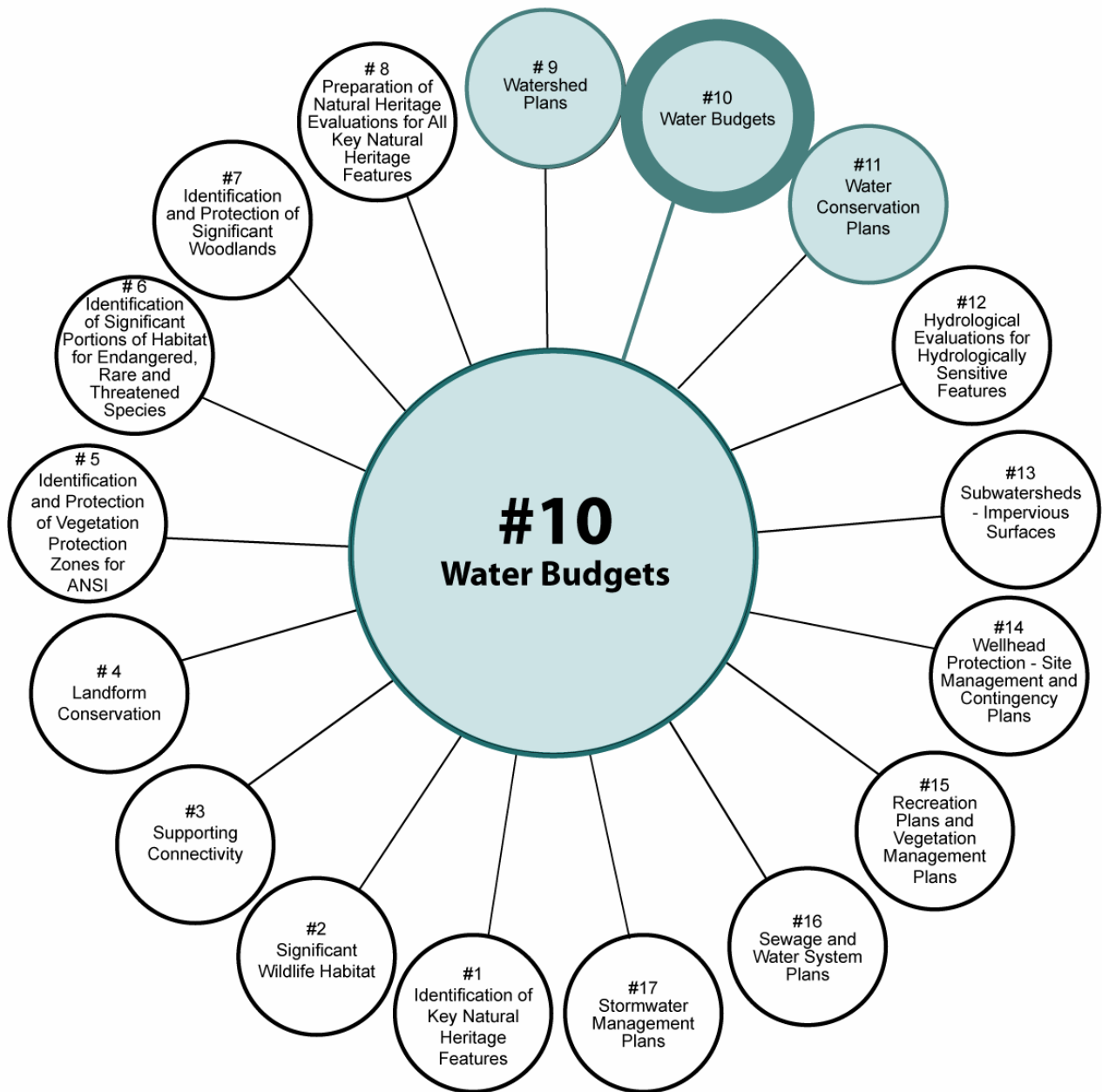
3   Watershed Plan Requirements of the Oak Ridges Moraine Conservation Plan

The ORMCP requirements pertaining to water budgets are outlined in **bold-italics** as follows:

"Water budgets and conservation plans

25.

(1)   *Every upper-tier municipality and single-tier municipality shall, on or before April 22, 2003, begin preparing a water budget and conservation plan, in accordance*

with subsection (2), for every watershed whose streams originate within the municipality's area of jurisdiction.

(2) *A water budget and conservation plan shall, as a minimum,*

    (a) *quantify the components of the water balance equation, including precipitation, evapotranspiration, groundwater inflow and outflow, surface water outflow, change in storage, water withdrawals and water returns;*

    (b) *characterize the groundwater and surface water flow systems by means of modelling;*

    (c) *identify,*

        i. *targets to meet the water needs of the affected ecosystems,*

        ii. *the availability, quantity and quality of water sources, and*

        iii. *goals for public education and for water conservation;*

    (d) *develop a water-use profile and forecast;*

    (e) *evaluate plans for water facilities such as pumping stations and reservoirs;*

    (f) *identify and evaluate,*

        i. *water conservation measures such as public education, improved management practices, the use of flow-restricting devices and other hardware, water reuse and recycling, and practices and technologies associated with water reuse and recycling,*

        ii. *water conservation incentives such as full cost pricing, and*

        iii. *ways of promoting water conservation measures and water conservation incentives;*

    (g) *analyse the costs and benefits of the matters described in (f);*

    (h) *require the use of specified water conservation measures and incentives;*

    (i) *contain an implementation plan for those specified measures and incentives that reconciles the demand for water with the water supply;*

    (j) ***provide for monitoring of the water budget*** *and conservation plan* ***for effectiveness.***"

4   Rationale for the Requirements

The ORM is a vital recharge zone for groundwater, which feeds wetlands, lakes, streams, and rivers. Aquifers within the ORM provide drinking water for local residents, as well as water supplies for agricultural, industrial, commercial, and recreational uses. Developing an understanding of the groundwater and surface water flow systems associated with the ORM is important for meeting the ORMCP objectives including the protection of the ecological and hydrological integrity of the ORM Area.

Water budgets for any study area basically require calculation of the various fluxes through the applicable hydrologic cycle reservoirs including the atmosphere, upon the ground surface and within the subsurface. However, the ORMCP water budget requirements expand beyond the quantification of the components of the water budget

equation. The water budget is to also include surface and groundwater modeling to characterize the flow of water on and beneath the surface. The term water budget as used throughout the remainder of this technical paper is to implicitly include the accompanying groundwater and surface water modelling tools as required by the ORMCP. The use of both groundwater and surface water models will assist in determining the pathways and timing that water takes in moving through the various reservoirs.

The ORMCP also incorporates the requirement for setting targets to maintain aquatic ecosystems. There has recently been a push to relate hydrologic cycle variations, both natural and anthropogenic, to ecosystem response. The link between the abiotic effects of variations in the hydrologic cycle to the biological community is considered an emerging science (Hunt and Wilcox, 2003; Rogers and Biggs, 1999). One of the ultimate goals of understanding flow systems (of which water budgets are a part) is to evaluate ecosystem health and response.

Developing and applying water budgets for watersheds of the ORM will provide for a much more comprehensive understanding of water resources on the ORM, and provide valuable input to land and water management decisions.

4.1　Anticipated Uses of Water Budgets

It is anticipated that the water budgets prepared for the ORM (including the surface and groundwater models) will be used in the following ways:

(a)　to set quantitative hydrological targets (e.g. water allocation, recharge rates, etc.) within the context of watershed plans;

(b)　as a decision-making tool to evaluate, relative to established targets, the implications of existing and proposed land and water uses within watersheds, including, for example, restoration and rehabilitation projects identified in management plans;

(c)　to evaluate the cumulative effects of land and water uses within watersheds;

(d)　to provide a watershed-scale framework within which site-scale studies, such as a hydrological evaluation (Section 26 of the ORMCP) or a sewage and water system plan (Section 43 of the ORMCP) will be conducted;

(e)　to help make informed decisions regarding the design of environmental monitoring programs; and

(f)　to assist in setting targets for water conservation.

5　Water Budget Initiatives

Cumming Cockburn Limited, CVC, GRCA Studies

Water budget studies have been conducted and requirements have been investigated in Ontario for several years now. The need for guidance documents in the Province was recognized in the 1990's when The Watershed Management Committee consisting of staff from the Ministry of Natural Resources (MNR), the Ministry of the

Environment (MOE), the Ministry of Municipal Affairs and Housing and the Ministry of Agriculture, Food and Rural Affairs had a technical document prepared, Water Budget Analysis on a Watershed Basis, to standardize an approach by practitioners to undertake water budget analyses (Cumming Cockburn Limited, 2001). In addition to this document, both Credit Valley Conservation (CVC) and the Grand River Conservation Authority (GRCA) have been undertaking pilot water budget studies in partnership with the Province for the past several years and have to date prepared draft water budget modules stating the procedures that were taken by staff and consultants at these agencies in developing water budgets for their respective watersheds. Therefore, it is recognized that between this current technical paper, the draft water modules of the CVC and the GRCA, and the Water Budget Analysis on a Watershed Basis report, there is ample material that can be drawn upon by practitioners wanting to undertake water budget analyses. This technical paper seeks to build on the information contained in the Water Budget Analysis on a Watershed Basis report by providing information on various water budget aspects relating directly to the ORM. The MOE has prepared additional documents that contain information relating to various aspects of water budget calculations (MOE 1989; 1995; 2003).

Historical Oak Ridges Moraine Water Budget Investigations

Examples of historical water budget investigations within the general ORM area are largely restricted to the western half of the ORM. For example, investigations within the Credit River and Grand River watersheds have been conducted and utilize groundwater and/or surface water flow models. Brief summaries of these investigations can be found at the locations listed below.

Credit River Watershed (Western edge of ORM)

www.waterloohydrogeologic.com/consulting/project_pdfs/Water_Budget_web.pdf

www.waterloohydrogeologic.com/consulting/project_pdfs/Credit_River_web.pdf

www.creditvalleycons.com/

Grand River Watershed (West of ORM)

www.waterloohydrogeologic.com/consulting/project_pdfs/Grand_River_web.pdf

www.grandriver.ca

The City of Toronto is conducting an assessment of stormwater management known as the Toronto Wet Weather Flow Management Master Plan. Part of this investigation has utilized predominantly surface water models (HSP-F) to provide a current understanding of flows and to assess future scenarios. Further information can be found at: www.toronto.ca/water

York Peel Durham Toronto (YPDT), Conservation Authority Moraine Coalition (CAMC) Initiatives

Since 2002, a coalition of municipalities and conservation authorities has been conducting investigations aimed at providing a quantitative understanding of the hydrogeology and water budget for the ORM. This group is currently led by the Conservation Authorities Moraine Coalition (CAMC/YPDT Groundwater Study) with partner agencies including the Regional Municipalities of York, Peel and Durham, the City of Toronto, and the nine Conservation Authorities having watersheds on the

moraine. Other contributing or partner agencies include the MOE, the Ontario Geological Survey (Ministry of Northern Development and Mines), and the Geological Survey of Canada. The study area for these investigations is shown in Figure 2 and encompasses the entire area of the nine conservation authorities, an area much larger than the moraine, but chosen to allow for balancing of the fluxes of water through the hydrologic cycle associated with the Moraine, particularly through the subsurface. This investigation will be referred to hereinafter as the CAMC/YPDT study.

Figure 2 Oak Ridges Moraine study area
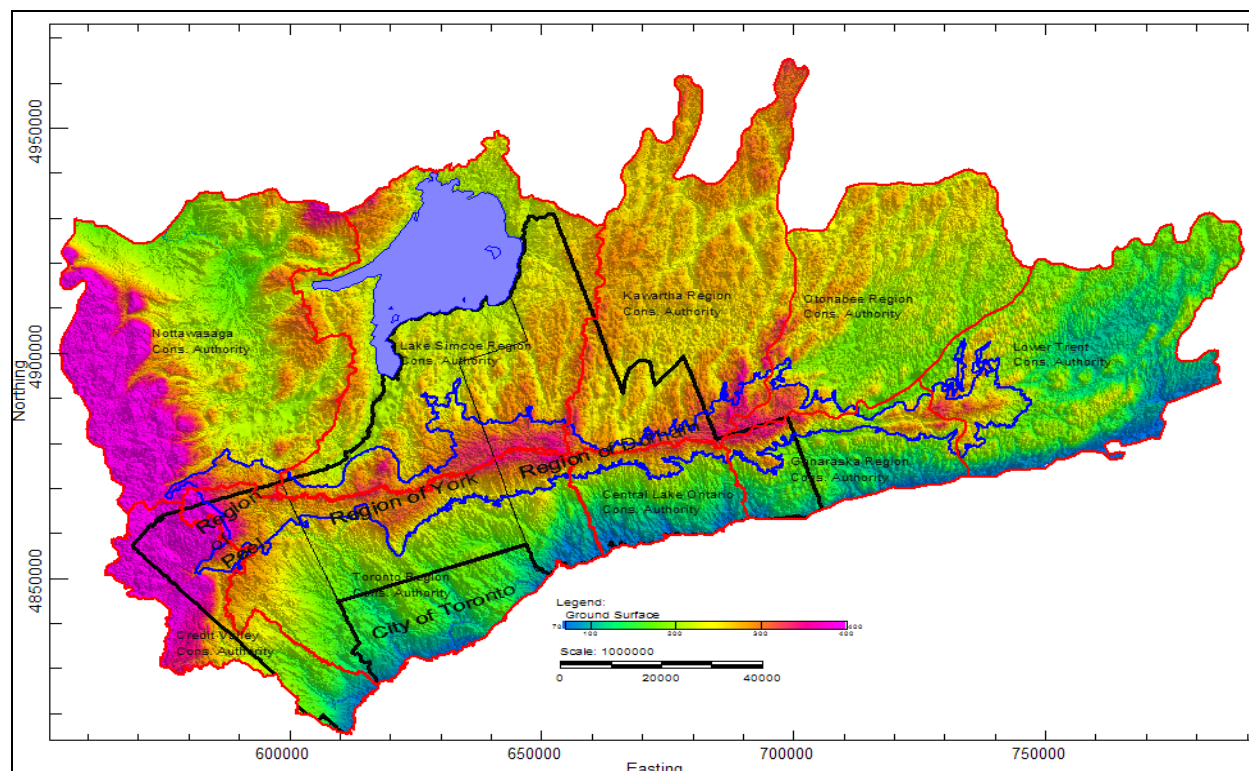
It is expected that future water budget initiatives can benefit from the CAMC/YPDT work completed or in progress. While by no means considered complete, this work provides significant progress in the compilation of mapping and data, development of a geological framework, preliminary water budgets and a three-dimensional numerical groundwater flow model. It is anticipated that this project will incorporate the work being conducted by the Trent Conservation Coalition and by the Simcoe County partnership under the MOE Municipal Groundwater Study Program. Future water budget initiatives can be viewed as pieces fitting into the larger regional puzzle being constructed; ultimately providing a detailed regional understanding of the flow systems for much of south-central Ontario as shown in Figure 2. This regional study ultimately will provide much of the necessary information needed (e.g. data, geological and hydrogeological framework) to undertake watershed or subwatershed scale water budget studies. In a similar vein, detailed understanding derived from any watershed or subwatershed scale water budget undertaking can also be re-incorporated back into the regional "flow-system" picture. The data compiled and the tools constructed to date will add benefit to any future water budget work, and have implications to the scope of work necessary for future water budget projects. As such, this work is referenced where appropriate, so that future duplication of efforts can be avoided.

6 Water Budgets

In simple terms a water budget for a given area can be looked at as water inputs, outputs and changes in storage. The inputs into the area of investigation (precipitation, groundwater or surface water inflows, anthropogenic inputs such as waste effluent) must be equal to the outputs (evapotranspiration, water supply removals or abstractions, surface or groundwater outflows) as well as any changes in storage within the area of interest. This can be expressed as:

$$\text{Inputs} = \text{Outputs} + \text{Change in storage}$$
$$P + SW_{in} + GW_{in} + ANTH_{in} = ET + SW_{out} + GW_{out} + ANTH_{out} + \Delta S$$

Where;

P	= precipitation,
SW_{in}	= surface water flow in,
GW_{in}	= groundwater flow in,
$ANTH_{in}$	= anthropogenic or human inputs such as waste discharges,
ET	= evaporation and transpiration,
SW_{out}	= surface water flow out,
GW_{out}	= groundwater flow out
$ANTH_{out}$	= anthropogenic or human removals or abstractions,
ΔS	= change in storage (surface water, soil moisture, groundwater).

When only a portion of a watershed is investigated, the inputs must be measured and accounted for in the water budget. If an entire watershed or subwatershed is investigated then the surface water inputs would be zero and this term (SWin) would be removed from consideration. Groundwater inflow (GWin) into the watershed or subwatershed (if any) would still have to be taken into account.

An extremely important point regarding water budget calculation is that many assume that the sustainability or "safe yield" of a groundwater flow system can be determined from recharge estimates. This may not always be the case (Theis, 1940; Sophocleous, 1997; Bredehoeft, 1997; 2002). As stated by Bredehoeft (2002), "The size of a sustainable ground water development usually depends on how much of the discharge from the system can be captured by the development. Capture is independent of the recharge; it depends on the dynamic response of the aquifer system to the development." While an estimation of the various components of the hydrologic cycle can be useful, ultimately the emphasis should be expanded (as is the case with the wording in the ORMCP) to include developing tools (e.g. surface and groundwater models) that will allow us to understand, estimate and analyse the various states of dynamic equilibrium that will be attained in response to various stresses imposed upon the flow system. In other words, the water budget result is one of many tools used to understand how water moves throughout the flow system.

6.1 Components of a Water Budget

As mentioned previously, a water budget is basically a quantification or accounting of the various components of the hydrologic cycle for a study area as shown in Figure 3. Precipitation reaching the land surface is distributed in numerous ways. When the ground surface has a low permeability, precipitation

runs off directly towards surface depressions and streams or evaporates back into the atmosphere. When precipitation falls on permeable soils, however, the run-off component can be relatively small (except when soils are frozen or already saturated, i.e. late winter, early spring) and precipitation enters the soil profile where it becomes subjected to free water evaporation, or if vegetation is present, transpiration. The combination of these two processes is termed evapotranspiration. The potential evapotranspiration (PET) is the amount of water that would evaporate and transpire if water was available to the plants and soils in unlimited supply. Since this is not the case in southern Ontario, the term actual evapotranspiration (AET) is used such that AET is less than or equal to PET.

Figure 3 Water budget components (from Gerber and Howard, 1997)
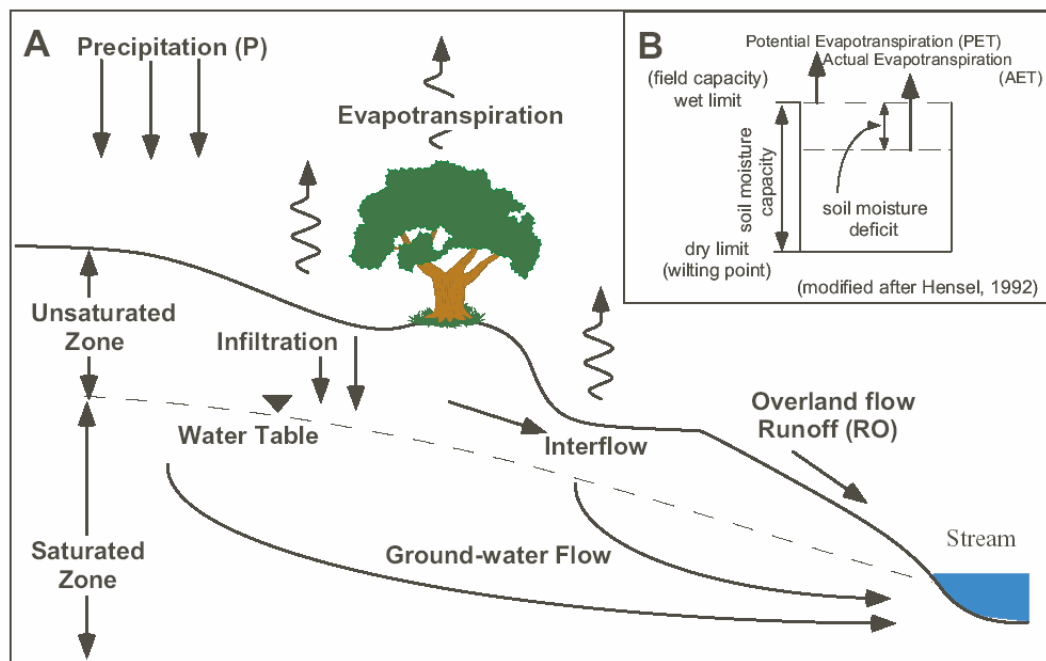
Water that remains after evapotranspiration has the potential to increase the soil moisture content of the soil, and eventually infiltrate to the groundwater reservoir, or move upon the ground surface, termed runoff. In theory, the soil moisture content cannot exceed its maximum or 'field capacity', also known as the 'wet limit', and any excess will drain from the soil to the groundwater system as infiltration. The lower limit of soil moisture content is known as the 'dry limit' (Figure 3 (B)). Prior to reaching the groundwater system, water in the unsaturated zone can be directed via field drains or highly permeable layers in the unsaturated zone, horizontally as 'interflow' to nearby streams. Groundwater may be transpired by plants or discharge to springs and surface water bodies where it eventually evaporates into the atmosphere to complete the hydrologic cycle.

Essentially, there are three compartments to consider in the water budget determination as shown in Figure 4: the ground surface; the unsaturated zone and the saturated zone. Precipitation falls onto the ground surface and then can either: i) be evapotranspirated back to the atmosphere; ii) runoff from the

surface to surface water bodies (e.g. streams, lakes and wetlands); iii) move downward to the unsaturated zone or iv) be removed for human water supply purposes. In turn, water that moves to the unsaturated zone can either: i) be evapotranspirated back to the atmosphere; ii) move laterally as interflow to discharge to local surface water bodies; or iii) move downward to the saturated zone. Similarly, water that moves to the saturated zone can: i) be evapotranspirated back to the atmosphere (e.g. via plants whose roots extend to near the water table); ii) move in the groundwater system and eventually discharge into a surface water body; or iii) be removed for human water supply purposes.

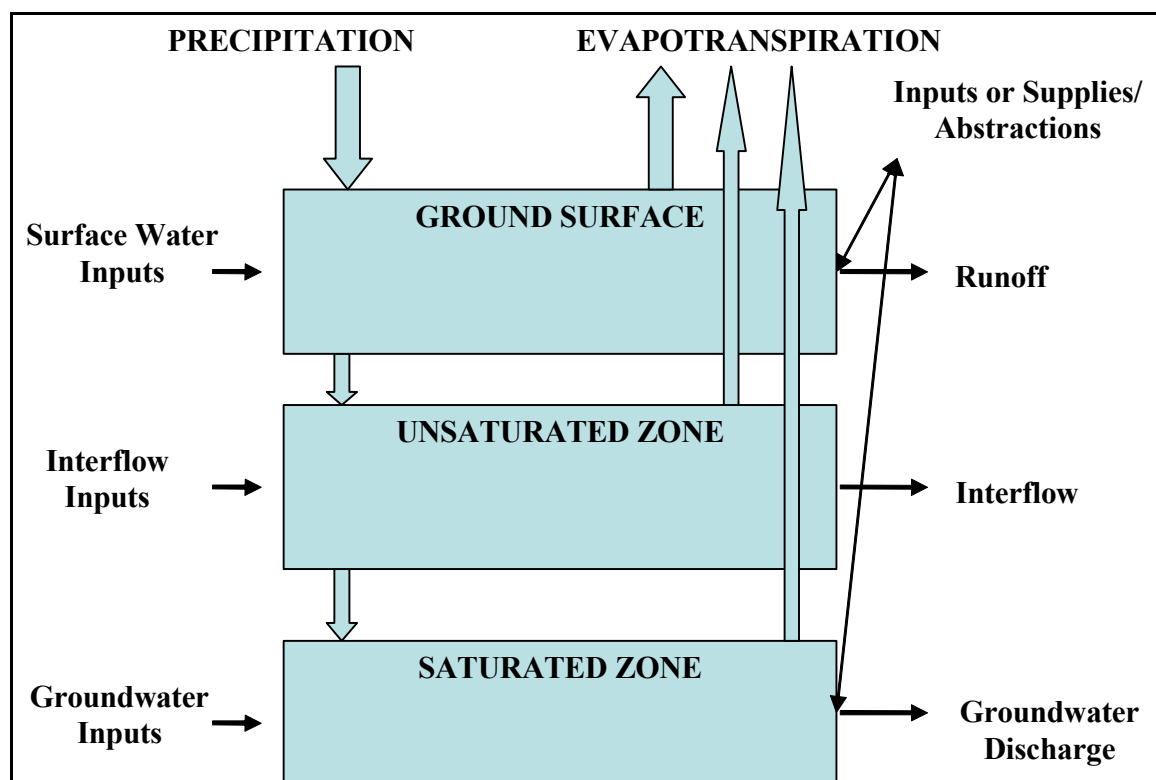**Figure 4 Schematic representation of water budget components**

Figure 4 illustrates that evapotranspiration can occur from any of the three compartments. This figure also shows anthropogenic inputs and/or abstractions. These are both related to human intervention in the water cycle. Inputs would occur in an instance where water external to a watershed (e.g. a water supply from Lake Ontario or Lake Simcoe) was being brought into, and disposed of, within the watershed, thereby increasing the water volume in the watershed. Supplies or abstractions would occur where water was being withdrawn from either a surface water body or the groundwater system and was being removed from the watershed (e.g. a water supply within the watershed, but with treated wastewater disposed directly to Lake Ontario or Lake Simcoe). It is important to note that these human interventions are often difficult to account for in a water budget owing to the fact that a certain portion of the withdrawn water is likely re-circulated back within the same watershed (e.g. through lawn watering or through leakage from municipal infrastructure, etc.). Figure 4 also shows inputs into the three compartments (i.e. surface water inputs, interflow inputs,

groundwater inputs). As mentioned earlier, due to the fact that the water budgets required under the ORMCP are to be undertaken on a watershed or subwatershed basis, these terms will, in most cases, tend to be negligible with the exception of groundwater inputs mentioned above.

Mathematically, the water budget can be expressed as follows (from Dunne and Leopold, 1978; Singer, 1981 and Walton, 1970):

$$P = RO + AET + I + D + A \pm \Delta l \pm \Delta s \pm \Delta g \qquad [1]$$

where

P	= precipitation
RO	= surface runoff
AET	= actual evapotranspiration
I	= interflow
D	= groundwater discharge
A	= anthropogenic inputs (septic systems) and/or supplies/abstractions
Δ**l**	= change in land surface storage
Δ**s**	= change in soil moisture storage
Δ**g**	= change in groundwater storage

Following from equation 1:

$$\text{Stream Flow Discharge (SFD)} = I + D + RO \qquad [2]$$

$$\text{Infiltration (Inf)} = P - AET - RO - \Delta s - \Delta l \qquad [3]$$

and

$$\text{Aquifer Recharge (R)} = P - AET - RO - \Delta s - \Delta l - I \qquad [4]$$

Over long periods of time in an unstressed, natural state basin (no groundwater pumping), the natural inputs will balance the natural outputs so the change in storage will be zero (Freeze and Cherry, 1979; Domenico and Schwartz, 1998). Soil moisture storage may vary considerably on a daily basis but the net change (Δs) over an annual cycle will be negligible compared to other water budget components. Similarly, groundwater storage and land surface storage may fluctuate on a monthly or annual basis, but Δg and Δl will approach zero (steady state) over an extended period of time provided other water budget components remain essentially constant. If Δs, Δl and Δg equal zero, then substitution of equation [4] into equation [1] reveals that

$$\text{Aquifer Recharge (R)} = D + A \qquad [5]$$

Similarly, substitution of equation [2] into equation [1] shows that

$$\text{Stream Flow Discharge (SFD)} = P - AET - A \qquad [6]$$

If groundwater pumping is small, (i.e. A ~ 0), then annual recharge can be equated to groundwater discharge (depending on size of study area and the nature of the groundwater flow system),

$$R = D \qquad [7]$$

and stream flow discharge will be equal to the difference between precipitation and actual evapotranspiration

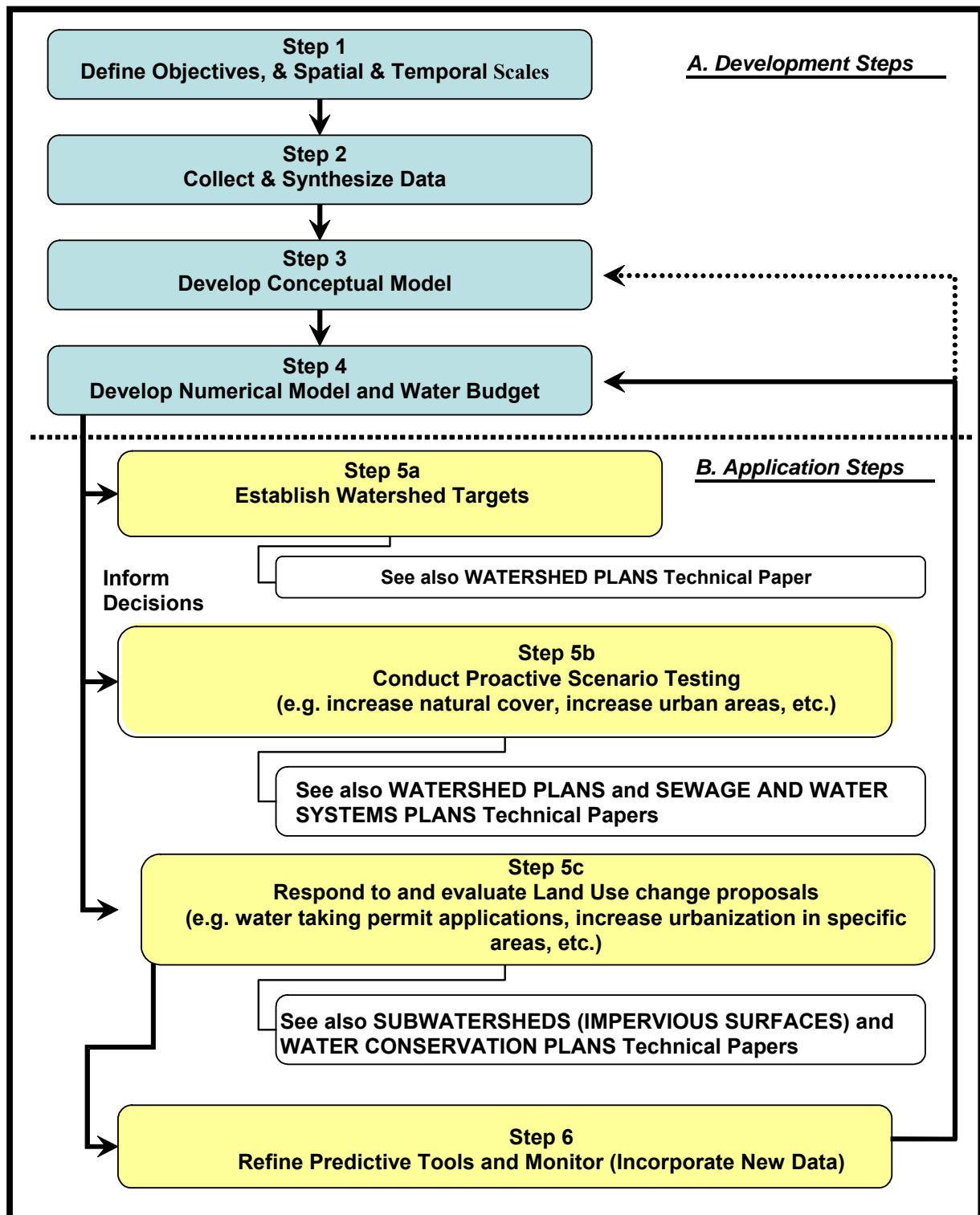i.e.   **SFD = P - AET**   [8]

Interaction of the processes affecting the various components of the hydrologic cycle is very complex and often non-linear. For example, it is difficult to measure evapotranspiration easily, yet it is often the largest flux. Estimates of other components, such as recharge, are the residual of large values with an associated error that is compounded in estimates of the smaller flux (Lerner et. al., 1990). Given the associated error inherent in estimates of the various water budget components, ideally multiple methods should be compared, calibrated and incorporated into the water budget calculation.

7   Implementing the Requirements

The steps required to complete a water budget analysis can be summarized to include the following (see Figure 5):

1.   determine the **objectives** of, as well as the **spatial boundaries and temporal scales** for, the water budget analysis;

2.   acquire and synthesize existing available **data**, collect more data if deemed necessary; determine or estimate (using water table and/or potentiometric surface maps) whether inter-basin transfers of water occur and whether the surface watershed coincides with the groundwatershed;

3.   develop an initial overview understanding (**conceptual model**) of fluxes in the study area (e.g. precipitation, recharge, runoff, evapotransporation). This includes developing an understanding of the geologic system as well as mapping of key surficial features (e.g. wetlands, large paved areas, etc.) that play a significant role in either subsurface or surface water calculations and/or numerical modelling. This initial understanding will aid in determining the calculation procedures and/or models chosen for the study;

4.   undertake **numerical modelling** efforts linking results from both the surface and groundwater calculations and/or models. The key to this step is calibration to observed data or phenomena;

5.   **establish watershed targets** and conduct **scenario testing** to establish the potential impacts of land use change and water use; and

6.   **monitor** and/or collect information to fill in data or knowledge gaps and **refine** models and water budget components as new information becomes available.

Figure 5 Key steps in developing and applying a water budget

A. Development Steps

Step 1
Define Objectives, & Spatial & Temporal Scales

Step 2
Collect & Synthesize Data

Step 3
Develop Conceptual Model

Step 4
Develop Numerical Model and Water Budget

B. Application Steps

Step 5a
Establish Watershed Targets

Inform
Decisions

See also WATERSHED PLANS Technical Paper

Step 5b
Conduct Proactive Scenario Testing
(e.g. increase natural cover, increase urban areas, etc.)

See also WATERSHED PLANS and SEWAGE AND WATER SYSTEMS PLANS Technical Papers

Step 5c
Respond to and evaluate Land Use change proposals
(e.g. water taking permit applications, increase urbanization in specific areas, etc.)

See also SUBWATERSHEDS (IMPERVIOUS SURFACES) and WATER CONSERVATION PLANS Technical Papers

Step 6
Refine Predictive Tools and Monitor (Incorporate New Data)

7.1 Step 1: Define Objectives, & Spatial & Temporal Scales

Clearly defining the objectives of the water budget exercise will help to: i) determine the study area that has to be evaluated; ii) determine the most appropriate model to be used; and iii) set the temporal scale of the necessary calculations. It is expected that key objectives for ORM water budgets will be the investigation of potential impacts to aquatic ecosystems from proposed land or water use changes. The selection of the study area should acknowledge that surface watersheds and groundwatersheds do not always coincide. Also the presence of inter-basin transfers either in or out of the study area should be incorporated.

7.1.1 A Word About Scale

The volumes of water within the various reservoirs of the hydrologic cycle associated with the ORM vary both spatially and temporally. Water budget studies must consider this variability and how it relates to the intended objectives of the study. For instance, climate varies appreciably across the geographic area encompassing the ORM controlled by such factors as topography, prevailing winds, proximity to major lakes such as Lake Ontario or Lake Simcoe, and human influences (e.g. urbanization). Deforestation may increase stream and peak flood flows while decreasing evapotranspiration. Urbanization can increase cloudiness, precipitation and extreme winter temperatures while decreasing relative humidity, incident radiation and wind speed (Phillips and McCulloch, 1972; Brown et al., 1980).

Ecosystem processes also operate on a variety of spatial and temporal scales. Scale dependency in ecosystems may be continuous, every change in scale bringing with it changes in patterns and processes, or there may be "domains" characterized by relatively sharp transition from dominance by one set of factors to dominance by another set (Wiens, 1989). Relationships between physical and biological attributes may be evident at broad scales but overwhelmed by biological interactions at finer scales.

Human observation of ecological processes may also be made at a variety of scales. For logistical reasons, expanding the extent of the area of observation usually requires decreasing the resolution. This leads to an increased ability to detect broad-scale patterns and processes and a reduced ability to detect fine-scale details. If we study a system at an inappropriate scale, we may not detect the actual system dynamics but only artifacts of scale.

Although constrained by the scale of observation, analysis, interpretation and management may also be done at a variety of scales. For example, groundwater systems may be interpreted at regional, watershed, and site scales. Analysts need to be cautious about translating observed relationships between domains of scale and aware of the potential for spatial and temporal lags. Scales of management are critical: to obtain a desired ecosystem response, managers need to undertake a

management action at the appropriate scale or understand how the ecosystem response will translate across both spatial and temporal scales. A multi-boundary, multi-scale perspective is necessary to allow various ecological processes to be considered.
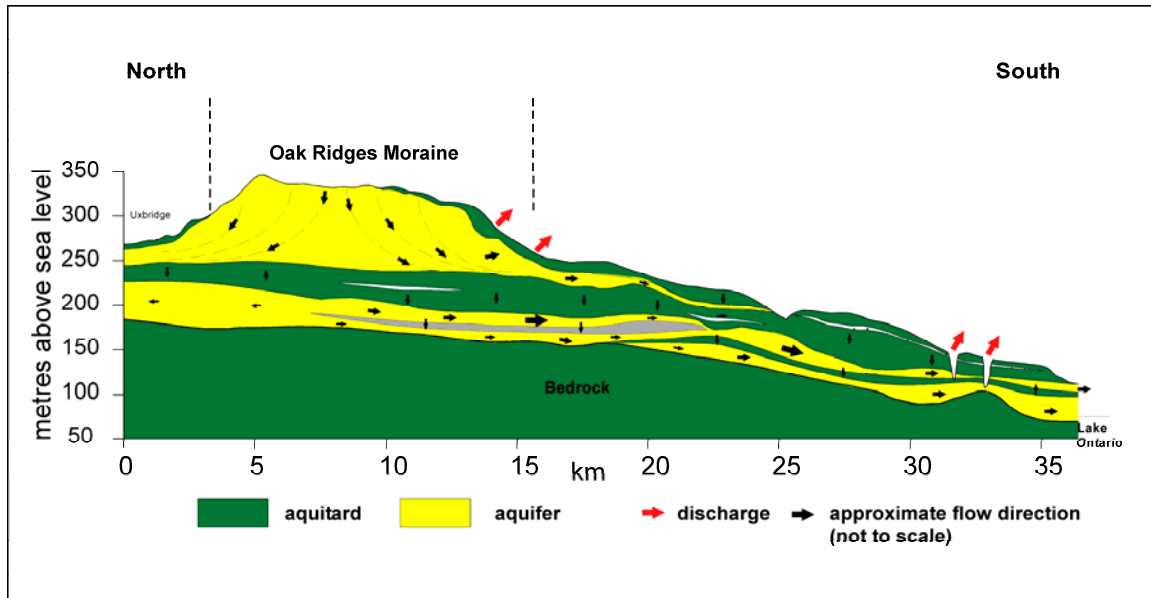
7.1.2 Spatial Scale

The size of the study area necessary to effectively quantify a water budget depends on the details of the situation under consideration. In order to deal with situations effectively, it is imperative that a regional understanding be available from which to draw upon. Any situation at hand can then be placed into the regional context, thus allowing water managers a ready access to a regional understanding so that they can effectively consider and select the most appropriate boundaries for their water budget study. The CAMC/YPDT regional ORM analysis provides a regional framework from which individual water budget analyses at any scale smaller than the whole can be "cookie-cut" out of the regional picture. For example, for any watershed scale water budget analysis, rather than making assumptions or attributing residuals to trans-boundary flow, the groundwater flux across the watershed boundaries can be estimated from the regional numerical flow model.

ORM Boundary Considerations in Water Budgets

Water budgets carried out to meet the requirements of the ORMCP need to encompass a much larger area than the ORM itself in order to "close" or "balance" the water budget. This is necessary because aquifers situated and recharged beneath the ORM often discharge, mainly to various stream reaches, at locations remote from the Moraine. This is illustrated in Figure 6 for the Duffins Creek basin where regional deep aquifers that occur beneath the ORM do not discharge until stream valleys have eroded down into the aquifers remote from the ORM and closer to Lake Ontario (Gerber and Howard, 2002). Although the watersheds defined for streams originating on the ORM are obviously not entirely located within the ORMCP area, it is expected that water budget analyses will be prepared on a watershed basis, including those portions of watersheds located outside of the ORMCP area. Municipalities are only expected to adhere to the policy requirements of the ORMCP for those parts of the watershed within the Plan area, however, analysis and reporting on a watershed basis is necessary. Ideally, water budget models should be set up on a watershed basis but should also include the capability to quantify a water budget for the ORM portion of the watershed. The Watershed Planning technical paper defines subwatershed boundaries that represent the minimum spatial building blocks for preparing a watershed plan.

Figure 6 Conceptual groundwater flow model for the south slope of the Oak Ridges Moraine within the Duffins Creek watershed (from Gerber and Howard, 2002)

Surface Water Divide versus Groundwater Divide

Another consideration relating to spatial scale involves situations where the surface drainage watershed or sub-watershed boundaries do not correspond to the groundwater flow divides. This applies to groundwater flow within aquifer systems that cross surface water divides. Watershed or sub-watershed water budget studies need to expand the scale of the analysis to include a suitable area to understand the relative magnitude of this trans-boundary exchange.

For the purposes of the ORMCP, the areas to be investigated are either (in an ideal case) entire watersheds or (in a less than ideal case) subwatersheds. As such, they will tend to look at the entire (sub)watershed area right to the top of the ORM and the surface water inputs to the water budget equation will be zero. In Ontario, because the topography is generally subdued, groundwater flow divides tend to be synchronous with the surface water divides. The topography is one of the key drivers of the groundwater flow system and, given the subdued topography, there is very little driving force to develop deep groundwater flow systems. Therefore, the majority of the active component of the groundwater system tends to be shallow. Groundwater in the deeper bedrock units of the Michigan basin of south central Ontario tends to be brine-like, having elevated concentrations of dissolved constituents because the water is moving very slowly and has been in the groundwater system likely for thousands of years. This has provided ample time for the water to interact with the soil and rock materials thereby increasing the concentrations of dissolved constituents. There is likely very limited exchange between this deeper more stagnant water within the deeper bedrock and the water that is moving more dynamically

in the shallow groundwater system; therefore this deeper water is not part of the water cycle that is under consideration in this technical paper.

Although definitions are not fixed, in Ontario, there tends to be few "regional" groundwater flow systems, say on the order of 50 to 100s of kilometers. The only exception would be where more deeply incised bedrock channels can convey groundwater many kilometers, perhaps crossing several major watersheds. The Laurentian Channel which passes beneath the ORM in the vicinity of Nobleton is one such feature. Given this generalized setting, the groundwater inputs to the water budget equation may also (but not always) be zero since there are only a few areas where groundwater flows beneath the ORM topographic divide.

Water takings from large laterally extensive aquifer systems may induce changes that extend beyond the surface watershed or subwatershed boundaries. This deep aquifer system may be separated from the near surface flow system by extensive thicknesses of low permeability aquitard material, which means that recharge occurs over a large area and the shallow and deep flow systems may be partially or effectively separated. Again, analysis needs to be conducted at a suitable scale to fully understand this situation. The study area chosen for a water budget analysis will also depend on many factors including, but certainly not limited to, the position within the flow system and pumping schedules and quantities.

Transfers of Water Between Watersheds

Any water budget analysis also should consider inter-basin transfers of water either into or out of the study area. For example, a municipality may obtain much of its water supply from groundwater. The wastewater may be exported by sewer to areas outside of the surface watershed where it is treated and then discharged. This loss of water from the watersheds where the groundwater pumping is focused should be accounted for. Conversely, some quantity of imported water may be circulated to the natural system through septic systems, lawn watering, pipe leakage, etc. These transfers should also be considered.

7.1.3 Temporal Scale

The amount of water within various hydrologic cycle reservoirs also varies temporally over a range of different time scales. Using an example from the Duffins Creek watershed, Figure 7 shows the annual trend in the various water budget components expected for the ORM area for 1989. Figure 8 shows annual groundwater level trends for the water table within Halton Till at a site near Stouffville. The water level fluctuation trends are typical for the ORM area; however, the magnitude and timing of the fluctuations will vary depending on location within the flow system, and will be particularly controlled by geologic deposits and position within unconfined and confined deposits. The groundwater level changes for various hydrogeologic regimes are known from active monitoring data being collected at numerous locations across the moraine through the

Provincial Groundwater Monitoring Network (PGMN). The pattern of fluctuation is what is being stressed in this discussion.

The hydrologic patterns shown in Figure 7 and Figure 8 can be subdivided into four general periods, typical for the ORM area. Note that the actual length of each period will change with time depending on climate and location. Period 1 occurs from approximately mid-December to the end of February. Precipitation is generally in the form of snow with the thickness of the snowpack increasing. The temperature is generally below freezing. Evaporation from the snowpack is minimal and the recharge to the water table is almost zero, except for periodic melting events. Groundwater storage is depleting, as evidenced by declining water levels, and streamflow is primarily groundwater discharge.

Period 2 spans from February to April. The rise in temperature to above freezing means that most precipitation is in the form of rain, and with melting of the snowpack, leads to high streamflow and floods. In Ontario, April is the month when streamflow runoff is generally at a maximum (Sangal, 1984). Percolating water exceeds the field capacity or wet limit of the soil as indicated by a water table rise. The evapotranspiration is insignificant because the temperature is still low and plant growth is minimal. This is a major period of groundwater recharge.

Period 3 occurs from May to September. This period is characterized by high temperatures and high evapotranspiration rates resulting from significant plant growth. Precipitation is in the form of rain and the majority of it is retained by the soil to satisfy an increasing soil moisture deficiency. Percolation to groundwater storage occurs only during large storms when the field capacity (wet limit) of soil is exceeded. It should be noted that groundwater recharge can also occur during periods of soil moisture deficit through such features as fractures, and by runoff which collects in ditches (or dry kettles and swales in the case of the ORM) and infiltrates (Rushton and Ward, 1979). The water table is steadily declining as discharge to streams is greater than recharge.

Period 4 occurs from September to mid-December. Precipitation is still in the form of rain with some snow. The growing season is finished and evapotranspiration is low. Soil moisture has returned to field capacity (wet limit) as shown by the water table rise. This is the second major period of the year where groundwater recharge exceeds discharge. It should be noted that a water table rise can occur disproportionately in response to rainfall. Novakowski and Gillham (1988) found the magnitude of a water table response was much greater than expected based on the specific yield of the soil materials studied. Such a response was attributed to the presence of a capillary fringe and an increase in gas phase pressure caused by an infiltrating wetting front. In fine-grained soils, the capillary fringe can extend for several metres above the water table. The capillary fringe has a small percentage of non-saturated porosity, thus a small recharge event can produce a large water table rise (Trudell et al., 1986).

Figure 7 Annual variation in water budget components for the Duffins Creek watershed (figure from Gerber and Howard, 1997)
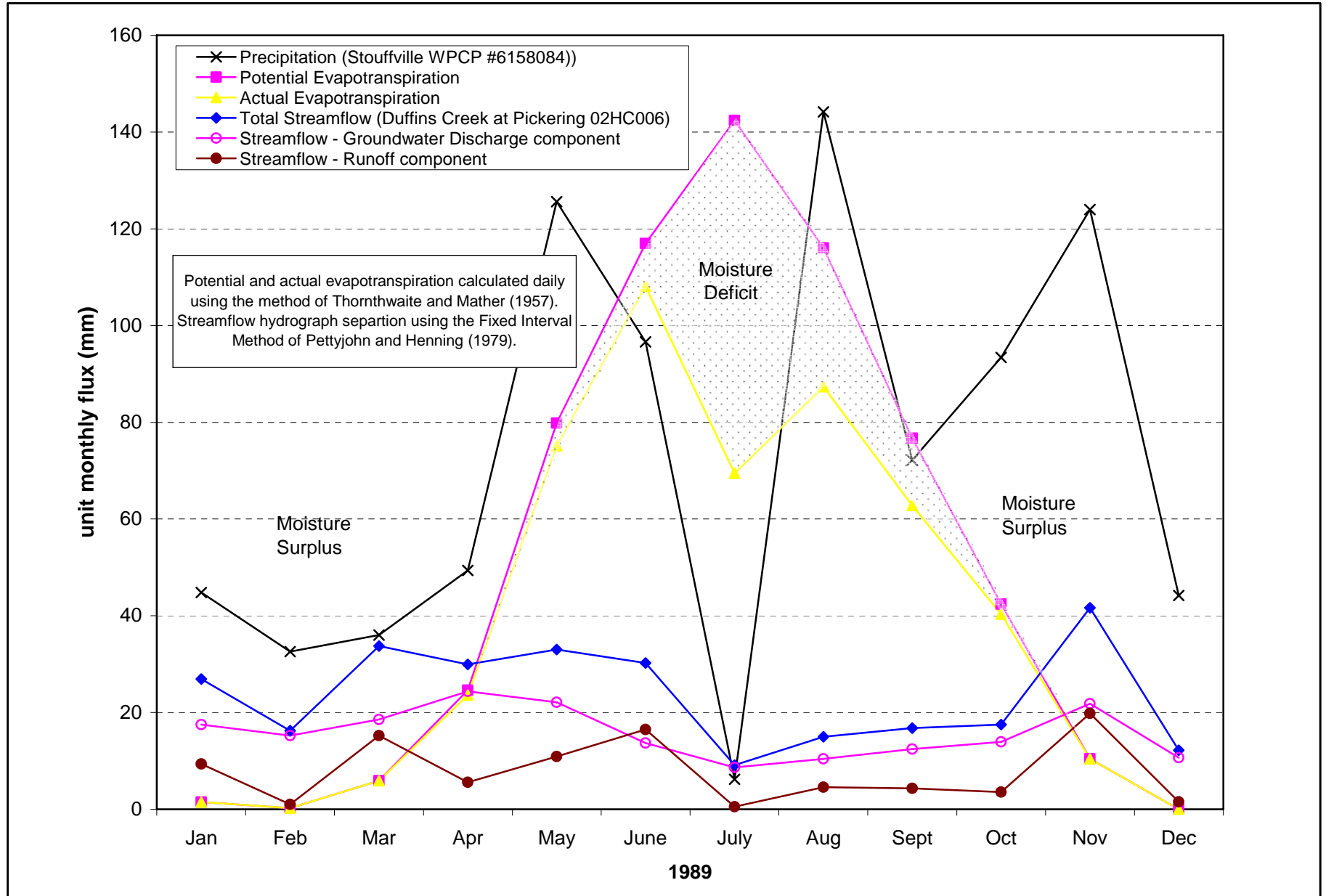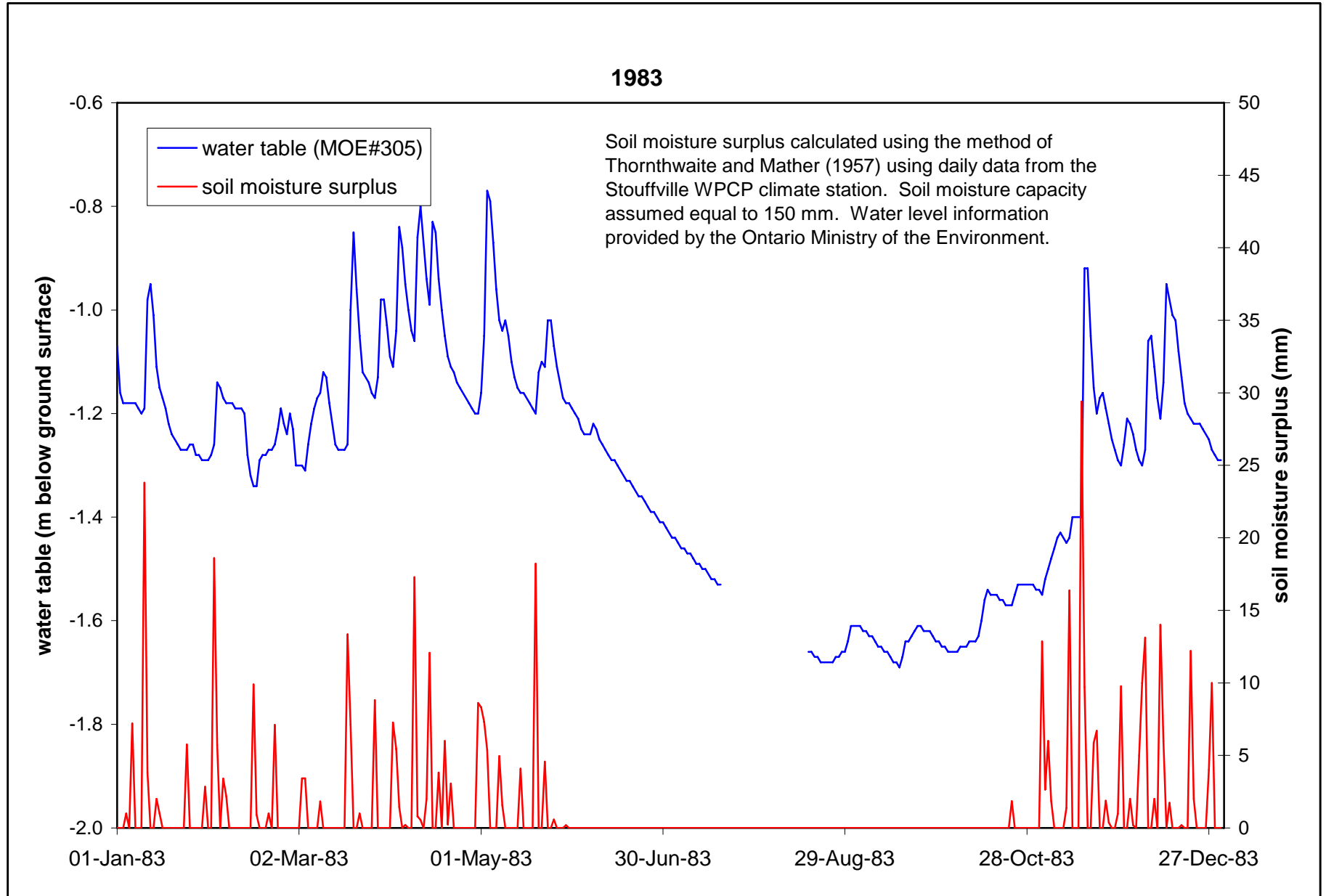
Figure 8 Annual water table fluctuation within Halton Till at a site near Stouffville (from Gerber and Howard, 1997)

1983

Soil moisture surplus calculated using the method of Thornthwaite and Mather (1957) using daily data from the Stouffville WPCP climate station. Soil moisture capacity assumed equal to 150 mm. Water level information provided by the Ontario Ministry of the Environment.

Legend:
- water table (MOE#305)
- soil moisture surplus

The water budget for the various components of the hydrologic cycle also varies on a time scale longer than seasonal. Figure 9 shows annual average and a five year moving average of water levels in Lake Ontario at Toronto since 1906. Also shown on this figure are annual total precipitation and a five year moving average of total precipitation since 1847. The five year moving averages for both Lake Ontario levels and annual precipitation shows that there have been three major drought periods over the last 100 years that include the early to mid-1920's, the 1930's, and the late 1950's to 1970. Studies that use data since 1970 are therefore considered to represent above average moisture conditions, or a saturation state higher than average. Water budget studies should consider whether the climate information used for any calculations are representative of a drought period (lower than average basin saturation state), average conditions or a moisture surplus (higher than average basin saturation state) period. By making appropriate adjustments to climate-related information, water budgets can also be used to investigate the potential implications of possible future climate change.

Figure 9 Long term annual total precipitation and annual average Lake Ontario water level at Toronto

Lake Ontario at Toronto
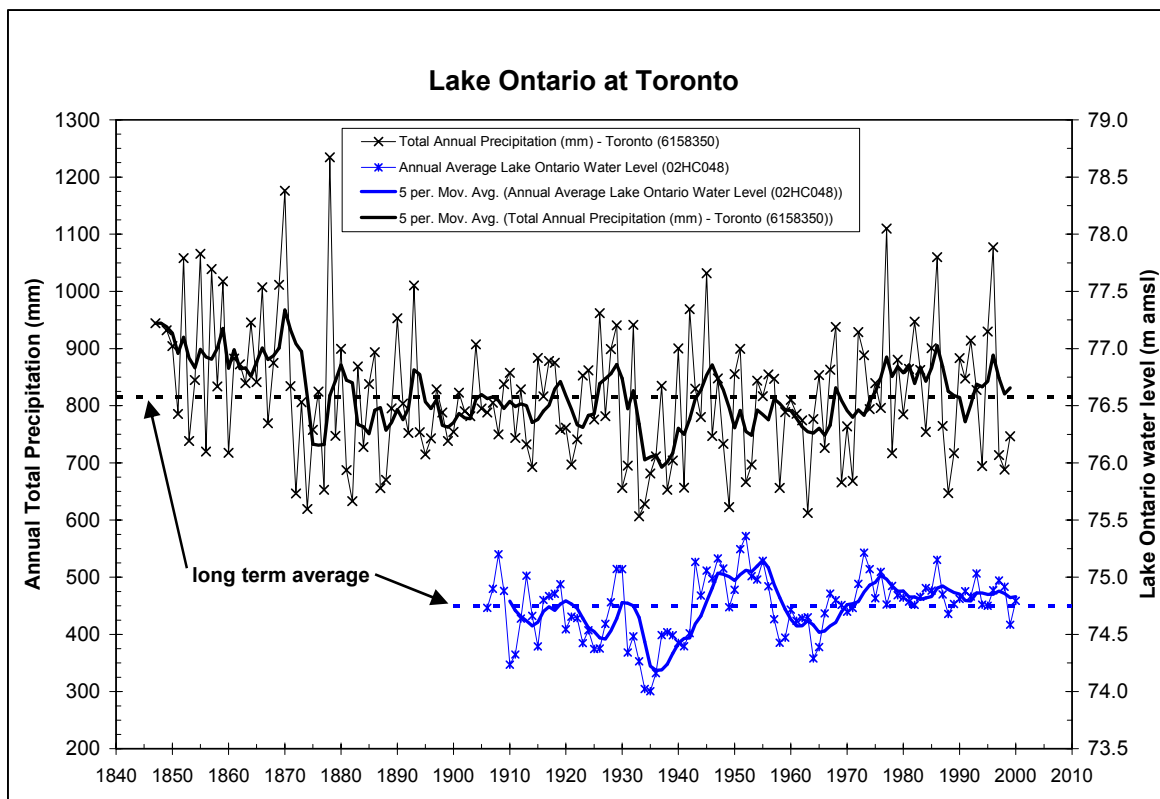
7.1.4 Summary

A water budget can be done on any scale provided that the necessary components of the water budget can be taken into account. However, because the volumes of water present in the various reservoirs of the hydrologic cycle vary both spatially and temporally, the question then

becomes what scale is best to consider when conducting water budget calculations. The answer is whatever scale is necessary depending on the application. For instance, a watershed scale water budget may not be large enough to close the water budget if groundwater is flowing in or out of the surface water basin. Fortunately regional studies (CAMC/YPDT study) are being conducted that provide inter-basin groundwater flow estimates. One must also consider the saturation state of the study area required for a particular application. For instance, streamflow and groundwater levels vary seasonally and the ORM area is considered to be in a higher saturation state during the spring snowmelt when groundwater levels and streamflow are highest. In late summer and fall the ORM area would be considered to be in its lowest saturation state.

Three important considerations should be taken into account in undertaking water budget investigations:

- climate data representative of the geographic area of concern (which may vary within a study area) should be used;

- an area large enough to close the water budget should be chosen (or estimates of groundwater transfers should be accounted for through a more regional understanding of the flow system); and

- data from a time period representing a certain saturation state both annually and long-term (drought versus non-drought conditions) should be considered (depending on the water budget objectives). For ecosystem sensitivity issues, input data (climate, streamflow, groundwater levels) from a period of time when the study area is in an average to low saturation state should be considered to allow for a degree of conservatism.

The level of detail incorporated into any water budget analysis depends on the study objectives and the data available. In Section 5.1 it was suggested that in a natural state, unstressed basin that long-term changes in land surface, soil moisture and groundwater storage are often negligible; however, this is not always the case. Also, inter-basin flows may be difficult to adequately quantify. It is suggested that as an initial approach that water budgets start in a more simplistic state where storage changes and natural inter-basin flows are ignored. It is also suggested that average saturation state conditions be analysed. This means that input data and calibration targets represent average climate conditions, average groundwater levels and average streamflow conditions. This provides an initial understanding of the system and allows managers to examine how water is balanced by using these simplifications. Future analyses could then build on this initial understanding to determine the nature of inter-basin transfers and storage changes and hydrologic response of the basin to low and high saturation states. If significant, these components would then be incorporated into a refined water budget. In this way the water budget, and indeed the overall understanding of water movement within the

watershed, is quantitatively improved over time and as more data become available.

7.2 Step 2: Collect and Synthesize Data

In this step, existing data sources should be examined to determine whether there are any climate stations, groundwater monitors, or surface water flow gauges within the area of investigation. Given the spacing of the existing monitoring networks, stations may have to be used that are outside of the study area. Should this be the case, then care must be taken to choose data that are representative of the study area. Note that the availability of data will also factor into the decision as to what models or calculation procedures will be used to estimate the water budget. It is at this step where it should be determined whether sufficient existing data are available. This decision process also hinges on the objectives for the analysis as determined in Step 1.

The CAMC/YPDT Groundwater Study has already put in place an extensive water related, ORM focused, database that can be used. The CAMC/YPDT study has compiled hydrological and geological data across the ORM including much of the information available from the Federal and Provincial governments as well as from partner agencies. This includes:

- Base mapping (watershed boundaries, Digital Elevation Model, streams, soils, roads, land cover, etc.);

- Climate data including daily precipitation, temperature and snowpack thickness measurements;

- Spatial distribution of hydraulic head data (groundwater levels) for various aquifers and aquitards in the geological framework (from well record data and other data sources);

- Pumping test data to characterize hydraulic conductivity (permeability) of geological units;

- Geological characterization of aquifers and aquitards (from well records);

- Surface water flows (long term as well as more spatially diverse low flow measurements);

- Water use information including actual pumping rates and Permit To Take Water (PTTW) information;

- Sewage treatment plant discharges; and

- Geomorphological characterization of stream channels.

To date, most of the emphasis has been placed on the western parts of the Moraine; however, with the incorporation of information from the Trent and Simcoe studies, the level of effort will become more equitable across the study area. The compiled information is currently available to all of the partner agencies wishing to undertake water budget analyses. Also note again that the CVC and the GRCA are preparing various modules for the MNR and the MOE that generally describe data requirements for water budget investigations.

Studies for all watersheds on the ORM should work towards the same level of understanding of the water budget. It will take longer to arrive at a high level of understanding in the watersheds that currently have little information available. The level of detail for those watersheds in the lesser developed parts of the moraine may vary due to: i) decreased development pressures; ii) lower pumping/water taking stresses; and iii) the sparse data available for undertaking technical studies. This is the case for the largely un-gauged tributaries draining off of the moraine in the east. The ORMCP (Section 14(3)b) requires the completion of a water budget prior to the approval of residential development in the City of Kawartha Lakes, the County of Northumberland and the County of Peterborough.

7.3   Step 3: Develop Conceptual Model

This step involves the development of an initial overview understanding (conceptual model) of the various fluxes in the study area (precipitation, recharge, runoff, evapotransporation, etc.). This involves a preliminary synthesis and assessment of the available data to gain an appreciation of how much water is available in the study area and its relative partitioning between the ground and surface water systems. This step also involves the development of an understanding of the geologic system and consideration of surficial features (e.g. wetlands, large paved areas, etc.) that would have to be built into the modelling framework for both subsurface and surface water models. The conceptual understanding developed at this stage will aid in the selection of the calculation procedure or numerical model chosen for further analysis. It is again highlighted that through the CAMC/YPDT Oak Ridges Moraine groundwater study, a significant amount of work has already been undertaken in this regard.

An initial synthesizing of the available data can be used to gain an appreciation of the various fluxes in the study watershed. For instance, using average annual precipitation, and calculated evapotranspiration from a local climate station, coupled with annual surface discharge rates at a long-term streamflow gauging station, one can quickly determine whether or not the discharge at the gauge station appears reasonable with respect to the climate data on an annual basis. If it appears too low or too high, then there are likely subsurface geological conditions that are acting to direct water into or out of the area of consideration. These geological considerations will have to be built into the modelling process of the water budget exercise.

7.4   Step 4: Develop Numerical Model and Water Budget

This step involves developing a greater understanding of the three-dimensional flow system including both the surface and subsurface characteristics. Surface characteristics include streams, lakes and wetlands and the nature of the storage and conveyance of water that these features provide. Subsurface characteristics include the architecture (thickness and extent) of aquifer and aquitard units and their hydraulic parameters which dictate how ground water will move through the geological framework. Numerical models are developed and used to account for, at a more refined level of detail, the fluxes through the various reservoirs that comprise the hydrologic cycle. Such processes include, but are not limited to:

- Precipitation in the form of both rain and snow, and snow melt processes and events;

- The evaporation of water from surface water bodies (and the subsurface) back to the atmosphere;

- The transpiration of water by vegetation back to the atmosphere;

- The use and diversion of water in support of various human endeavours;

- The movement of water across the ground surface as runoff and streamflow; and

- The movement of water through the subsurface within both the saturated and unsaturated zones.

In a given watershed or study area there are a multitude of components and processes that comprise the hydrologic system. It is impossible to measure and characterize every single component/process. As mentioned above, in a water budget analysis the volume of water entering the system will equal the volume of water leaving the system (assuming the change in storage is negligible); otherwise the analysis has neglected the contribution of at least one component/process. Numerical models are tools used to simplify the representation of these processes and enable quantification and evaluation of the hydrologic system at the watershed, sub-watershed or site scale. Although models provide hard quantitative values, it is important to recognize the uncertainty in numerical modelling and to use the models appropriately in making water management decisions. Numerical models are simply tools that can be used to better understand how watersheds function and therefore to guide and enable better water management decisions.

The CAMC/YPDT Oak Ridges Moraine Study provides an initial numerical groundwater modelling approach for all watersheds that originate on the Moraine. An initial regional model covers the entire ORM, while a subsequent more detailed, sub-regional Core Model covers much of the western portion of the ORM. This study provides a solid starting point for those conservation authorities and municipalities seeking to initiate water budget studies.

7.4.1 Numerical Models

A numerical model is a type of mathematical model used to approximate a field situation by solving governing equations that represent the physical processes of the hydrologic system. Analytical models provide a direct solution of the governing equations for homogeneous systems, whereas numerical models simulate more complex systems by solving the governing equations approximately (Anderson and Woessner, 1992).

A lumped parameter model is a type of numerical model that solves the equations describing a system at a large scale by assuming that average values for physical parameters can be used to describe or predict the behaviour of a system. In a lumped parameter model the spatial position is not considered important to answer a question such as the total runoff in a watershed. In this situation runoff may be estimated by a simple

equation. These types of models are applied to large-scale problems (Cumming Cockburn Limited, 2001; MAGS, 2003).

A physically based model is a type of numerical model that solves equations where spatial position is an important consideration. Physically based model equations are derived from fundamental physical principles and/or extensive observations to describe the causes and effects of the system processes and their combined effects on the system behaviour. In these models, the actual rather than average (lumped) physical parameter value is important. For example the runoff from a building site may depend on the infiltration capacity of the soil types on-site as well as the runoff contributed to the site from surrounding areas. In this example the infiltration capacities of the on-site and off-site soils are independent of each other but the total runoff from the site is dependent on inputs from the adjacent areas, among other factors. Physically based models simulate small-scale to large-scale problems by incorporating spatial variability and interdependence of processes (Cumming Cockburn Limited, 2001; MAGS, 2003).

Physically based numerical models take advantage of readily available datasets that exist within Geographical Information Systems (GIS) and describe the spatial variability of the physical properties or parameters (e.g. soil type). These models are considered universally applicable models in that they can be used to make predictions at the small scale and can be summed to make predictions at the large scale (upscaling). In reality, due to the complex, multi-scaled and heterogeneous nature of the coupled atmospheric-surface-hydrologic system, there are many factors that affect the physical basis, and hence the universal applicability of physically based numerical models (Cumming Cockburn Limited, 2001; MAGS, 2003). However, the upscaling of a physically based model is generally more applicable than downscaling of a lumped parameter model where averaged values are spatially distributed by area-weighting while neglecting physical processes and interactions. Therefore, it is necessary to be fully aware of inherent limitations of a particular model in order to confidently apply the model-derived understanding of the system and the predictions to water management decisions.

7.4.2 Types of Numerical Models for Water Budget Analysis

There are three main types of numerical models that can be used for water budget analysis:

1.   Surface water models;

2.   Groundwater models; and

3.   Conjunctive models.

Commonly an integrated approach is used where output from both a surface water model and a groundwater flow model is iteratively compared. Traditionally assumptions are made about all processes in a model. The processes of greatest interest are those that are explicitly represented in the model equations. The processes considered least

important are treated as lumped processes and are specified as inputs or outputs to the model and may be spatially variable but are not explicitly derived by equations in the particular model.

For example, the groundwater recharge input in a groundwater flow model is assigned directly to the model as an input value and must be estimated by other means, such as field observations or derived as model output from a surface water model. Similarly, groundwater recharge may not be explicitly simulated in a surface water model but treated as a fitting parameter specified as an output.

A particular model domain (area) is chosen where the processes outside of the model domain are well characterized such that they can be specified as input or output values. Similarly, where data on these external processes are not available and of secondary importance, they may be specified from estimates based on other studies or knowledge of physical processes. By constraining the model domain to simulation of the processes of interest, the mathematical solution is simplified.

Table 1 lists examples of each of the three main types of models, the processes simulated and the processes that aren't simulated but treated as inputs or output quantities to the model. A discussion of most appropriate application of each type of model follows.

7.4.2.1 Types of Numerical Models for Water Budget Analysis

Surface water models are most appropriately applied where the goal of the budget analysis is to answer questions relating to runoff and peak flows over short time periods (hours/days), as well as net infiltration over long time periods (years). Changes in water budgets due to changes in climate, land use, surface water takings, wetland modifications, storm water management and flow diversions are directly evaluated with surface water models. These models are often used to predict water quality based on predicted flows.

These models solve the equations describing the hydrologic processes at the surface and in the unsaturated zone and are usually calibrated and validated using storm event data. Generally these types of models involve the most rigorous simulation of climate processes. Surface water models, such as GAWSER (Schroeter and Associates, 1996; Schroeter et al., 2001), work in a continuous simulation mode allowing incorporation of multiple storm events and low flow conditions over periods ranging from hours to years.

Groundwater recharge and groundwater discharge to rivers are secondary fitting-parameters in these models. Surface water models are appropriate tools for water budget analysis where changes in surface and unsaturated zone processes are the focus of the budget analysis. These models do not include detailed

calculations of saturated groundwater flow processes but can be used to estimate net infiltration input data for groundwater models.

The treatment of groundwater recharge as a "black box" output limits the application of these types of models to areas of intermittent rivers or to the prediction of peak flows where the contribution from groundwater is a small percentage of the total flow during a storm event. In periods of low flow the groundwater discharge (assumed equal to recharge over time periods where change in storage is zero) component of the water budget is much more significant and the "black box" approach is likely to fail to accurately predict groundwater recharge between storm events. In addition, the surface water model domain (watershed) may not coincide with the groundwater flow domain whereby some recharge may, in reality, discharge outside the simulated watershed.

Table 1 Commonly applied numerical models for water budget analysis (table from Waterloo Hydrogeologic Inc., 2002. "Water Budget Analysis – Selecting an Appropriate Numerical Model, Draft Module")

Model	Type of Model	Lumped Parameter vs. Physically Distributed Based Model	Source	Processes Simulated	Scale
GAWSER	Surface Water	Lumped/ Physical/ Distributed	University of Guelph	Climate: Budget Approach Surface: Detailed Equations Unsaturated: Budget Approach Saturated: Budget Approach	Watershed / Subwatershed
HSP-F	Surface Water	Lumped	U.S. EPA	Climate: Budget Approach Surface: Detailed Equations Unsaturated: Budget Approach Saturated: Budget Approach	Watershed / Subwatershed / Site
SWMM	Surface Water	Lumped General Water Budget	U.S. EPA	Climate: Budget Approach Surface: Detailed Equations Unsaturated: Budget Approach Saturated: Budget Approach	Subwatershed / Site
SWAT	Surface Water	Lumped/ Physical	U.S. DA	Climate: Detailed Equations Surface: Detailed Equations Unsaturated: Budget Approach Saturated: Budget Approach	Watershed / Subwatershed / Site
QUALHYMO	Surface Water	Lumped	Ontario OMOE	Climate: Budget Approach Surface: Detailed Equations Unsaturated: Budget Approach Saturated: Budget Approach	Subwatershed / Site
AGNPS	Surface Water	Physical/ Distributed	U.S. DA Natural Resources Conservation Centre	Climate: Budget Approach Surface: Detailed Equations Unsaturated: None Saturated: None	Watershed / Subwatershed
SHE	Surface Water	Physical/ Distributed	Danish Hydrologic Institute	Climate: Budget Approach Surface: Detailed Equations Unsaturated: Budget Approach Saturated: Budget Approach	Watershed / Subwatershed
HELP	Surface Water	2-D Physical	U.S. Army Corp. Engineers	Climate: Simple Budget Approach Surface: Detailed Equations Unsaturated: Detailed Equations Saturated: None	Site

Ⓥ Ontario

Model	Type of Model	Lumped Parameter vs. Physically Distributed Based Model	Source	Processes Simulated	Scale
WATER BUDGET	Surface Water	Physical	Cumming Cockburn Ltd.	Climate: Detailed Equations Surface: Detailed Equations Unsaturated: Budget Approach Saturated: Budget Approach	Watershed / Subwatershed / Site
MODFLOW	Groundwater	3-D Physical Finite Difference	U.S. Geological Survey	Climate: None Surface: Surface Water Bodies Only Unsaturated: Net Recharge Only Saturated: Detailed Equations	Watershed / Subwatershed / Site
FEFLOW	Groundwater	3-D Physical Finite Element	WASY Inc.	Climate: None Surface: Surface Water Bodies Only Unsaturated: Detailed Equations Saturated: Detailed Equations	Watershed / Subwatershed / Site
Mike She	Conjunctive	3-D Physical Finite Element	DGI Inc.	Climate: Detailed Equations Surface: Detailed Equations Unsaturated: Detailed Equations Saturated: Detailed Equations	Watershed / Subwatershed / Site
MODFLOW-HMS	Conjunctive	3-D Physical Finite Difference	Hydro Geologic Inc.	Climate: Detailed Equations Surface: Detailed Equations Unsaturated: Detailed Equations Saturated: Detailed Equations	Watershed / Subwatershed / Site
InHM	Conjunctive	3-D Physical Finite Element	University of Waterloo	Climate: Detailed Equations Surface: Detailed Equations Unsaturated: Detailed Equations Saturated: Detailed Equations	Watershed / Subwatershed / Site

Ontario

7.4.2.2 Groundwater models

Groundwater models are most appropriately applied where the goal of the water budget analysis is to answer questions relating to river discharge, groundwater levels and groundwater-surface water interactions in areas of groundwater extraction. Changes in water budgets due to changes in climate, land use, groundwater takings, and groundwater and surface water body interactions are directly evaluated with groundwater models.

Groundwater models can be used to evaluate changes over hours or days to seasons or years. However, groundwater monitoring data are typically only available representing the average or long-term steady-state condition. More detailed monitoring data may be available for shorter time periods such as a storm event for small areas (subwatershed), which allows model calibration to a transient event. However, net recharge still must be defined by other means. Typically groundwater models are used to evaluate changes in the steady-state water budget.

These models solve the equations describing the hydrologic processes in the saturated zone and at the interface between surface water bodies and the saturated zone. Groundwater models are usually calibrated to observed static water levels in wells and the observed discharge in rivers. Spatial variability of geological features (hydraulic conductivity / porosity) and the hydraulic gradients determine how groundwater will flow and define areas of potential groundwater recharge and discharge. Groundwater models solve equations that simulate the three-dimensional complexity of the subsurface. Homogenous two-dimensional models for groundwater flow also exist but fail to simulate local and regional flow systems and are generally not appropriate for detailed water budget analysis.

Local flow systems are generally shallow systems where water recharged within a subwatershed discharges within the same subwatershed. More intermediate or regional flow systems are deeper systems where groundwater recharged within a subwatershed may discharge to an adjacent or a more distant subwatershed. Groundwater models can simulate the superposition of these systems, recognizing that groundwater flow does not always adhere to surface water boundaries. The surface water model approach to groundwater recharge/discharge has no physical mechanism for dealing with regional or inter-watershed flow systems.

Evaluation of groundwater-surface water interactions involves components of water budget analysis. Groundwater–surface water interactions are most appropriately simulated with a groundwater flow model as the physical connection between the surface water features and the groundwater system is represented by equations

that determine the flux across this interface (stage in river, head in aquifer, hydraulic conductivity of river bed etc.). This type of evaluation can define the reaches where a river is losing or gaining water and how these will change as various stresses are applied to the system (e.g. reduction in recharge).

Groundwater models do not incorporate detailed equations describing climate processes and the processes in the unsaturated zone that control the amount of groundwater recharge to the saturated subsurface (groundwater system). Groundwater recharge in a groundwater model, as in a surface water model is a fitting parameter. However, in a groundwater model, the rate of recharge is better defined than in a surface water model by the simulated physical processes and the available groundwater data. This is especially true when looking at annual time scales where recharge rates can be defined based on topography, soil type and annual precipitation. Factors such as soil-moisture conditions are less important; however, recharge remains a fitting parameter that needs to be well characterized at the time scale of interest. Field measurements and surface water models provide the best methods for estimating recharge to a groundwater model.

7.4.2.3 Conjunctive models

Conjunctive groundwater models solve the governing equations for both surface water and groundwater simultaneously but simplify the representation of climate processes (Figure 10). These models recognize that surface water and groundwater processes are components of one larger system. Using only a surface water or only a groundwater model can lead to over-simplification of processes and may limit the model to making predictions at a particular spatial or temporal scale.

Figure 10 Numerical model domains (figure from Waterloo Hydrogeologic Inc.)
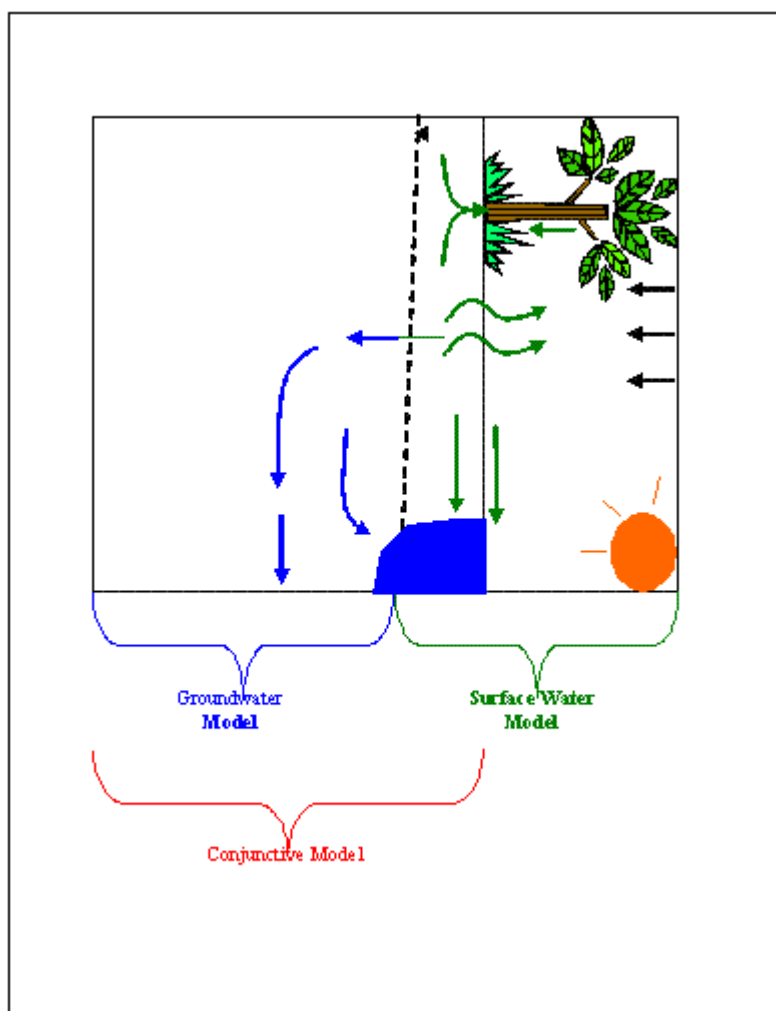
Typically conjunctive models are physically based models, incorporating small-scale spatial variability, and continuous simulation of climate (not explicitly). This approach to modelling provides detailed analyses of small-scale features, but also enables spatial and temporal upscaling. The model is also not limited to the boundaries of the surface water divides (catchments), but will be constrained by the boundaries of the regional groundwater flow. However, the complexity of the processes simulated with conjunctive models requires a large amount of data that is not typically available. In addition, users of these types of models require highly specialized knowledge of both surface water and groundwater systems and the numerical methods used to simulate the systems to ensure that model assumptions are valid for a particular analysis.

Conjunctive models are most appropriately applied in areas where the interaction between the surface, unsaturated zone and saturated zone are considered equally important. In Ontario, conjunctive models are the most appropriate models for water

budget analysis as hydrologic processes that control peak flows and maintain groundwater discharge are linked to both surface water and groundwater processes. Therefore a simultaneous solution of equations describing surface water and groundwater processes involves the least amount of simplification for the processes, spatial scale, and time scales of interest. However, due to a lack of appropriate data, the high cost of conjunctive modelling software, and associated complexity of the equations and model solution, currently a more reasonable approach is the use of integrated surface water-groundwater modelling.

7.4.2.4 Integrated model approaches

In Ontario, surface water and groundwater systems are dynamically linked due to climatic and geologic conditions. An integrated surface water-groundwater modelling approach attempts to use the strengths of two or more models to reduce the uncertainty in parameters that are simplified in a particular model. A number of examples of integration of surface water and groundwater models exist for Ontario and other jurisdictions including FEFLOW / GAWSER (Waterloo Hydrogeologic Inc., 2002), MODFLOW / GAWSER (GRCA, 2002), and MODFLOW/HSP-F (Ross et al., 1997 and SDI Inc. 1997 as described in Camp et al., 2001).

The integrated approach simply involves iterative comparisons of the results from each model. For example, an initial surface water model simulation may predict 300 mm/year of recharge. This value is used as an input to the groundwater model to determine whether this value is valid given the properties of the saturated zone. Integral to this comparison is the use of calibration data that is common and different between the two models (e.g. fluxes in a river and groundwater heads in wells). If the recharge value predicted by the surface water model is not supported by the groundwater model changes can be made to the surface water model. These changes may include diverting water to another subwatershed or increasing or decreasing another component such as evapotranspiration. Following these modifications, the surface water model will predict a new groundwater recharge value that should be tested in the groundwater model.

Essentially in an integrated model one model provides output to the second model without being directly affected by feedback. The quantity of data required for these simulations is less than is required for a conjunctive model, since a single time scale or spatial scale can be simulated that is common between the two models. In a conjunctive model, the entire dataset needs to exist at the same time and spatial scales. However, the integrated approach still has to address differences in spatial scale/model domain, and time scale since the models are not created for the

same purpose. Ideally these models will be developed in parallel to ensure efficient integration.

7.4.3 Strategy for Model Selection

The most appropriate numerical model for water budget analysis will depend primarily on the dominant flow processes (surface water or groundwater). If changes in groundwater discharge will significantly affect the flow in a river, then the model used should simulate the complexities of the groundwater system. If flow in the river is most affected by surface runoff and through flow during and following storm events (intermittent streams), then the model must be able to simulate the complexities of the surface water processes. In most watersheds in Ontario changes in groundwater discharge and storm event processes will affect the flow in the river such that linking of surface water – groundwater models, or the use of conjunctive models is most appropriate for water budget analysis.

Effective application of a numerical model for water budget analysis requires:

1.   Definition of specific objectives of the analysis at the start;

2.   Identifying the characteristics of the hydrologic system through development of a conceptual model (review existing reports: size, spatial variations, land use variability, topography, geologic structure, etc.);

3.   Determination of the "Scale of the Problem" or the level of detail that needs to be included (e.g. subwatershed versus site scale or forested versus open areas) depends on processes;

4.   Determination of the appropriate time scale;

5.   Collection or compilation of sufficient data to evaluate each process;

6.   Suitability for linkage to GIS;

7.   Ease of calibration and validation;

8.   Recognition and minimization of the uncertainty in the analysis; and

9.   Re-evaluation of the applicability of the analysis prior to addressing new objectives.

Secondary considerations include:

10.   Available resources (e.g. for model application, training and maintenance, etc.); and

11.   Model availability, preferably from an organization that provides regular updates and technical assistance.

Figure 11 presents a flow chart of the decision process and provides general guidance for selecting the most appropriate type of numerical model. It is important to keep in mind that as one moves through the

decision tree, assumptions are made about the physical system at each decision box. In the end one must be able to support these assumptions with field evidence and model validation, and/or assess and present the uncertainty in any predictions made with the use of the model.

Figure 11 Numerical model selection process (figure from Waterloo Hydrogeologic Inc.)
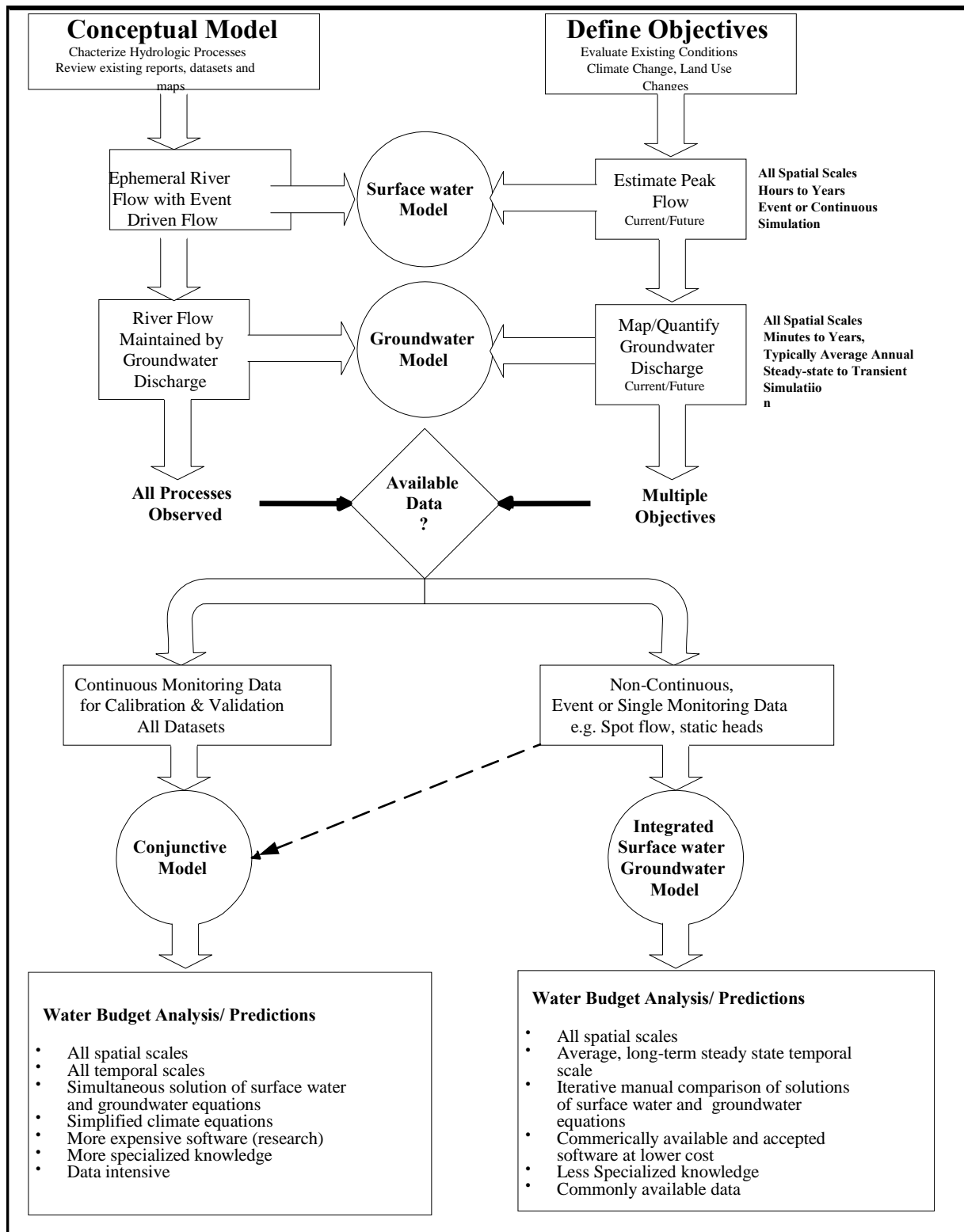
7.4.4 Summary

In summary, this section has dealt with the approach for selecting the most appropriate numerical model for the water budget analysis. As mentioned previously and often throughout this technical paper, the most appropriate model is dictated by the objectives of the analysis and the data available. Different models can provide similar output given the error inherent in water budget calculations. This error can be largely attributed to the complexity of the natural physical processes that are often difficult to explicitly incorporate in models. The key component of any successful modelling endeavor then depends on the skill and experience of the modeller, and on successful calibration to various types of observations. For example, a groundwater flow model containing various layers of differing hydraulic conductivity (K) should not be calibrated to hydraulic head measurements only, as numerous K ratios can provide a "calibrated" solution. This type of model should also be calibrated to various fluxes and their spatial distribution, such as the groundwater discharge component of streamflow, and the observed hydraulic response to groundwater takings such as a municipal pumping well. Only by calibrating to hydraulic head and fluxes will a unique solution be approached. Further details on the model calibration/verification process are provided in Anderson and Woessner (1992) and Hill (1998) for groundwater models. Before using any model for interpretive or predictive scenarios, it should be determined that it adequately explains the observed hydraulic observations and responses to stresses such as pumping.

The following summarizes the important points of the model selection process:

- The first step is to characterize the hydrologic system through the development of the conceptual model using available data and reports (Step 3 of Figure 5);

- Well-defined objectives will ensure that the most appropriate model is chosen that explicitly simulates the dominant hydrologic processes;

- In Ontario, most hydrologic systems need both groundwater and surface water models;

- A conjunctive model provides the best solution to simulating the system but may simplify climate processes, however available data and time scales of interest may mean the integrated model provides the best solution; and

- Model calibration and validation using consistent spatial and time scales suitable to meet the objectives of the study will minimize uncertainty.

It is important to remember that the modelling tools developed in this step need to calculate and understand the dynamic nature of the flow system.

The model must be able to adequately simulate the historic and current conditions found within the watershed. This is particularly critical to the confidence of estimates to be provided in Step 5 where future scenarios are simulated.

7.5   Step 5a: Establish Watershed Targets

Section 25(2) of the ORMCP states that "A water budget and conservation plan shall, as a minimum, …(c) identify, (i) targets to meet the water needs of the affected ecosystems…"

Targets should be developed within the overall context of the watershed plan (see Watershed Plans Technical Paper). The first estimates of ecosystem water needs are developed as part of the watershed characterization phase. Watershed goals and objectives developed through the watershed planning process set the stage for the development of specific indicators, measures and targets (Table 2). Note that the watershed plan may include targets for a broader suite of variables than those that are directly relevant to the water budget.

Targets are intended to:

- provide points of reference for predictive modelling and the development of land and water management strategies;

- direct management (maintenance, improvement, or restoration); and

- form the basis of the monitoring program that will be used to evaluate whether goals and objectives are being met.

Long-term monitoring is required to confirm and, if necessary, refine the ecosystem targets and so it is appropriate to view the target setting process within the adaptive management framework recommended for watershed plans. Adaptive management is a process that explicitly recognizes changes in natural systems, stresses learning from experience and monitoring, and revisiting management strategies, as well as goals, objectives, and targets, to adapt them as required in light of new information gained.

In the context of the ORM, relevant targets may need to be developed for stream ecosystems, kettle lake ecosystems, and wetland ecosystems.

Table 2 Definitions of Indicators, Measures and Targets

Indicator	a measurable attribute or combination of attributes that provide reliable, outcome-oriented, managerially and scientifically useful evidence of ecological integrity or trends in ecological integrity. For example, water quantity indicators, such as water levels or flows, that are ecologically relevant (e.g. stream flow stability may be an indicator of the suitability of stream habitat for certain biological communities).
Measure	a single measurable parameter or statistic which provides information regarding the status and trends associated with an attribute. For example, specific measures of each indicator (e.g. a relevant measure of stream flow stability may be the ratio of the 30-day minimum stream flow to the mean annual stream flow for a site).
Target	specific, quantitative, spatially and temporally bounded benchmarks for measures that determine achievement of objectives. For example, monitoring results or model predictions will be compared against specific targets set for the purpose of maintaining, improving, or restoring ecological integrity (e.g. a target value of X for the 30-day minimum stream flow to mean annual stream flow ratio).

7.5.1 Choosing Measures of the Water Needs of Ecosystems

With respect to the integrity of aquatic ecosystems, targets are needed for measures in four categories:

- water quantity (quantity, pattern, timing, water level);

- water quality (including physical, chemical, and biological characteristics of water);

- habitat (characteristics and condition of the instream and riparian habitat); and

- Biological (composition, distribution, abundance, and condition of aquatic biota) (MacKay, 2001).

Water quantity measures are strongly correlated with numerous water quality, habitat, and biological measures. For example, streamflow has been described as a "master variable" regulating the ecological integrity of flowing water systems (Poff et al., 1997). The Instream Flow Council (IFC, 2002) suggests considering flow characteristics needed to maintain or restore ecological processes in the following areas: hydrology, water quality, geomorphology, connectivity and biology, which encompass the above categories suggested by MacKay (2001).

Flow characteristics may be used as indicators for a variety of ecological requirements. Characteristics of the flow regime with ecological relevance include the magnitude, frequency, timing, duration, and rate of change of flow (IFC, 2002; Poff et al., 1997; Richter et al., 1996). In some cases, sequences of flow characteristics may also be important. For

example, it may be important for the timing of a high flow event to coincide with the reproductive behaviour of local species. A measure of the timing characteristic could be the day of the year that the maximum flow occurs and the target might be Day X plus or minus Y days. The duration of the high flow event (or flooding associated with it) may determine whether the life-cycle requirements of species can be met, or whether species will experience excessive stress, and so a target may be needed for this measure of the duration characteristic as well.

For streams, targets may be established for specific measures of the characteristics of the flow regime. This approach may almost certainly be extended to non-riparian wetlands and kettle lakes where the characteristics of the hydrologic regime (i.e. the magnitude, frequency, timing, duration, and rate of change of water levels) are important to the maintenance or restoration of ecological integrity.

Studies have been undertaken in Ontario to test methods for determining instream flow requirements for water management. Results from these studies are presented in reports by Cataraqui Region Conservation Authority, Grand River Conservation Authority, and Long Point Region Conservation Authority, and summarized in a Synthesis Report entitled "Establishing Environmental Flow Requirements". These reports provide useful information, including examples of techniques that could be used for selecting hydrologic measures and for setting environmental flow targets for rivers and streams. The reports are available on Conservation Ontario's website at: www.conservation-ontario.com.

7.5.2 Setting Quantitative Targets

There is growing support for setting targets based on the natural flow regime (Richter et al., 2003; IFC, 2002; Poff et al., 1997). Maintaining hydrologic regimes with intra- and inter-annual variability is necessary to maintain and restore the natural form and function of aquatic ecosystems. Surface water and groundwater models can be set up to "hind-cast", or simulate historical conditions. In this mode they can be used, along with analysis of any historical flow records available, to determine the "natural" flow regime for target-setting purposes.

Table 3 Guidelines for Quantitative Targets

- Targets should be based on sound ecological principles.
- Targets should be developed using an integrated ecosystem approach and interdisciplinary cooperation.
- Targets should address ecological requirements at multiple levels of organization rather than the requirements for a single species or a few indicator species.
- Some targets may be based on human requirements.
- Targets should be based on conservative estimates of water quantity and quality required to meet human needs and aquatic ecosystem needs.
- Targets indicative of good health are required rather than thresholds to ill health.
- Targets may vary in space and time.
- Short-term targets may be set in the interim as progress is made toward meeting long-term targets.
- Targets should be refined, as necessary, based on monitoring over time and as knowledge of the flow system and its interactions with the biological community increases.

Wherever possible, more than one approach to target setting should be explored to ensure that the most appropriate targets are selected (i.e. look for converging lines of evidence). Target setting should address ecological integrity at multiple levels of organization (i.e. population, community and ecosystem) over a range of spatial and temporal scales, using a variety of measures (Table 3). There are many challenging scale issues; a few points are presented for consideration in Table 4.

Table 4 Considerations With Respect to Spatial and Temporal Scales

- Both space and time should be considered explicitly (e.g. seasonal and annual variability, including long duration cycles such as drought, and location within a watershed are critical elements).
- Upstream-downstream responses and linkages between physical, chemical, hydrological, and ecological processes need to be taken into account.
- Where restoration is required, both short-term and long-term targets may need to be established: long-term targets represent conditions of a restored ecosystem; interim targets may be used to guide shorter-term management.
- Targets should match management requirements (e.g. land use changes, water takings) in terms of scale and resolution.
- Targets and management action should seek to address interactions that translate across various scales within a hierarchy (e.g. acting at one scale should not compromise ecological integrity at another scale).

Interdisciplinary Approach to Setting Targets

Estimating the water needs of the ecosystem requires input from an interdisciplinary group of scientists with expertise in, for example, the habitat requirements of native species and communities, as well as the hydrological, geomorphic, and biogeochemical processes that affect various habitats and that support primary productivity and nutrient cycling (Richter et al., 2003).

The participation of water managers in the process of identifying targets for ecosystem water needs is also beneficial. Water managers can help scientists choose measures and express targets in a way that facilitates practical implementation. By participating, water managers (and others) may gain an appreciation of the challenges associated with target setting, given scientific uncertainties, and the need for long-term monitoring and refinement of the ecosystem targets over time.

Expert workshops to develop targets may be particularly useful (e.g. see Rogers and Bestbier, 1997). The participants should be briefed on the rationale and purpose of setting targets. Background information should be supplied in advance of workshops to inform the participants of the process for target setting, knowledge gained from watershed characterizations, and knowledge which may be transferred from other areas. Much work needs to be done by organizers and participants in advance to make the workshops successful. During the workshops, experts draw upon existing data, research results, ecological and hydrological models, and professional judgment to identify ecosystem targets. Participants need to be assured that targets that are set to guide management are not immutable. One of the purposes of monitoring will be to test the validity of the measures and targets.

The products of the workshops would include:

- Selected measures (i.e. move from a full list to a short list with reduced overlap and redundancy) including spatial and temporal scales of measurement;

- Descriptions of the measurement techniques (or reference existing protocols); and

- Established targets.

Criteria such as those in Table 5 have been proposed for the collective, integrated suite of measures finally selected (adapted from Environment Canada, 2001; Noss, 1990).

Table 5 Criteria for Measures

- Relevant to ecologically significant phenomena;
- Sufficiently sensitive to provide an early warning of change;
- Capable of providing continual assessment of a wide range of stress;
- Able to discriminate between natural fluxes and anthropogenic stress;
- Applicable throughout a watershed (of measures not targets);
- Simple, easily measured, understood and applied;
- Informative, comparable, repeatable and defensible between sites and times;
- Cost effective to measure; and
- Able to make use of existing information.

7.6 Steps 5b & 5c: Conduct Scenario Testing

In this step the tools developed in Step 4 are used to conduct testing of future scenarios and predict changes to the flow system that would occur based on projected future land and/or water use. The implications of these future scenarios can then be evaluated by comparing the predicted changes to the flow system to the targets that have been established to meet the water needs of the ecosystem. It is important that the spatial distribution of change is determined, not just an estimate of change within each reservoir of the hydrologic cycle.

It is anticipated that scenario testing will proceed along two avenues, namely proactive and reactive. Proactive scenario testing will include large-scale (watershed scale) "what if?" situations, such as exploring the implications of increases in natural cover, the cumulative impacts from an increase in urban areas, the potential implications of possible future climate change, etc. The Watershed Plans Technical Paper (see section on "Develop Management Alternatives") and the Sewage and Water System Plans Technical Paper refer to using models in predictive mode to assess the response of the watershed to alternative scenarios. This is part of the proactive scenario testing process.

Reactive scenario testing will involve an assessment of specific land use or water use proposals such as a major development application or a water-taking proposal. This type of scenario testing is referenced in the Subwatersheds (Impervious Surfaces), Water Conservation Plans, and Sewage and Water System Plans Technical Papers.

Though the watershed water budget may be a helpful tool to assist in evaluating site-specific proposals, the use of other tools, such as pumping tests and field monitoring, may also be necessary.

7.7 Step 6: Refine Predictive Tools and Monitor

Figure 12 shows a suggested hierarchy of monitoring related to the water provisions of the ORMCP. The scope of monitoring will vary for each program or project based on the requirements of the ORMCP, environmental targets identified in a plan, and specific conditions of an approval.

It is suggested that details of the monitoring to be undertaken, such as the frequency at which samples will be collected or observations made, the locations to be monitored, the methods to be used, and the duration of monitoring be designed to suit the specific needs of the particular program or project.

The Ontario government, in consultation with municipalities, shall over time identify performance indicators for monitoring the effectiveness of the ORMCP (see the Implementation section of the ORMCP). The Province, in partnership with appropriate stakeholders, shall establish a monitoring network to collect, summarize, and evaluate performance indicator data to:

- assess changes in the ecological integrity of the ORM;

- assess the effectiveness of the policies of the Plan in achieving the Plan's vision and objectives;

- help identify improvements that would address problems encountered in implementing the Plan.

In addition to satisfying the needs of local watershed plans or specific projects, monitoring at the other scales (i.e. at the site, site vicinity, and watershed scales) may provide valuable information that will contribute to the overall monitoring of the ORMCP.

Figure 12 Hierarchy of monitoring related to the water provisions of the ORMCP
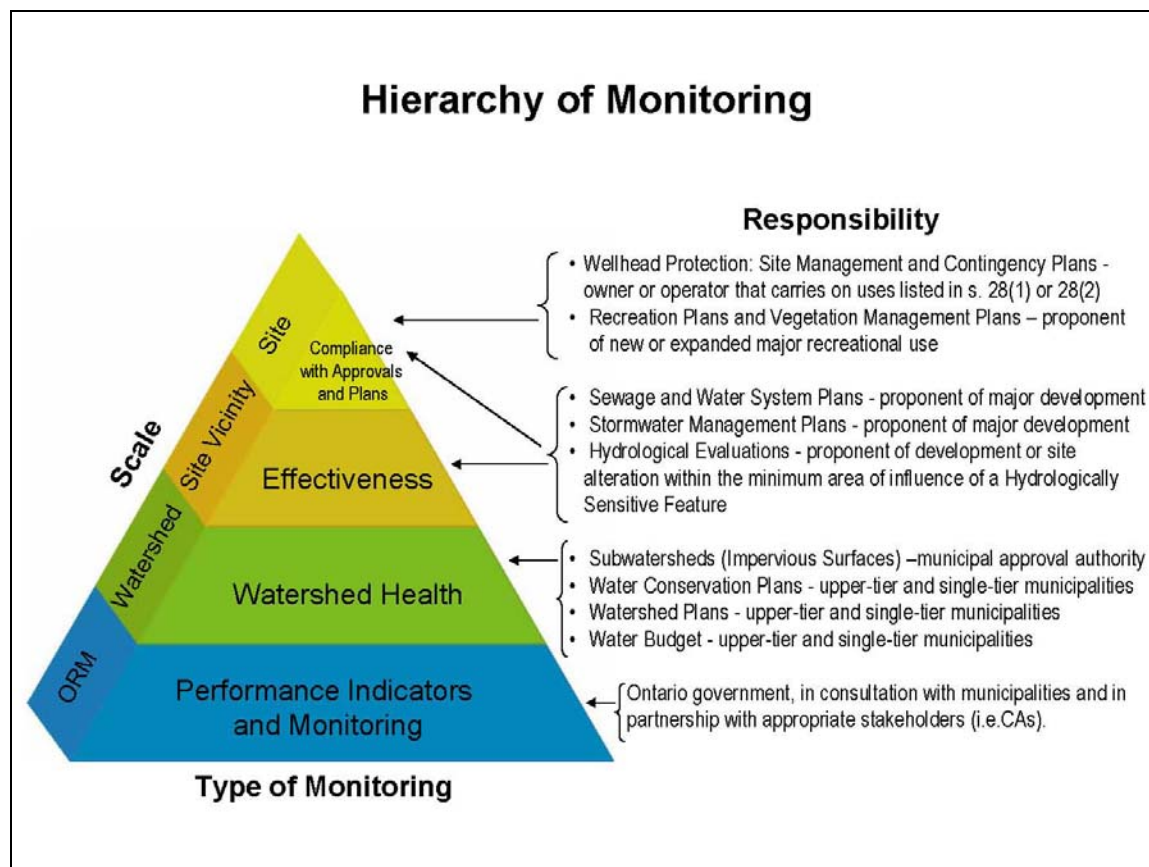
The water budget report should include an outline of proposed monitoring to be undertaken. The requirement to monitor is specified in the ORMCP as part of the responsibilities of upper-tier and single-tier municipalities in preparing water budgets and water conservation plans. The ORMCP, Section 25 (2), states that "a water budget and conservation plan shall, as a minimum,…(j) provide for monitoring of the water budget and water conservation plan for effectiveness".

The monitoring to be carried out is at the watershed scale. With respect to a water budget, the purpose of the monitoring is:

• to validate and refine the water budget;

• to validate and refine ecosystem targets;

• in cases of land or water use change, to determine that the flow system is responding as predicted; and

• to keep the water budget up-to-date, reflecting the latest watershed conditions.

Ongoing monitoring of the various components of the water budget, such as climatic variables (e.g. temperature, precipitation), streamflow (both continuous and low-flow characteristics), groundwater levels, plus water levels of wetlands and kettle lakes, at suitable densities both spatially and temporally, is suggested.

The water budget report should also specify who will take responsibility for ongoing monitoring. The ORMCP water budget monitoring could be integrated with existing watershed monitoring programs, for example, those maintained by conservation authorities.

Ontario

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