Integrated Surface and Groundwater Model Review and Technical Guide

Prepared by

AquaResource Inc.

For

The Ontario Ministry of Natural Resources

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Team Member	Affiliation
Mike Garraway	Ministry of Natural Resources
Lynne Milford	Ministry of Natural Resources
David Van Vliet	AquaResource Inc.
Sam Bellamy	AquaResource Inc.
Steven Murray	AquaResource Inc.
Christian Gabriel	AquaResource Inc.
Jon Paul Jones	University of Waterloo
Patrick Delaney	DHI Water and Environment
Ying Qiao	DHI Water and Environment
Chris Neville	S.S. Papadopulos & Associates, Inc.

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Preface

The role of water resources managers continues to expand, and often requires one to understand and predict hydrologic changes that may depend on the complex inter-relationships between groundwater and surface water. An understanding of the hydrologic cycle, including individual groundwater and surface water processes, can be accomplished by a combination of field observations and numerical models. While field observations offer the benefit of being a tangible measurement of a single aspect of a hydrologic system at a particular location, they do not capture the complex relationships associated with groundwater and surface water interactions. Combined with the use of good quality field measurements, numerical models offer the benefit of being able to simulate and represent hydrologic processes in areas not covered by field measurements.

Water resources studies have historically relied on either a surface water model or a groundwater model to quantify water budgets and evaluate the effects that human activities or climate changes might have on water resources within a study area. However, each of these types of models over-simplifies groundwater and surface water interactions. An accurate and complete understanding of the hydrologic cycle requires a physical representation of both surface water and groundwater processes, as well as the link between the two. Over the past several years, there has been an emergence of integrated hydrologic models, which are numerical models capable of simulating both surface-water and groundwater flow processes, in addition to the exchange of water between them.

This report has been prepared to provide water resources practitioners in Ontario and elsewhere with technical guidance on the application of integrated hydrologic models to understand hydrologic systems and to predict hydrologic impacts. The first goal of this report is to provide a detailed review of five of the most popular integrated models (GSFLOW, MIKE SHE, HydroGeoSphere, MODHMS and ParFlow). Each of these models differs in their representation and implementation of hydrologic processes and numerical solution techniques. This report provides a summary of each of the model's capabilities and compares them with an evaluation matrix.

The authors of this report selected three models (HydroGeoSphere, MIKE SHE and GSFLOW) for further evaluation. A case study is presented in which these three numerical models are used to simulate groundwater/surface water interaction within a subwatershed in the Credit River basin in southern Ontario. Different scenarios (e.g., increased groundwater pumping and urbanization) were simulated with each model. The case study demonstrates some of the unique simulation capabilities of integrated models and provided the authors with the ability to evaluate specific modeling criteria.

The final chapter of this report provides a series of conclusions and recommendations designed to support a water resources practitioner when implementing an integrated hydrologic model on a particular project. It summarizes the specific benefits of the integrated modeling approach over traditional models and recommends specific types of projects where this it is most valuable. Finally, the report describes a series of modeling steps that practitioners should consider in the development and application of an integrated hydrologic model.

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1. Introduction

A water budget is an accounting of the amounts of water that move over, through and below the ground surface including water used by humans. The Province of Ontario has recently initiated various programs requiring the development of water budgets on a watershed, subwatershed, or local scale. Much of this development is in support of the Ontario Ministry of Environment (MOE)-led Clean Water Act, 2007 which requires the development of water budgets to identify subwatersheds under hydrologic stress as well as specific threats to drinking water quantity. The Province has identified that water budgets can be used to:

- estimate the amount of water flowing through a watershed,
- help understand the processes and pathways of the water,
- identify communities where the reliability of the water supply is questionable,
- highlight key factors that may limit the reliability of these water supplies, and
- identify significant groundwater recharge areas.

The water budget process requires a thorough understanding of all aspects of water resources including surface water, groundwater, groundwater/surface water interactions, and water use. In addition, a water budget must consider these aspects under average, transient, and future conditions. Computer models are typically used to simulate the hydrologic and hydrogeologic processes contributing to a water budget. Most often, separate surface water and groundwater models are developed for a particular application and various methods are employed to account for, and simplify, the hydrologic processes governing the transfer of water between groundwater and surface water.

Integrated hydrologic models consider both the surface water and groundwater systems simultaneously, and allow feedback from one system to be considered by the other. This type of modelling approach allows a more complete water budget analysis to be undertaken and enhances the understanding of interactions within a hydrologic regime.

While integrated models are able to provide a more complete representation of the hydrologic processes, they have not yet seen widespread application within Ontario. To address this knowledge gap, the Ontario Ministry of Natural Resources (MNR) initiated this study to investigate the applicability of applying integrated hydrologic models to Ontario watersheds. This study provides a review of several integrated model codes and applies; a selection of these codes to Ontario case studies. This document provides guidance on the development and calibration of integrated models. It highlights their advantages and also presents some of the challenges that must be considered before starting a project.

1.1 What is an Integrated Hydrologic Model?

Integrated hydrologic models simulate overland, channel, near-surface, and subsurface hydrologic processes, as well as the interactions between each process. Traditional surface water models represent overland, channel and near-surface processes, and typically simplify subsurface processes. Similarly, groundwater flow models simplify or neglect surface water processes and solve only for the flow gradients within the subsurface. Groundwater models mostly rely on specified groundwater recharge rates as the primary input of water into the model.

Integrated models consider surface water processes, and include a three dimensional (3D) representation of the groundwater system (see **Figure 1.1**). Liquid water, in the form of either rainfall or snowmelt, is applied to the ground surface, where surficial processes such as interception storage, depression storage and infiltration to the unsaturated zone are considered. Soil-water content is removed from the unsaturated zone via evapotranspiration, which is heavily influenced by vegetation cover. When the soil-water content is greater than field capacity, water will percolate downwards toward the saturated zone. Water percolating beneath the unsaturated zone is considered groundwater recharge, and typically is the primary inflow to the saturated system. Water can also be supplied to the saturated zone by watercourses that lose water. Based on the hydraulic properties of the subsurface (e.g., aquifers/aquitards), and connections between aquifers and watercourses, groundwater flows downgradient, ultimately discharging to a surface water feature (e.g., watercourse or lake) as baseflow. Differences in hydraulic head between the groundwater table and watercourse, along with hydraulic conductivity, will determine the direction and magnitude of flow between the groundwater system and watercourses. In areas where depth to groundwater is shallow, (i.e., the

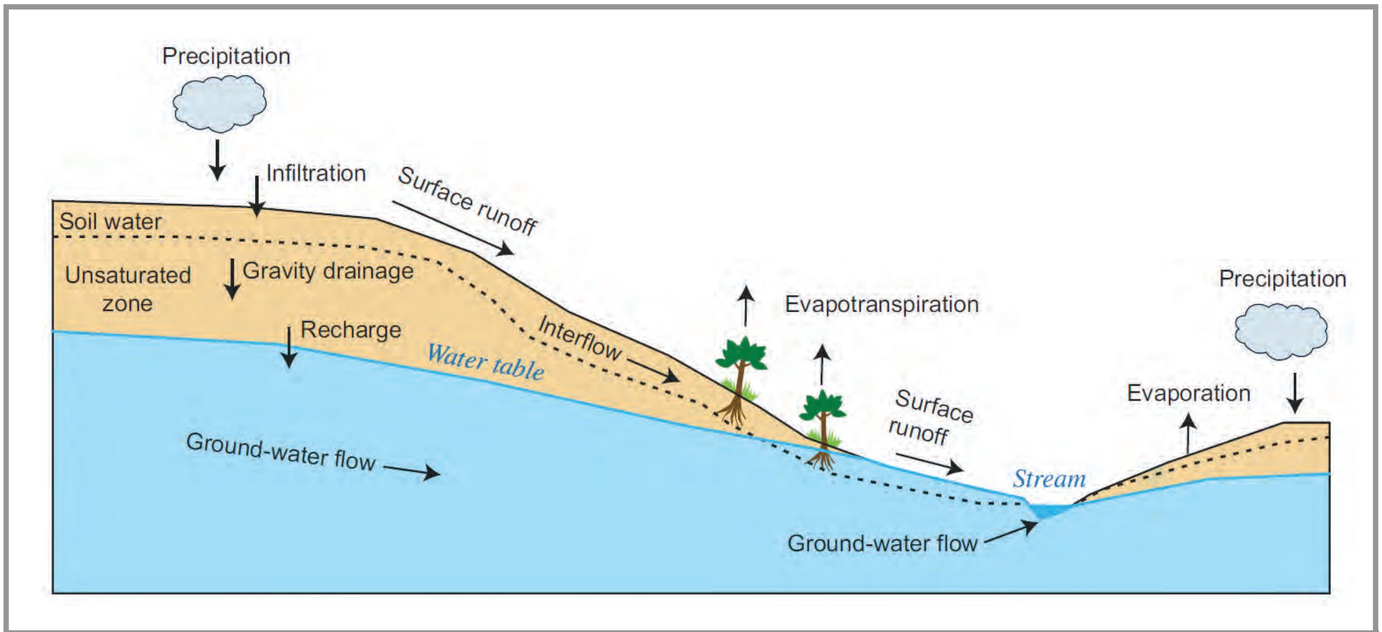

Figure 1.1 Integrated Hydrologic Conceptualization (USGS, 2008)

water table is close to ground surface), the soil water content in the unsaturated soil zone will be supported by the high water table and will sustain higher rates of evapotranspiration in addition to modifying the infiltration characteristics of the upper soil zone. The coupling of surface and sub-surface processes in integrated models allow the impacts of groundwater and surface water withdrawals on streamflow hydrographs and groundwater levels to be simulated.

1.2 Uses of Integrated Models

Integrated modelling has the potential to support a variety of water management activities. Examples of such areas are summarized below:

- Water Budgets for Drinking Water Source Protection. Under the Province's Clean Water Act (2007), water budgets are required to be completed for watersheds across Ontario in a tiered approach. The requirements of such studies include the estimation of basic hydrologic water budget components, including recharge, snowmelt, evapotranspiration, runoff, and groundwater inflow. With each advancing tier of this approach, the water budget components are required to be calculated at a high level of detail for municipal drinking water sources that may be under hydrologic stress. The need for advanced detail requires the use of tools to accurately simulate streamflow, particularly during low flow conditions. Integrated models offer the potential to develop better estimates of water budget parameters within this context, particularly those that rely on the integrated aspects of surface water and groundwater, because all components of the water budget are accounted for simultaneously. A higher level of confidence in the estimated parameters will correspond to additional confidence in Percent Water Demand estimates and subwatershed stress classifications.
- Groundwater and Surface Water Interactions. Groundwater and surface water interactions include those processes in which surface water enters the groundwater system (e.g., groundwater recharge) and groundwater discharges into wetlands, rivers, and lakes. Typically, these interactions are handled separately in the surface water and groundwater models and an effort is made to iterate between the two models until both estimates produce comparable results (i.e., baseflow). In many cases, these interactions are critical to the water-budget process, where groundwater recharge and discharge rates are used directly in the estimation of water supply for the groundwater stress assessment. Similarly, groundwater discharge represents a vital part of the ecological flow requirement of a stream or wetland, and the estimation of these water budget parameters should improve with integrated models.
- Improved Efficiency of Water Budget Calculations. For most of the water budget studies completed to

date, separate surface water models and groundwater models have been developed, and then iteratively calibrated until the recharge rates predicted by the surface water model result in acceptable groundwater model calibration and baseflow prediction. There is an opportunity to potentially reduce the amount of time needed to calibrate these models using an integrated model.

- Low Water Response. In recent years, some watersheds have experienced extremely low streamflows in one or more important surface water bodies. An integrated model would be a valuable tool for evaluating various Low Water Response alternatives because of their ability to simulate a physically based surface water and groundwater interaction. These models may be used to demonstrate the potential effectiveness of changes in water management policies. Additionally, water resource practitioners can use integrated models to increase their understanding of the hydrologic response of a particular watershed, in particular the watershed's response to drought conditions.
- Hydrologic Impact Assessments. Integrated models are able to simulate impacts to one system (e.g., groundwater), that result from changes to the other system (e.g., surface water) in a more sophisticated and complete manner. For example, in a non-integrated modelling approach a land use change may be reflected within an updated recharge distribution, supplied by a surface water model. This recharge distribution is then applied within a groundwater model. The continual coupling between the two models can be tedious and therefore often neglected in the face of time and resource constraints. In an integrated approach, multiple impacts from one system to another and vice versa can all be accommodated simultaneously (i.e. effects of land use change on recharge to the groundwater system, and the effects of pumping from the groundwater system on surface water bodies). Therefore, assessments that evaluate impacts on the overall flow regime caused by land use change, increased water withdrawals or climate change, would be well served by using an integrated model.
- Other MNR and Conservation Authority Programs. The majority of water management efforts require a detailed understanding of watershed processes to make informed decisions. These efforts include Subwatershed Studies, which generally evaluate the impact of land use changes and best management practices on surface water and ecological features, to inform future land development within the subwatershed. By having a detailed understanding of all of a watershed's major hydrologic processes, an agency can better formulate policies and best management practices. Integrated models can be used to build this understanding, and inform water managers on the degree of surface-groundwater interaction within a given watershed. In addition, the Province's Permit to Take Water program requires the evaluation of water takings on hydrologic and ecological resources, and these evaluations would benefit by using integrated models.

1.3 Outline of Document

This report is divided into the following four sections:

Section 1. Introduction

Section 2. Review of Integrated Water Resource Models

This section includes a desktop review of integrated model code capabilities and limitations. A comparative matrix is also included which summarizes capabilities of each model code. The integrated models evaluated are: MIKE SHE; GSFLOW; HydroGeoSphere; ParFlow; and MODHMS.

Section 3. Credit River - Subwatershed 19 Case Study

Building from pre-existing Hydrologic Simulation Program - Fortran (HSPF) and MODFLOW models, three integrated models were developed for Subwatershed 19 of the Credit River watershed. The three integrated models were used to assess impacts caused by changes in groundwater pumping and land use. The modelling team's experience in developing and applying each model is also documented. The following models are evaluated: MIKE SHE, GSFLOW and HydroGeoSphere.

Section 4. Grand River - Mill Creek Case Study

This section describes a second case study, where a MIKE SHE model is developed for the Mill Creek tributary of the Grand River.

The focus of this case study is on model calibration and performance.

Section 5. Integrated Surface and Groundwater Modelling Conclusions and Guidance

The final section includes guidance from the modelling team to other water resource practitioners wishing to develop and apply an integrated model. This section also summarizes the major strengths and weakness for each of the three considered model codes.

2. Review of Integrated (Water Resource) Models

This section presents information pertaining to integrated models as well as an in-depth review of selected hydrologic models. Preceding the model review, background information is presented that describesdes the different types of hydrologic models (Section 2.1), a brief history of the development of integrated models (Section 2.2), and the different ways in which these models can be linked (Section 2.3). It should be noted that some of this background information has been updated and modified from the previous study of Gordon et al. (2005). After the introduction of this background material, a generalized description of five integrated models is presented (Section 2.4); MIKE SHE (Graham and Butts, 2005; DHI, 2009a,b), HydroGeoSphere (Therrien et al., 2009), GSFLOW (Markstrom et al., 2008) MODHMS (HydroGeoLogic, 2000) and ParFlow (Maxwell et al., 2009). The model description section is followed by an inter-model review (Section 2.5) and discussion (Section 2.6). Although the list of modelling codes is growing larger as available computing resources are becoming more capable of facilitating them, many integrated codes are designed to address specific types of environmental problems. The five models chosen for this review are more applicable to general hydrologic investigations.

2.1 Background Information and Types of Hydrological Models

Note: Much of the material presented in Section 2.1 is derived from Refsgaard (1996).

2.1.1 Modelling Terminology and Definitions

In the context of this report, a model is a software program that employs a set of mathematical expressions and logical statements that are combined to simulate and analyze a hydrologic system. Typically, the user builds a model with field data gathered from the watershed being analyzed. The parameterization of the model often requires data are not recorded or available from field observations. This supplemental data can come from technical literature or from other watersheds that have similar characteristics to the hydrologic system in question.

Model input data, regardless of their origin, can be classified as either a parameter or a variable. Parameters are constants in the mathematical expressions or logical statements of the model and remain constant during the simulation period (e.g., soil water content capacity of a soil type). Conversely, a variable is a quantity that varies in space and time. Variable data can be a series of inputs to or outputs from the model, but also a description of conditions in a component of the model (e.g., time-series data describing the changes in vegetation leaf area throughout a year). The data requirements for a typical integrated model include surficial information such as soils, topography, land use, vegetative cover, evapotranspiration and streamflow data. In the subsurface, the necessary input information may include hydraulic conductivity distributions, soil wetting and drying relationships and the porosity of the subsurface materials.

2.1.2 Process Conceptualization

Different hydrologic models conceptualize flow processes in different ways, but most of these conceptualizations can be considered to be either lumped or distributed. A lumped model is one in which the flow catchment is considered to be one discrete unit. The variables and parameters in a lumped model represent average or effective values for the entire catchment. HSPF and the Nedbør-Afstrømnings-Model (NAM) model contained within MIKE-11 are examples of models that lump the hydrologic response to a catchment basis (Bicknell et al., 1997; DHI 2009c). By contrast, a distributed model incorporates the spatial variations of all variables and parameters. When a model accounts for spatial variations associated with most parameters and variables but holds others constant, it is often referred to as semi-distributed. Any groundwater model that explicitly accounts for the spatial variability of hydraulic conductivity in the subsurface is an example of a distributed model. Distributed models tend to require considerably more parameter and variable input data than lumped models.

2.1.3 Hydrologic Models

Nearly all hydrologic models are either stochastic or deterministic. Stochastic models have at least one component of randomness built into their governing equations or input data. Due to this randomness, seemingly identical inputs can result in different model outputs. Conversely, a deterministic model is one where two identical sets of input parameters and variables yield identical model output. A deterministic model has no components that behave stochastically.

Hybrid models can be considered both stochastic and deterministic. Hybrid hydrologic models usually consist of a deterministic code made stochastic by employing it in conjunction with, for example, a parameter estimation program like Parameter Estimation by Sequential Testing (PEST) (Doherty, 2010).

Most of the surface water work and nearly all of the groundwater work done by hydrologic practitioners in Ontario utilizes deterministic models (but could also be considered hybrid due to the way many are calibrated). Therefore, the rest of this discussion will focus on specific types of deterministic hydrologic models. Most of the earlier hydrological models developed in the 1960's and 1970's were lumped empirical models. During the late 1970's and throughout the 1980's, lumped conceptual models became more prevalent (although some employed semi-distributed structures). While these two trends were occurring, physically-based models were also being developed. However, it was not until the mid 1980's, when computers became faster and more readily available, that these types of models began to be popular. Below we describe these three different types (empirical, conceptual and physically-based) of deterministic models in more detail.

Empirical Models

An empirical model is one that is created with little or no consideration of the underlying physics that governs the surface and/or subsurface flow processes. The model is simply based on an analysis of concurrent input and output time series data. During the calibration process, the user adjusts one or more arbitrary parameters or variables in the model (i.e. fitting coefficients within the governing equations) until a computed value of interest (e.g., streamflow) yields an acceptable match to observed values. However, it is difficult to judge the reasonableness of the values of the parameters and variables being adjusted by the user because they have no physical basis and cannot be independently measured in the field.

A primary advantage of empirical models is their relative simplicity and short computation times. Given enough hydrologic data, so that they can be properly conditioned through calibration, empirical models are capable of rapidly producing bulk watershed responses at very large scales. Their short computation times also make empirical models good candidates for certain types of uncertainty analysis work that requires the model to be run hundreds or thousands of times, or as a baseline result for simplified systems to compare with other models and assess their performance. A drawback of empirical models is that the quality of their predictions degrades substantially when applied to situations outside of the range of conditions for which they were calibrated. Moreover, because of their lumped nature, applications of empirical models should be limited to determining bulk behavior and not local-scale features within a system.

Conceptual Models

A conceptual model is one that is developed on the basis of physical processes that are determined from observations in the watershed. In a conceptual model, physically sound structures and equations are used together with empirical or semi-empirical ones. However, the physical significance is often not so obvious that the entire model's input parameters and variables can be determined directly from field measurements alone. Instead, most of the input values are determined indirectly through calibration.

The parameters used for the empirical equations in a conceptual model can be determined only by calibrating the model to extensive rainfall and stream flow records. Once calibrated, these types of models will often generate reasonable rainfall-runoff predictions and are especially useful in regional-scale forecasting applications. For example, conceptual rainfall-runoff models are often used to infill gaps in streamflow data where precipitation data is available to cover the time period in question.

Physically-based Models

A physically-based model employs basic mathematical representations of flows of mass, momentum, and various forms of energy to describe watershed processes. At its most basic level, a physically-based model consists of a number of linked partial differential equations with parameters that have direct physical significance and can be evaluated by independent field measurements. In principle, the physically-based processes only require representative physical characteristics of the watershed input into the model for the results to be realistic. Of course, in reality, calibration is still warranted.

Physically-based models represent the current state-of-the-art in simulating groundwater - surface water interactions. Moreover, physically-based models can also be calibrated using considerably less historical data (e.g., rainfall, observation well and streamflow records) than would be required by their empirical and conceptual counterparts (e.g., see discussions by Beven and O'Connell, 1982; Bathurst, 1986a; Bathurst and O'Connell, 1992). However, physically-based models require significantly more information about the physical characteristics of the watershed being analyzed (and take longer to complete their simulations) than do empirical and conceptual models. It should also be noted that for certain hydrologically complex watersheds (such as systems with particularly strong surface water - groundwater interaction processes occurring, fractured rock systems and systems with highly variable subsurface properties), modelling might be challenging unless adequate data are available. Further, characterization data should be present at the scale at which the modelling is being conducted. It should be noted that all of the models included in the inter-model review presented below are physically-based integrated models.

2.2 Development of Integrated Models - A Brief History

Freeze and Harlan (1969) were the first to recommend modelling that regarded the surface and subsurface flow regimes as a single interactive system. In their paper, a 'blueprint' outlined the feasibility of coupling the partial differential equations describing surface and subsurface hydrodynamic processes within a single physically-based, distributed modelling framework. Shortly after the publication of this seminal work, groundwater - surface water interaction models of varying degrees of sophistication began to appear in the literature.

Pinder and Sauer (1971) investigated the effects of bank storage with a model that coupled one-dimensional (1D) channel flow to two-dimensional (2D) saturated groundwater flow. Smith and Woolhiser (1971) developed a code that linked 1D overland flow to 1D unsaturated subsurface flow and tested it against rainfall-runoff responses observed in the laboratory and at a small experimental plot in Nebraska, with limited success. Freeze (1972a,b) advanced the representation of processes simulated by groundwater - surface water interaction models one step closer to the 'blueprint' by adding 1D channel flow capabilities to an existing 3D variably-saturated subsurface flow model (Freeze, 1971) and then employed it to demonstrate the importance of subsurface flow processes on streamflow generation. The earlier Freeze (1971) model was later applied to a hydrologically complex hill slope to examine subsurface flow contributions from snowmelt runoff (Stephenson and Freeze, 1974). The agreement between the simulated and observed responses was poor, and the discrepancies were attributed to limitations pertaining to calibration abilities, computational constraints, theoretical understanding of the processes involved, and lack of data. Subsequent to the work of Stephenson and Freeze (1974), research concerning the progressive development of groundwater - surface water interaction models in North America slowed dramatically, although there were some exceptions to this trend (e.g., Cunningham and Sinclair, 1979; Smith and Hebbert, 1983). North American research activity on integrated models began to increase again in the 1990's, alongside the advent of economical and powerful desktop computers, an improved theoretical understanding of the relevant hydrological processes, and the availability of high-quality data assembled over long observation periods at well-instrumented sites.

In the mid 1970's, three European organizations (the British Institute of Hydrology, the Danish Hydraulics Institute and the French consulting company SOGREAH) were brought together by the Commission of European Communities to determine how to overcome a number of environmental concerns that could not be addressed using conventional lumped empirical (i.e., 'black box') codes. This collaboration resulted in the groundwater - surface water interaction model Systéme Hydrologique Européen (SHE), which is capable of simulating 2D overland flow and 1D channel flow on the surface, as well as 1D unsaturated and 2D depth-averaged saturated flow processes in the subsurface (Abbott et al., 1986a, b). Since its inception, SHE has been applied to a number of sites around the world (e.g., Bathurst, 1986a, b; Refsgaard et al. 1992; Jain et al., 1992) and, in subsequent years, has inspired a number of daughter models including SHE/SHESED (Bathurst et al., 1996), SHETRAN (Ewen et al., 2000) and MIKE SHE (Refsgaard and Storm, 1996).

Over the last several years, there has been an increase worldwide in both the development and use of physically-based, distributed models being applied to integrated flow problems. As a consequence of this increase in activity, there have also been a number of discussions in the literature regarding issues associated with the use of integrated models based on the Freeze and Harlan (1969) 'blueprint' (e.g., Abbott, 1996; Beven, 1989, 1993, 1996a,b, 2000, 2001a,b, 2002a,b; Beven and Binley, 1992; Grayson et al., 1992; Loague and VanderKwaak, 2004; Smith et al., 1994). According to Beven (2002b), the primary limitation of models based on the Freeze and Harlan (1969) 'blueprint' is that the governing equations are not capable of adequately representing catchment processes. To advance his argument, Beven (2002b) cites a number of case studies in which physically-based, distributed models were unable to reproduce observed rainfall-runoff responses, including work done at the well-characterized R-5 catchment in Oklahoma (e.g. Loague and Freeze, 1985; Loague, 1990a,b, 1991, 1992a,b,c,d, Loague and Kyriakidis, 1997). However, the models used in earlier studies conducted at the R-5 catchment did not incorporate all of the known streamflow generation mechanisms (infiltration excess and saturation excess overland flow, subsurface stormflow (interflow) and baseflow). Subsequent studies have shown that it is indeed possible to reproduce observed rainfall-runoff responses at R-5 given a physically-based, distributed model that makes no assumptions with respect to which of these mechanisms dominate the system response (VanderKwaak and Loague, 2001; Loague and VanderKwaak, 2002, Loague et al., 2005). In other words, models that do not incorporate certain hydrodynamic processes should not be applied to systems where those processes are important.

2.3 Integrated Model Linkage Techniques

For a given time step, an integrated model solves for surface flow, groundwater flow and the exchange of both across the land surface. There are three basic techniques used to connect these processes in a model and each technique varies in terms of its ease of implementation into the model structure. In order of ease of implementation, the techniques are:

- externally-coupled;
- iteratively-coupled; and
- fully-coupled.

Externally-coupled models solve for surface flow and subsurface flow processes separately and in succession without iteration within a time step. Computed surface water heads are typically considered a general head boundary condition while solving the subsurface flow equations, while subsurface heads are used for the surface water flow calculations (Fairbanks et al., 2001). This approach can also use fluxes (i.e., transfer of volume of fluid per unit area per unit of time) instead of hydraulic head. As discussed in the work of Morita and Yen (2000, 2002), surface flow is typically solved for first in an externally-coupled model and the result is passed on to solve for subsurface flow before advancing to the next time step. Examples of integrated models that employ external coupling include Smith and Woolhiser (1971), Liggett and Dillon (1985), Abbott et al. (1986b), Di Giammarco et al. (1994), Refsgaard and Storm (1996), Wallach et al. (1997) and Markstrom et al. (2008). Although easy to implement, the externally-coupled technique has been shown to be prone to convergence problems and degradation of the flow solution if too large of a time step size is specified by the user (Fairbanks et al., 2001). The optimal time step for each of the coupled processes may be different but must be selected to ensure conservation of mass between coupling processes.

Iteratively-coupled models solve the surface and subsurface flow equations separately but iteratively within each time step, with the corresponding heads or fluxes acting as a common internal boundary condition between the two regimes (Morita and Yen, 2002). The model advances to the next time step when the iteration errors of each flow solution drops below a user-defined tolerance. Examples of iteratively-coupled models include Pinder and Sauer (1971), Freeze (1972a), Akan and Yen (1981), Schmitz et al. (1985) and Bradford and Katopodes (1998). It could be inferred from the Fairbanks et al. (2001) study that general applicability of iteratively-coupled models may be limited because "appropriate" time step sizes are too small for practical simulations, and therefore limited due to computational effort required.

Fully-coupled models solve surface flow, subsurface flow and the fluid fluxes between these two regimes simultaneously at each time step. Although the fully-coupled technique is more difficult to implement into a model, it is arguably the most robust and least error-prone of the three coupling approaches. Examples of fully-coupled models include VanderKwaak (1999), HydroGeoLogic, (2000), Maxwell et al. (2009) and

Therrien et al. (2009). Fully-coupled integrated flow models have also been referred to in the literature as 'fully-integrated' models (e.g., Jones et al., 2006; Jones et al., 2008).

An important implication of the coupling technique is the use of uniform or varied time step lengths in the various hydrologic processes represented within a given model. Because fully-coupled models solve all processes simultaneously, the time step size can be uniform throughout all the modelled hydrologic processes. To adequately represent hydrologic processes, a fully-coupled model must proceed at a time step determined by the most dynamic processes considered. In iteratively-coupled models, the time step size may be chosen as is warranted by the dynamics of various hydrologic processes (e.g., streamflow processes use relatively small time steps, saturated groundwater flow processes use relatively large time steps). Depending on the dynamics of the watershed, a significant computational overhead may be incurred by a fully-coupled model.

It should be noted that a fourth coupling approach also exists that could be termed a "non-coupled" (or "decoupled") technique. This approach uses separate models for surface and groundwater, but links them via shared input or output parameters. An example is when infiltration rates calculated by a surface water model are imported as recharge values in a groundwater model. A great deal of effort is exerted in the groundwater modelling community to define recharge values and this non-coupled example represents a significant improvement over older methods that used uniform recharge values or determining recharge through calibration, which can produce non-unique solutions. However, the infiltration values calculated by the surface water model are unconstrained by any subsurface processes not included in that model's structure (such as interbasin flow) which could affect their distribution and magnitude. As a result, the groundwater modeller using these data is often required to make manual adjustments to these values to compensate for discrepancies due to the lack of subsurface feedback.

2.4 Selected Integrated Models

The following section briefly describes five integrated models. The five models are: 1) GSFLOW; 2) MIKE SHE; 3) HydroGeoSphere; 4) MODHMS; and 5) ParFlow. In terms of the coupling of surface and subsurface processes, as examined in Section 2.3, HydroGeoSphere, MODHMS and ParFlow are fully-coupled models whereas GSFLOW and MIKE SHE are externally-coupled models. The five models chosen for evaluation are representative of the major conceptual approaches outlined in the previous section. ParFlow, HydroGeoSphere and MODHMS are integrated codes in which basic surface water capabilities were added to a scientifically rigorous groundwater model. These three models are examples of a groundwater-oriented approach to developing an integrated model. Conversely, the MIKE SHE model has substantial surface water simulation capabilities to which subsurface processes were added. MIKE SHE is an example of a surface water oriented approach to developing an integrated model. Finally, GSFLOW is a code in which an existing surface water model with a defensible history (PRMS) was coupled to an existing groundwater model that also has a defensible history and is considered an industry standard (MODFLOW 2005).

For all five models, the data needs are similar. In addition to fundamental needs such as the definition of boundary conditions and observed data, the basic requirements include:

- Land Surface Information:
  - Precipitation data;
  - Temperature data;
  - Streamflow data;
  - Potential evapotranspiration parameters or estimates;
  - Land-usage distribution;
    - Vegetation distribution and properties (rooting depth, leaf area index);
    - surface roughness of land classes;
    - depression storage of land use classes;
    - impervious fraction of land classes;
  - Topography
  - Hydraulic Information
    - stream channel network (spatial mapping)
    - stream channel geometry data (cross sections)
    - stream bed conductivity data
    - hydraulic structure data (physical dimensions, operation rules)
    - stream boundary conditions (e.g., waste water discharge, etc)

- Subsurface Information:

- o Hydraulic properties of the soils/sediments;
- o Hydraulic head/soil moisture data;
- o Unsaturated soil wetting/drying relationships; and
- o Pumping well rates and locations.

However, there are some differences between the models in terms of data requirements and how each model needs to be set up before the simulations can be initiated. For example, all of the models except HydroGeoSphere require streambed conductances. Conversely, HydroGeoSphere's internal processes calculate conductance on the basis of soil wetting and drying relationships parameters.

2.4.1 GSFLOW

GSFLOW is a physically-based and semi-distributed model that combines the saturated subsurface flow capabilities of the popular groundwater model MODFLOW (Harbaugh, 2005) to the surface water code PRMS (Leaveseley et al., 1983). The use of both MODFLOW and PRMS is well documented in literature and both have been developed on an ongoing basis. GSFLOW was created by linking these two models together using a program called the Modular Modelling System (MMS). It should be noted that GSFLOW v1.0.00, was released to the public in March, 2008 and not all of the capabilities of MODFLOW and PRMS codes were included in this initial version. Additional functionality has been provided to GSFLOW through subsequent releases. The current version of GSFLOW is 1.1.4 and was released on June 1, 2011.

The linkages between PRMS, MODFLOW-2005, and the Streamflow-Routing Package within MODFLOW-2005 are illustrated in **Figure 2.1**. As seen in this figure, GSFLOW solves between three 'Regions' of the system: Land (Region 1), Surface Water (Region 2) and Groundwater (Region 3). Each of these regions provides or accepts solved components (such as interflow, discharge, etc) from each other.

PRMS (Region 1) uses the Hydrologic Response Unit (HRU) concept to represent variability in hydrologic parameters. This involves grouping similarly responding soils and land cover types into a specific group (HRU). Each PRMS HRU is coupled to a corresponding MODFLOW grid cell, and provides a link between PRMS and MODFLOW.

Figure 2.2 illustrates the processes included in PRMS. The primary purpose of PRMS within GSFLOW is to partition precipitation into evapotranspiration, overland runoff, interflow and groundwater recharge. Processes related to canopy interception, snowmelt, and impervious land covers are also considered within the PRMS region. In the GSFLOW application of PRMS, the groundwater and subsurface reservoirs are effectively replaced with MODFLOW, and a varying water table is allowed to affect unsaturated zone processes.

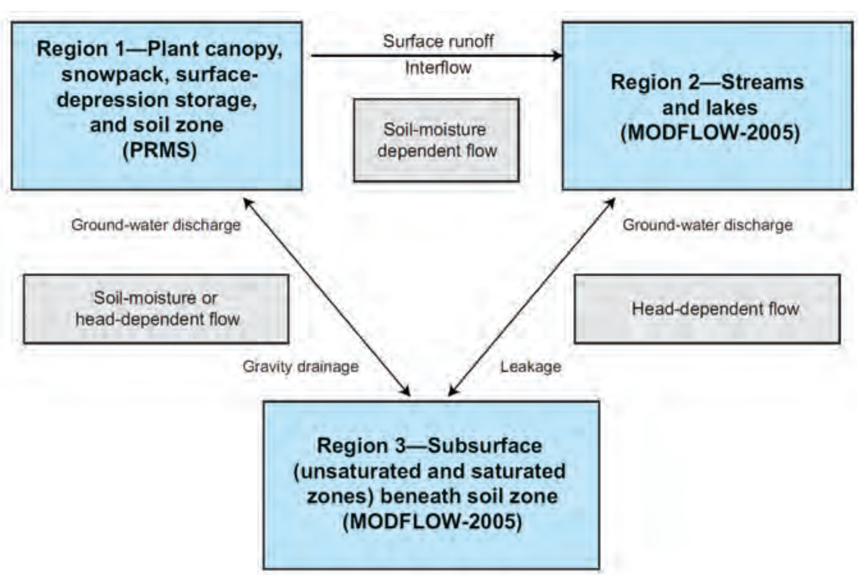

Figure 2.1 - GSFLOW Linkages (Source: USGS, 2008)

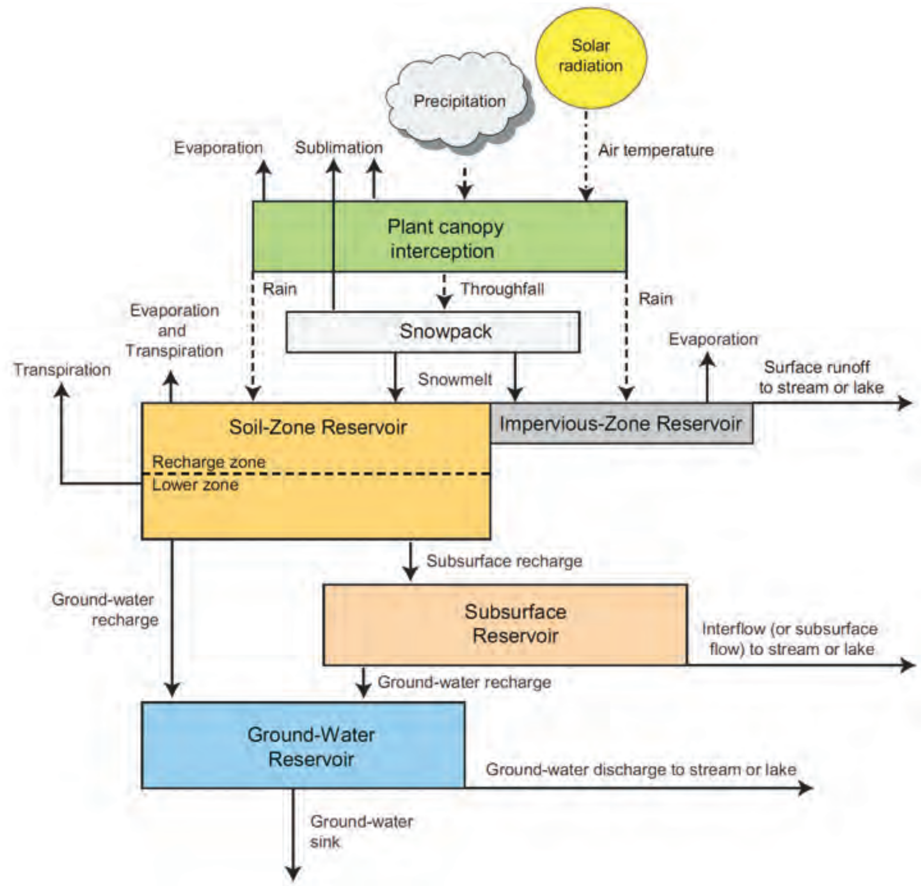

Figure 2.2 PRMS Process Schematic (Source: USGS, 2008)

Runoff is calculated as a non-physical "contributing area" concept, which assumes that as soil-water increases, the portion of a cell that generates runoff also increases. Each cell is assigned a relationship that governs the proportion of runoff that is generated from a unit of available precipitation, given the available storage in the soil-zone reservoir. As the available storage in the soil-zone reservoir decreases, more precipitation becomes overland runoff. Infiltration is calculated from a mass balance perspective, and is the remaining precipitation (minus interception storage) that does not become runoff. While runoff can be directed by the modeller to a downstream HRU or watercourse, there is no explicit overland routing included in GSFLOW.

Once infiltrated, water is supplied to the soil-zone, which is the link between PRMS and MODFLOW. The conceptualization of the soil zone was revised from the PRMS model for GSFLOW and is illustrated in **Figure 2.3**. In GSFLOW, the soil-zone is conceptualized into three storage reservoirs which occupy the same physical space; capillary, gravity, and preferential-flow. All three layers can interact with each other, the saturated/unsaturated zone, as well as provide slow and fast interflow depending on the level of saturation in the soil zone.

Drainage from the gravity reservoir (groundwater recharge) is first estimated through use of an empirical relationship that determines the maximum potential gravity drainage. The potential gravity drainage is modified to account for groundwater elevations and vertical hydraulic conductivities within the underlying finite difference cell.

The MODFLOW portion of GSFLOW handles both saturated and unsaturated flow. Unsaturated flow is represented using the kinematic wave approximation of the Richard's equation. Flow in the saturated zone is

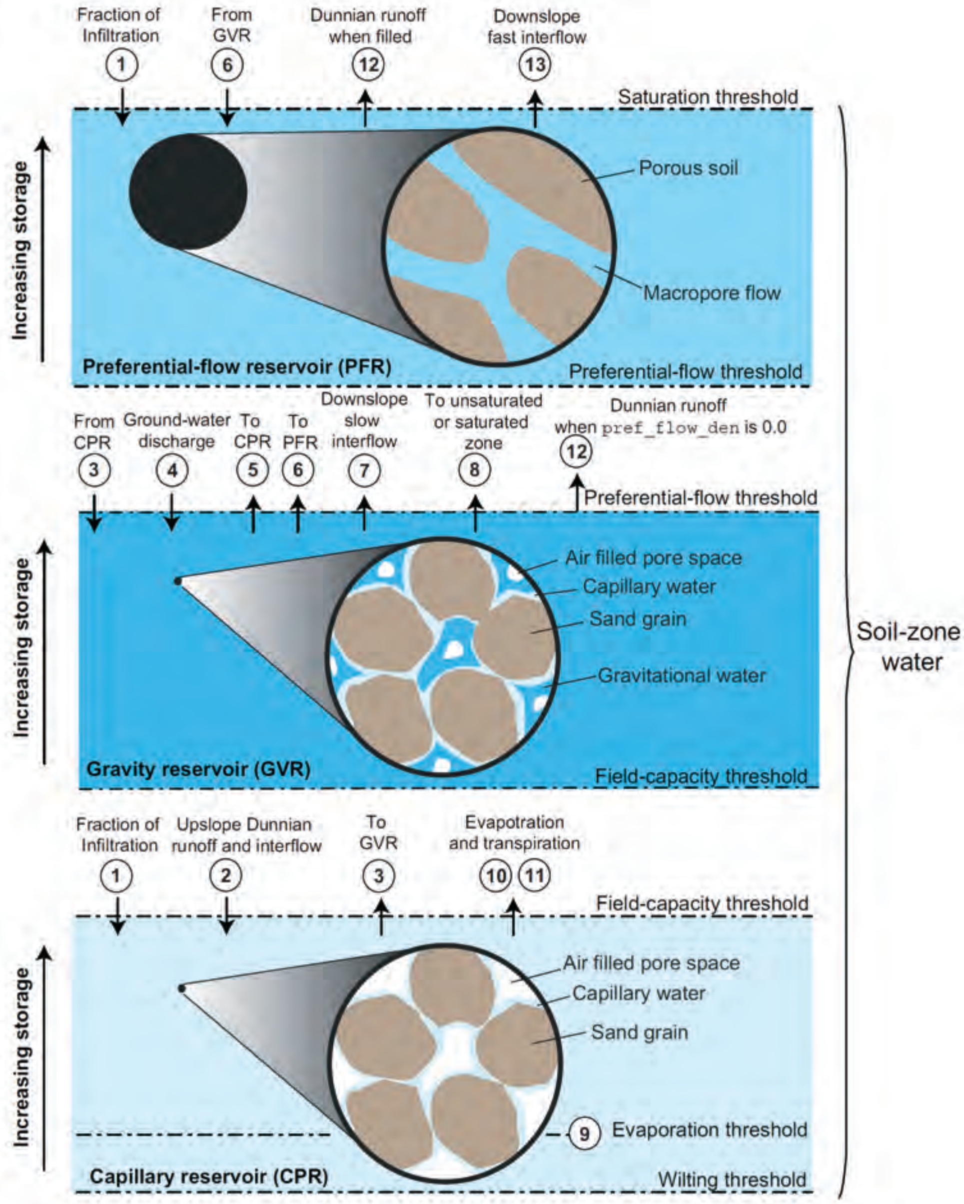

Figure 2.3 - GSFLOW Soil-water Reservoir Conceptualization

(Source: USGS, 2008)

governed by the partial differential equation for 3D flow of water with constant density.

The Streamflow-Routing Package included in MODFLOW-2005 is used to simulate watercourses. Runoff and interflow (simulated by the PRMS portion of GSFLOW), and groundwater discharge (simulated by the MODFLOW portion of GSFLOW), is accumulated within the Streamflow-Routing Package, and routed downstream. Groundwater discharge, or leakage, within the watercourse is calculated based on the groundwater head and surface water elevation. Leakage is limited by the amount of streamflow in the cell for each time step.

Routing can be carried out by one of two methods. The first is a simple additive procedure in which the outflow of a stream reach is equal to the sum of inflows and outflows within the reach. The second approach relies upon the kinematic wave approximation of the St. Venant equations. It should be noted that the kinematic wave approximation, as implemented in GSFLOW, neglects the diffusion of flood waves and the inertial terms of the St. Venant equations. As such, applying the kinematic wave approximation can introduce some degree of error in model predictions when surface wave attenuation is an important consideration (e.g., in reservoirs) or when employed in regions with relatively steep topographic grades. GSFLOW is capable of representing simple hydraulic structures (e.g., an overflow weir) which can be represented using stage-discharge curves. GSFLOW is not capable of physical structure hydraulics used to represent complex hydraulic structures (e.g., a multiple outlet dam), where the effects of structures on channel hydraulic are explicitly simulated. Further, GSFLOW is not capable of simulating hydraulic structure control operations.

The current version of GSFLOW has a fixed time step size of one day for all processes. This daily time step approach can be an issue in representing certain hydrologic processes. First, by not allowing saturated zone processes to be calculated at time steps greater than a day, GSFLOW is possibly introducing additional computational calculations to represent an otherwise slowly responding system. These additional calculations are realized as longer simulation times. Secondly, the fixed one-day time step may not have enough temporal resolution to properly represent the dynamics associated with the unsaturated zone, overland runoff, or rainfall intensity (e.g., short, intense convective rainfall events vs. long duration, low intensity regional rainfall events).

As stated above, GSFLOW was initially released to the public in March of 2008. As such, it does not have a very long history of applications or associated publications in the literature other than initial papers by its developers. The current version of GSFLOW does not have a GUI. GIS is not fully integrated into the model but can be accomplished using a separate program called GIS WEASEL. GSFLOW is well documented and can be freely downloaded from the USGS website (http://water.usgs.gov/nrp/gwsoftware/gsflow/gsflow.html).

GSFLOW training courses have been offered by the USGS at their National Training Center in 2007, 2009 and 2011. It is unclear how frequently these training courses will be offered in the future, however, training may eventually be provided from third parties.

2.4.2 MIKE SHE

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

Figure 2.4 presents the process schematic for MIKE SHE. With the exception of channel routing, all calculations, including precipitation, unsaturated flow, overland flow, and saturated flow are calculated on the same (uniform) grid basis. MIKE SHE links to MIKE-11, DHI's 1D hydraulic model, for channel routing.

After accounting for canopy interception and snowmelt processes, liquid water is supplied to the ground surface. A number of algorithms are available to account for infiltration and other unsaturated zone processes. These include: a 1D finite difference approximation of the Richards equation; gravity flow; or a 2-layer water balance with or without Green-Ampt infiltration. All flow is assumed to be vertical in the unsaturated zone. The thickness of the unsaturated zone is determined by groundwater heads (if utilizing the 3D finite difference method for saturated flow) for each time step. Water exchange from the unsaturated zone to the saturated zone is interpreted as groundwater recharge. When groundwater heads are greater than the ground surface, the thickness of the unsaturated zone reaches zero, groundwater discharge occurs, and becomes overland runoff. If the linear reservoir representation of groundwater is utilized the depth of the unsaturated zone is specified as a model input.

If net precipitation, (i.e., precipitation less canopy interception), falls at a rate greater than the infiltration rate, overland runoff is generated. Overland runoff can be simulated either in a lumped, or a distributed methodology. In the lumped approach, the model domain is divided into catchments. Runoff that is generated within a catchment is routed to the MIKE-11 channel located within the catchment. In this method,

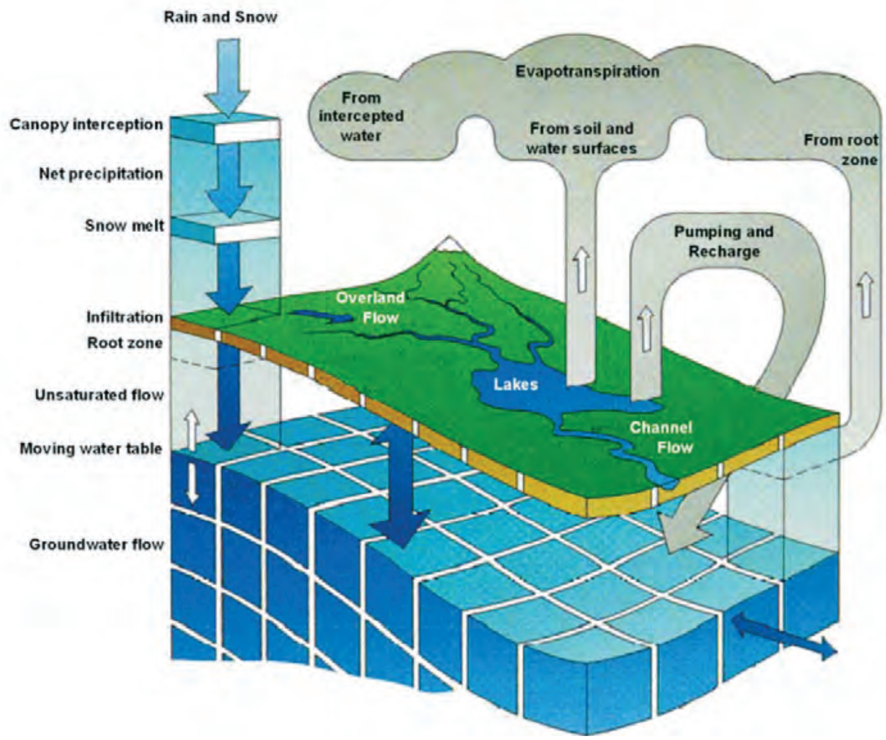

Figure 2.4 MIKE SHE Process Schematic (Source: DHI, 2009a)

runoff is assumed to reach the watercourse (e.g., runoff from one area flowing to an adjacent area, is not able to infiltrate in the adjacent cell). The routing method in the lumped approach is an empirical relationship between flow depth and surface detention together with the Manning equation. The method has been implemented in other models, such as HSPF. The distributed approach relies on a 2D diffusive wave approximation of the St. Venant equations. In this approach, overland runoff is routed over the ground surface until a MIKE-11 channel is reached. Runoff from one cell flowing to an adjacent cell is available for infiltration in the adjacent cell. This method respects ground surface topography, in that overland runoff generated by land areas that does not drain directly to a watercourse, will collect at the lowest point, causing ponding to occur, and will either evaporate or infiltrate into the unsaturated zone. The ability to consider closed depressions is particularly relevant when modelling the hydrologic response of moraines, where hummocky topography is prevalent. A potential drawback here is that the 2D diffusive wave approximation neglects inertial terms in the St. Venant equations and therefore is only strictly applicable to regions where the grade is 15° or less. When grades exceed this threshold, inertial terms begin to dominate flow behavior and the diffusive wave approximation will underpredict flow rates. This is generally more of an issue when applying diffusive wave approaches in certain mountainous terrains and much less of a concern for most of the conditions present in Ontario.

Saturated flow can be represented by one of two methods. The first method is a lumped, subwatershed based method that relies on the linear reservoir approximation. In this method, the model is divided into catchments. Groundwater recharge produced by cells within each catchment is routed through a linear reservoir to represent the delayed response inherent in groundwater systems. All outflow from the linear reservoir is supplied to MIKE-11 as baseflow to streams within that catchment. Inter-catchment groundwater fluxes are not supported. This method is an extremely simplified representation of the groundwater system, and is common to most hydrologic models (e.g., Guelph All-Weather Storm-Event Runoff Model (GAWSER), HSPF, Hydrologic Engineering Center Hydrologic Modelling System (HEC-HMS)). This method does not simulate groundwater flow, heads, or interactions with the surface water system. The second method for simulating the saturated zone relies on the solution of the 3D Darcy equation, using an iterative implicit finite difference technique. Two groundwater solvers are provided: a pre-conditioned conjugate gradient (PCG) solver, which is identical to the solver used in MODFLOW; and a successive over-relaxation (SOR) solver. As MIKE SHE is based on the finite difference method, it is very amenable to importing groundwater data from MODFLOW simulations. However, unlike MODFLOW, the grid structure in MIKE SHE must be uniform (i.e., variable grid-spacing is not allowed). Based on calculated groundwater heads, exchange (groundwater discharge), with either the ground surface or simulated watercourses, is simulated.

Channel flow is handled through a two-way linkage between MIKE SHE and MIKE-11. Overland runoff, interflow and groundwater discharge enters the stream channel and is routed downstream. A variety of routing algorithms are available, ranging from relatively simple Muskingum routing to the Dynamic Wave formulation of the St. Venant equations. If the 3D representation of the saturated zone is employed, groundwater discharge/leakage is calculated based on the surface water elevation, groundwater head, and a river-bed conductance term. Leakage from the watercourse to the saturated zone is limited by the volume of water within the stream.

There are two methods for calculating evapotranspiration: 1) Kristensen & Jensen; and 2) the two-layer unsaturated zone/evapotranspiration-mode. The Kristensen & Jensen method is based on a set of empirical equations and potential evapotranspiration rates, where as the two-layer mode utilizes potential evapotranspiration rates and a simple mass balance model of unsaturated zone water content. Potential evapotranspiration rates are supplied with a spatial distribution generated outside of MIKE SHE. Both methods rely on the user to specify root depth for differing land covers, which represents the depth of soil from which water can be removed by evaporative processes. Water is removed via evaporation from the following storage elements: water held in canopy interception; water on the soil surface; or uptake of soil-water by vegetation from the root zone. Once the reservoirs are emptied through evapotranspiration, water cannot be further removed until a precipitation event, or until increased groundwater elevations replenish soil-water content within the root zone. Evaporation and sublimation also occur from the snowpack.
Urban drainage and sewer systems can be modeled through optional linkage to DHI's MIKE URBAN model. Coupling of MIKE SHE and MIKE URBAN requires construction and calibration of a standalone version of a MIKE URBAN model.

The hydrologic processes (overland, channel, unsaturated, and saturated zone modules) of MIKE SHE are explicitly coupled which allows the time step of each component to be determined based on the response time of the component processes. The drawback to this coupling approach is that it is possible for the model to undergo convergence difficulties as each connected component iterates to a common boundary condition (e.g., conditions where a shallow water table is strongly fluctuating during the simulation period, causing the unsaturated zone in this zone to disappear and reform). However, these problems can be overcome by paying careful attention to convergence parameters and tolerances.

MIKE SHE comes with a well-designed graphic user interface (GUI) that allows the user to import various input data, assign boundary conditions to the system, and examine simulation results. MIKE SHE also provides the option of parameterizing the model using an ArcView GIS toolkit.

Applications of the MIKE SHE model have a very long publication record including the recent work of Vazquez et al. (2008), Hansen et al. (2007) and Thompson et al. (2004). Additionally, MIKE SHE has consistently ranked high in a number of model comparison studies including Gordon et al. (2005), Weber et al. (2004) and Camp Dresser & McKee (2001). Because the model is proprietary, the source code is not available. The model is well-documented and actively being maintained and updated. DHI, the developers of MIKE SHE, also provide numerous training courses on their software at locations around the world. MIKE SHE can be purchased online at: http://www.mikebydhi.com/. The cost of the code varies depending on the options the user wishes to include. Prices range from approximately $15,000 to $30,000, depending on the version purchased. All versions require the user to purchase annual service maintenance agreements for continued technical support and software updates. The annual cost of the service agreement is approximately $5,000.

2.4.3 HydroGeoSphere

HydroGeoSphere (HGS) is a physically-based and distributed model that has been developed by a consortium of researchers at the University of Waterloo in Ontario, Université Laval in Québec and HydroGeoLogic, Inc. in Virginia. The surface flow module of HydroGeoSphere is based on a modification of the Surface Water Flow Package of the MODHMS model which is fully-integrated into the 3D variably-saturated groundwater flow model FRAC3DVS (Therrien et al., 2004). HydroGeoSphere is a theoretically rigorous model that is currently being used by researchers worldwide (Sudicky, 2009).

The model processes include rainfall, evapotranspiration and interception, 2D overland and channel flow, 3D variably-saturated flow in the subsurface, baseflow, subsurface storm flow (interflow), soil moisture content and recharge processes. Overland flow is represented in the model using a 2D diffusive-wave approximation of the St. Venant equations. In the subsurface, Richard's and Darcy's equations are combined to describe 3D variably-saturated flow. Additionally, HydroGeoSphere is also capable of simulating the effects of fractures, macropores and tiles in the subsurface, which may be an important feature for some Ontario watersheds. HydroGeoSphere has evapotranspiration and interception modules similar to those found in MODHMS. HydroGeoSphere is not able to simulate hydraulic control structures because pipe flow processes have not been incorporated into its structure. Although thermal transport processes are incorporated in the most recent version of HydroGeoSphere, snowmelt is not. However, the authors of HydroGeoSphere are fully aware of this limitation and are currently implementing these processes into a forthcoming release (Sudicky and Park, 2011)

HydroGeoSphere employs the control volume finite element (CVFE). CVFE takes advantage of the superior local mass balance capabilities of the block-centered finite difference method while still maintaining the finite element method's flexibility to conform to irregular boundaries. The finite element method often results in significantly fewer elements in the mesh (when compared to meshes produced for irregular geometries using the finite difference method) which results in decreased computational effort. Moreover, HydroGeoSphere incorporates a number of advanced numerical techniques that can significantly reduce simulation times. Similar to MODHMS, HydroGeoSphere employs adaptive time stepping that optimizes time step sizes to convergence of the iterative solver and user-specified parameters.

The most current version of the code does not contain a GUI to facilitate pre- and post-processing, nor is it set up for integration in a GIS environment. It should also be noted that a 3D visualization program such as Tecplot is typically required to view HydroGeoSphere output. The HydroGeoSphere package consists of three primary components: 1) a preprocessor which converts user-input into the format required by the simulator, 2) the simulator and 3) a post-processor.

Unlike the other models discussed in this report, the user is not required to specify the location of the drainage network on the land surface. Instead HydroGeoSphere determines where water infiltrates, exfiltrates or forms surface water in drainage channels or wetlands during its execution. The drawback to this approach is that channel geometry information is usually poorly represented in the model. However, eit is possible to represent channel geometry information in the model, but only at the cost of significantly refining the numerical mesh along the drainage network.

Recent applications and publications pertaining to HydroGeoSphere include Brookfield et al. (2009), Brookfield et al. (2008), Lemieux et al 2008 and Li et al (2008). HydroGeoSphere is very well documented and the software package contains numerous examples. The model is being actively maintained and updated. The authors' provide short courses on operating the model on an as-needed basis. A non-academic version of the code costs $3,000, and can be obtained by contacting one of its authors (Ed Sudicky) at: sudicky@sciborg.uwaterloo.ca. HydroGeoSphere does not require service maintenance agreements to receive ongoing technical support. Tecplot can be purchased for ~$3,500 (depending on the version).

2.4.4 MODHMS

MODHMS is a physically-based, distributed model that integrates surface water processes with a groundwater flow processes and is compatible with that of the USGS's groundwater flow model, MODFLOW. The MODHMS model builds upon an early version of MODFLOW-

SURFACT, a proprietary groundwater model with full unsaturated zone considerations, developed by the consulting firm HydroGeoLogic Inc., headquartered at Herndon, Virginia. Although MODFLOW-SURFACT (and subsequently MODHMS) does not incorporate MODFLOW's source code into its structure, it was designed to be fully compatible with that MODFLOW's input and output as a separate module. Therefore, all of the customary packages for MODFLOW are available in MODHMS.

MODHMS, like the HydroGeoSphere and ParFlow codes discussed in this section, is an example of a fully-integrated model. MODHMS is capable of simulating 2D overland flow, 1D open channel or closed pipe flow (Priesmann slot), 3D variably-saturated flow in the subsurface, evapotranspiration and interception, baseflow, rainfall, subsurface storm flow (interflow), changes in soil moisture content and recharge processes. Overland flow and channel flow are represented in the model using 2D and 1D versions of the diffusive-wave approximation of the St. Venant equations, respectively. In the subsurface, Richard's and Darcy's equations are combined to simulate 3D variably-saturated flow. MODHMS has extensive evapotranspiration and interception modules that can be implemented in various manners across the land surface of the system being analyzed. The model also has the ability to simulate hydraulic control structures such as dams, weirs and culverts. Snowmelt is not included in the model.

MODHMS employs adaptive time stepping that customizes time step sizes to convergence of the iterative solver and user-specified parameters. The governing equations for surface water and groundwater are assembled in a single matrix and solved simultaneously, thereby eliminating potential convergence and mass balance difficulties as the surface and subsurface flow solutions iterate to a common head or flux boundary.

MODHMS comes with a module called AVI (ArcView Interface) that allows it to interface with ArcView GIS, thereby facilitating visual parameterization of the model. In the subsurface, a well-designed GUI (originally developed for MODFLOW-SURFACT) is used to parameterize the groundwater portion of the system, assign boundary conditions and generate the 3D finite difference grid. Alternatively, the subsurface parameterization can be accomplished using any standard MODFLOW pre-processing package such as Groundwater Vistas (Environmental Simulations Inc., 2011).

Applications and publications pertaining to MODHMS include Fairbanks et al. (2001), Jones et al. (2003) and Panday and Huyakorn (2004). The model was also ranked highly in an inter-model comparison study performed by Weber et al. (2004). MODHMS is well documented and contains numerous example problems. The model is proprietary; therefore, the source code is not available. The MODHMS package can be purchased by contacting HydroGeoLogic, Inc. at: sales@hgl.com and costs $5100 or more, depending on the options purchased. Information on training courses for MODHMS can be found at HydroGeoLogic Inc.'s website (http://www.hglsoftware.com/Modhms.cfm).

2.4.5 ParFlow

ParFlow is a physically-based and distributed model that has been developed by a consortium of researchers from the Colorado School of Mines, the Lawrence Livermore National Laboratory, the University of Bonn and the University of California at Berkeley. ParFlow was originally conceived as a groundwater simulator to be applied to large-scale high-resolution problems run on supercomputers. Surficial flow processes were recently added to the model (Kollet and Maxwell, 2006) as well as linkages to the Common Land Model (CLM) and atmospheric codes such as the Weather Research and Forecasting Model (WRF).

The model processes include rainfall, snowmelt, evapotranspiration and interception, 2D overland and channel flow, 3D variably-saturated flow in the subsurface, baseflow, subsurface storm flow (interflow), soil moisture content and recharge processes. Surficial flow processes are represented in the model using a 2D kinematic-wave approximation of the St. Venant equations that is linked to the subsurface by a unique overland flow boundary condition approach. In the subsurface, Richard's and Darcy's Equation are combined to simulate variably-saturated and fully saturated flow and are solved using the Finite Difference method. ParFlow employs adaptive time stepping and very robust solver and optimization algorithms, which significantly reduce simulation times compared to constant or fixed time stepping. The code is very modularized which makes it quite amenable to adding new capabilities to the code.

ParFlow was originally built for research applications, particularly in multiphase flow and transport problems. As such, many features that might be considered useful to water resource practitioners (e.g., hydraulic control structures, GUI, integration to GIS) are not currently in the code. However, the code is open source and these features may be incorporated by the hydrologic community to solve particular questions.

ParFlow has a substantial record of model applications that have been published or presented at conferences including Kollet and Maxwell (2006, 2008), Maxwell and Kollet (2008) and Abu-El-Sha'r and Rihani (2006). The authors are not aware of any inter-model reviews that include ParFlow. The model's source code was written in FORTRAN and has been designed to be compiled and applied in a LINUX platform. The model has also been applied in OS X 10.6 and in Windows XP SP3 using virtualization software to run Ubuntu Linux. Porting the model to a different operating system environment would likely require the user to recompile the source code. Although the model was originally intended to be run on supercomputers and mainframes, its current form can be run on desktop environments as well.

The code is freely available to the public as an open source model with a GNU's Not Unix or (GNU) license. Although the model has only recently been released to the public as an open source code, there is a high likelihood that it will continue to be maintained and upgraded due to the number of researchers already using the model. It is unclear what level of technical support is available to users of the code although ParFlow training courses have been offered at a number of recent groundwater conferences. The model is moderately documented (i.e., some of the document chapters could be expanded for better clarity) and can be downloaded from (http://inside.mines.edu/~rmaxwell/maxwell_software.shtml).

2.5 Review of Integrated Model Capabilities

This section provides an evaluation matrix which summarizes the abilities of each of the selected integrated models to represent watershed, groundwater, and river processes as well as additional considerations such as the availability of training and technical support for the models. A very brief description of the criteria used in each element of the evaluation matrix is given below. These descriptions are followed by the evaluation matrix and a discussion of the review results. Note that the study of Weber et al. (2004) was used as a template for the evaluation matrix used in this work.

2.5.1 Watershed Processes

- Rainfall
    - Distributed Rainfall: The model can apply different precipitation values in different regions of the model during the same time step.
    - Radar: The model is able to import and directly utilize precipitation information derived from radar data, or other distributed rainfall sources.
- Snowmelt
    - Temperature Index: Snowmelt processes can be constrained by temperature data.
    - Solar Radiation-based: Snowmelt processes can be constrained by solar radiation data.
    - Sublimation or other evaporative losses: Losses from the snowpack through sublimation or evaporation are considered.
    - Snow Moisture: The model distinguishes between wet and dry portions of the snow pack and therein regulates the release and retention of water in the snow pack.
    - Redistribution: The model can adjust snow melt rates to reflect the non-uniform distribution of snow within the subwatershed (Accumulation along tree lines, ditches).
- Evapotranspiration (ET)
    - Transient Canopy Interception: In addition to implementing basic ET processes, the model is capable of allowing canopy interception values to evolve as a function of time (i.e., using tabulated values input as a time series or by some other means).
    - PET Generation: The model can use meteorological data to generate potential evapotranspiration data (PET).
    - Soil Moisture Limiting ET: Evapotranspiration rates are limited by the available water stored in the soil.
- Overland Flow
    - Depression Storage: The model considers ground surface depressions and their ability to retain precipitation, allowing captured water additional time to infiltrate. Overland runoff is only created

when precipitation falls at a rate greater than the infiltration capacity and depression storage is satisfied.
    - Empirical: The model allows overland flow processes to be calculated using empirical relationships.
    - Physical: The model allows overland flow processes to be calculated using physically-based relationships (usually some form of the St. Venant equations).
    - Subcatchment /Lumped: The model considers the spatial variation of some parameters and variables while others are held constant.
    - Distributed: The model considers the spatial variation of all variables and parameters.
- Seasonal Parameters
    - Frozen Soils: The model can adjust infiltration parameters based on the presence of frozen soil.
    - Evapotranspiration: The model can adjust evapotranspiration parameters (e.g., leaf area index, rooting depth) as a function of time.
    - Surface roughness: The model can adjust surface roughness parameters as a function of time.
- Unsaturated Zone Processes
    - Fully 3D: The model allows soil moisture movement within the unsaturated zone to occur in all three spatial dimensions. Moreover, soil moisture movement calculations are physically-based (i.e., using a 3D variant of Richard's equation). This is the most comprehensive approach for this process but also the most computationally intensive.
    - 1D Vertical: The model considers soil moisture movement only in the vertical direction (i.e., lateral soil moisture movement is assumed to be negligible). Moreover, vertical movement is determined using a physically-based relationship such as the 1D Richards equation. In areas with thick unsaturated materials, this approach (as well as the 1D Lumped approach) may not fully represent the complexity of the unsaturated zones.
    - 1D Lumped: The model considers soil moisture movement in the vertical direction (i.e., lateral soil moisture movement is considered negligible) using a less rigorous approach.
- Groundwater Processes
    - Groundwater Flow Solution
        - Lumped: Flow processes occurring below the water table are determined using a lumped approach such as a linear reservoir. This type of approach treats the saturated zone much like a black box to which sources and sinks are applied.
        - 3D Numerical: Fluid flow processes occurring below the water table are calculated using physically-based equations that consider saturated flow in all three spatial dimensions.
    - Recharge from the unsaturated zone: The model is able to calculate recharge contributions from the unsaturated zone to the saturated zone.
    - Recharge from surface water features: The model is able to calculate recharge contributions from surface water features to the saturated zone.
    - Groundwater Discharge: Groundwater contributions to surface water features including contributions to baseflow, lakes and springs are calculated directly by the model and do not need to be user-defined.
    - Unprescribed seepage boundaries: The model is capable of generating seepage faces automatically without specification by the user.
    - Lenses: The model is capable of simulating geologic lenses, which are discontinuous features of contrasting hydraulic properties found within a geologic layer.
    - Water Budget Calculations and Reporting: The model calculates the contribution of each hydrological component to the total water budget either during each time step or in summary form at the end of the simulation.
    - Water Levels: The model can calculate and report water levels across the surface or distributed within the subsurface (i.e., allows for observation points that report stage height or total hydraulic head as a function of time).
    - Fractures: The model is capable of simulating flow in fractures that are represented as discrete planar features (and solute transport in the case of HydroGeoSphere).
    - Macropores: The model is capable of simulating macropore flow using a dual continuum or some other approach.
- Routing Processes
    - Channel Flow
        - Empirical Routing: The model has the option to determine channel flow contributions using an empirical approach such as the Muskingum routing method.
        - Hydrodynamic: The model has the option to

calculate channel flow contributions using a physically-based approach such as the diffusive wave or kinematic wave equation (or some other simplified variant of the Saint Venant equations).

- o Pipe Flow Open Channel: The model can explicitly simulate 1D open channel flow. This is usually done using some variant of the Manning equation. Note that in the context of this document, open channel pipe flow indicates that the model is able to analyze this process separately from other surface water flows. This is often required to explicitly include the impact that hydraulic control structures have on the rainfall-runoff process. Integrated codes such as HydroGeoSphere and ParFlow conceptualize flow occurring across the land surface as a continuous 2D sheet of water which has larger surface water head values in the stream channels and lakes. As such, channel flow processes in these models are treated as features within a larger continuum and not as discrete entities.
- o Closed Conduit Pipe Flow: The model is capable of simulating closed conduit pipe flow. In the context of this document, consideration of closed conduit pipe flow is limited to surface water features as opposed to subsurface applications such as pumping wells or tile drains.
- o Lakes
  - Hydrodynamic: Flow into, out of and within a lake is calculated by the model using physically-based equations.
  - Empirical Routing: The model is able to treat lake processes empirically where the lake is considered to be a black box reservoir that supply and demand terms are applied to.
- o Flooding
  - Overbank flow considerations: The model is able to simulate overbank flow due to flooding and track the movement and fate of water that has left the flooded channel.
- o Dams/Reservoirs
  - Stage/Discharge Curve: The model is capable of utilizing stage/discharge curves to represent the impact of structures on channel hydraulics.
  - Physical Structure Hydraulics: The model is capable of explicitly simulating the hydraulic effects of structures on channel hydraulics.
  - Control Operations: The model has options that allow the user to specify water movement in and out of hydraulic structures to vary dynamically based on current flow conditions.
- o Other Processes
  - Diversions: The model can simulate open channel surface water diversions into reservoirs, rice paddies, irrigation canals, etc.
  - Outfalls: The model can simulate closed conduit injections from surface water features such as lakes and streams. This feature is usually implemented in integrated codes (or surface water codes) as a source term on the land surface.

- Water Takings
  - o Surface Water: The model can simulate extractions from surface water features such as lakes and streams. This feature is usually implemented in integrated codes (or surface water codes) as a sink term on the land surface.
  - o Groundwater: The model's structure includes the use of extraction or injection wells.
  - o Irrigation-automated: The model contains algorithms to allow it to simulate irrigation processes explicitly, possibly including return flow.
- Water Quality
  - o Solute Transport: The model can simulate solute transport. This is typically accomplished using physically-based advection-dispersion relationships or some related formulation. In the context of this document, the solute is assumed to behave conservatively or have simply-defined decay or transformation properties.
  - o Erosion Processes: The model can simulate in-channel erosion processes.
  - o Sediment + Water Quality: The model can simulate sediment transport and its corresponding impact on water quality.
  - o Temperature: The model can simulate thermal transport processes.
  - o Biological Processes: The model can simulate biological processes affecting water quality.
- Other Considerations
  - o Adaptable Time Step: The model employs adaptive time stepping or another algorithm that does not require a fixed time step size.
  - o Variable grid refinement: The model supports the variable refinement of the model grid around areas of interest (e.g., wellfields).
  - o GIS data support: The model's pre-processor can import, display and assign GIS data directly.
  - o Graphical User Interface (GUI): The model

contains a GUI to aid the user in pre- and post-processing data.
- o Source Code availability: The source code for the model is available.
- o Tech Support available: Technical support for the model is available.
- o Training: The developers or third parties offer short courses to help users become more familiar with the operation of the model.
- o Water Budget Post-processing: The model offers features that allow the user to develop water budget reports.
- o Credibility:
  - Detailed documentation: The model comes with a user's manual and possibly a technical manual.
  - Example and verification problems: The manual and model documentation provide many example and verification problems for the model.
  - Testing: The model has been applied to real systems for validation purposes using measured field data.
  - Independent Peer Review: The model has been independently reviewed by third parties. The model has been examined as part of an inter-model comparison study.
  - Frequently applied outside of development team: The model is commonly used by people not directly associated with the development team.
  - Publication record: The model has a record of applications that have been reported in peer-reviewed technical literature.

2.5.2 Integrated Model Evaluation Matrix

Criteria		HGS	MIKE SHE	MODHMS	GSFLOW	ParFlow
Watershed Processes	**Rainfall**					
	Distributed Rainfall	•	•	•	•	•
	Radar		•			
	Snowmelt					
	Temperature Index		•		•	•
	Solar Radiation - Based		•		•	•
	Sublimation or other evaporative losses		•		•	
	Refreezing		•			5*
	Redistribution		•			5*
	Evapotranspiration					
	PET Generation				•	
	Soil Moisture Limiting ET	•	•	•	•	•
	Transient Canopy Interception	•	•	•	•	•
	Overland Flow					
	Depression Storage	•	•	•		•
	Empirical Routing		•			
	Physical Routing	•	•	•		•
	Subcatchment/Lumped Routing		•			
	Distributed Routing	•	•	•		•
	Seasonal Parameters					
	Frozen Soils					•
	Evapotranspiration	•	•	•	•	•
	Surface Roughness					

	Criteria	HGS	MIKE SHE	MODHMS	GSFLOW	ParFlow
Unsaturated Zone Processes	**Soil Moisture**					
	Fully 3D	•		•		•
	1D Vertical		•		6*	
	1D Lumped		•		6*	
Groundwater Processes	**Groundwater Flow Solution**					
	Lumped		•			
	3D Numerical	•	•	•	•	•
	Recharge from unsaturated zone	•	•	•	•	•
	Recharge from surface water features	•	•	•	•	•
	Groundwater Discharge	•	•	•	•	•
	Unprescribed Seepage Boundaries	•	•	•	•	•
	Geologic Lenses	•	10*	•	•	•
	Water budget calculations and reporting	•	•	•	•	•
	Water levels	•	•	•	•	•
	Fractures	•				
	Macropores	•	•		•	
Surface Water Processes	**Channel flow**					
	Empirical Routing		•		•	
	Hydrodynamic	•	•	•	9*	•
	Pipe flow					
	Open channel		•	•		
	Pressure		•	•		
	Lakes					
	Hydrodynamic	1*	1*	•		5*
	Empirical Routing		•	•	•	
	Flooding					
	Overbank Flow Conditions	•	•	•		•
	Dams/Reservoirs					
	Stage / Discharge Curve		•	•	•	
	Physical Structure Hydraulics		•	•		
	Control Operations		•			
	Other Processes					
	Diversions		•	•	•	
	Outfalls	•	•	•	•	•
Water Takings	Surface Water	•	•	•	•	•
	Groundwater	•	•	•	•	•
	Irrigation - Automated		•			

	Criteria	HGS	MIKE SHE	MODHMS	GSFLOW	ParFlow
Water Quality	Solute Transport	•	2*	•	•	•
	Erosion Processes		3*			
	Sediment Transport					
	Sediment/ Water Quality		3*			
	Temperature	•	3*			•
	Biological Processes		3*			5*
Other	Adaptive time stepping	•	•	•		•
	Variable Grid Refinement	•	11*	•	•	
	GIS Data Support		•	•	4*	
	GUI		•	•	7*	
	Source code availability	•			•	•
	Tech Support Available	•	•	•		
	Training	•	•	•	8*	
	Water Budget Post Processing	•	•	•	•	•
	Credibility					
	Detailed Documentation	•	•	•	•	•
	Testing	•	•	•	•	•
	Many Example/Verification Problems	•		•		
	Independent Peer Review		•			
	Use outside of development team	•	•	•	•	•
	Publication Record	•	•	•		•

*Notes:

1. HydroGeoSphere and MIKE SHE can treat flow to, from and within lakes using the 2D diffusive- wave equation.
2. Although MIKE SHE has solute transport capabilities; these capabilities have not been extensively tested.
3. Erosion, sediment transport, thermal and biological processes accomplished through MIKE SHE linkage to MIKE 11 and or ECO Lab module.
4. GIS support through the USGS program GIS Weasel or PRMS pre-processor, not through GSFLOW directly.
5. Through ParFlow's linkage to CLM (Common Land Model; Dai et al., 2003).
6. The unsaturated zone of GSFLOW is considered in both PRMS and MODFLOW portions of the model. The 'soil zone' within PRMS employs a 1D lumped empirical model, which links to the unsaturated zone of MODFLOW which employs a 1D vertical model.
7. The GUI of GSFLOW is limited to viewing and manipulating basic model set up and some has some output generation. The GUI does not facilitate model input generation or model output analysis.
8. GSFLOW training has been provided by the USGS and is offered to non-USGS staff
9. GSFLOW employs a variant of the kinematic-wave approximation that neglects hydrograph attenuation (diffusion of flood waves is neglected).
10. MIKE SHE automatically averages the conductivity values around the area containing the lens so that the system is easier to solve. The PCG based solver used in MIKE SHE has trouble achieving a stable solution where there is a high hydraulic conductivity contrast between adjacent materials (e.g., a clay lens is embedded in a sand or gravel layer). The more robust groundwater solvers used in models such as HydroGeoSphere and ParFlow are usually able to solve these sort of situations readily and therefore do not implement this lens averaging technique.
11. In the 2011 release of MIKE SHE a sub-gridding option has been added to the overland flow module. This allows for overland flow calculations to be performed at a higher resolution that unsaturated and saturated zone calculations (e.g., 50 m resolution in the overland domain with 200m resolution in the saturated and unsaturated domain).

2.6 Discussion of Integrated Model Review

Not all of the evaluation criteria included above is considered to have equal merit. In addition, many of the criteria were chosen to reflect options that are specific to a particular model. The MIKE SHE model, for example, has the most options, compared to the models presented by far which gives the user flexibily regarding the degree of complexity represented within a given hydrologic process. These options, such as solute transport and soil erosion, were included in the criteria matrix, regardless of importance to Water Budget calculations.

2.6.1 GSFLOW

The main advantage of GSFLOW is that has been developed and will be maintained by the U.S. Geological Survey. GSFLOW is basically a linking of two very well established surface water and groundwater models (PRMS and MODFLOW-2005, respectively). The model is very amenable to customization due to its modular structure and open source code.

Some of the drawbacks of GSFLOW include:

- GSFLOW is a relatively young integrated model compared to the other codes in this review. As such, its use is not as widespread in the hydrologic community. June 2011 saw the release of GSFLOW 1.1.4. The code is evolving relatively quickly as it is further refined and as features are added. Currently, the model does not include all the capabilities of the standalone PRMS and MODFLOW models. A number of the potentially desirable features present in either the PRMS or MODFLOW codes are disabled in GSFLOW (see Table 2 in Markstrom et al., 2008). Examples include overland routing, advanced channel routing and physically-based infiltration algorithms;
- GSFLOW does not support adaptive time stepping, which has negative implications on simulation time. The fixed one-day time steps limit the ability of GSFLOW to represent highly transient processes (e.g., intense rainstorms or overland flow) and may yield an incorrect partitioning of precipitation to overland runoff and infiltration;
- The model is designed to be run on a single processor and cannot currently take advantage of today's multi-core desktop computers to improve run times; and
- The model is limited in its flexibility to represent various hydrological processes at different levels of complexity.

2.6.2 MIKE SHE

The major advantage of the MIKE SHE code is its flexibility; many of the major hydrologic processes can be represented at varying levels of complexity. MIKE SHE also has a very modular structure that allows it to be linked to other codes quite readily (its linkage to MIKE 11 was emphasized in this report but MIKE SHE is amenable to linkage with other models as well through its compliance with the OpenMI standard set in Europe). MIKE SHE can readily import and use data generated for MODFLOW simulations.

Just prior to the release of this report, DHI released the 2011 version of MIKE SHE. This latest release is a significant update over previous versions, and includes support for 64 bit and multi-core processors. These updates have resulted in substantial improvements in model run times.

Some potential drawbacks that need to be considered before choosing MIKE SHE for a given application include:

- The model uses a discretization technique that only allows for uniform, square block elements. This poses two primary problems; 1) For natural systems that are irregularly-shaped (the general case) the grid will be unnecessarily large and contain a number of element blocks that are outside of the area of interest, 2) the grid cannot be refined locally around hydrologically active features like pumping wells or surface water features;
- The model assumes flow in the unsaturated zone only occurs in one dimension (vertical). This assumption may be appropriate in areas where the depth to the water table is significant, particularly in areas with a high degree of vertical heterogeneity. This may lead to difficulties in representing interflow, or other portions of the streamflow regime influenced by horizontal flow in the unsaturated system;
- The number of options available to the user means that the MIKE SHE code may have a steeper learning curve when compared to the other integrated codes. However, it should be noted that all of the integrated models in this review will have rather steep learning

curves when compared to standard surface water or groundwater codes;
- The manner in which the model links the various flow components, explicit coupling, makes it prone to convergence errors in regions where surface water - groundwater interactions are changing rapidly. This is less of a problem as the user gains more experience with the code;
- The source code is proprietary and not available to the public for examination and modification; and
- Purchase price of the code and ongoing service maintenance agreement costs.

2.6.3 HydroGeoSphere (HGS)

The primary advantages of HydroGeoSphere are its implementation of a control volume finite element approach which makes it's numerical meshes more amenable to systems with irregular geometry, while conserving mass and its physically based representation of hydrologic processes and the robust numerical techniques used to couple these processes. A secondary advantage of HydroGeoSphere is its ability to simulated flow and transport through discrete fractures.

Some of the drawbacks of HydroGeoSphere include:

- The model does not include winter processes. Snowmelt is arguably one of the most important hydrological processes in Ontario;
- HydroGeoSphere requires 3rd party software (Tecplot) to visualize most of its output. The model also does not have a GUI to help the user pre-process data for input into a simulation;
- The model is designed to be run on a single processor and cannot currently take advantage of today's multi-core desktop computers (note that a parallelized version of the code is currently being developed);
- The model is not flexible in terms of representing various hydrological processes at different levels of complexity; and
- HydroGeoSphere simulations cannot incorporate hydraulic structures (e.g., dams, weirs, etc.).

2.6.4 MODHMS

This model has a well-designed GUI and is fully compatible with MODFLOW. MODHMS is a finite difference model that supports variable grid resolution and can be used with other MODFLOW packages. Therefore, it can handle small-scale surface water features has a robus set of solvers to choose from (PCG, SOR, SIP, etc), similar to GSFLOW. MODHMS uses adaptive time stepping techniques and an advanced physically-based evapotranspiration module.

Some of the drawbacks of MODHMS include:

- The model does not include winter processes. Snowmelt is arguably one of the most important hydrological processes in Ontario.
- The source code is proprietary and not available to the public for examination or modification;
- The model is not flexible in terms of representing various hydrological processes at different levels of complexity (e.g., representing groundwater flow using a linear reservoir approach when subsurface data is sparse);
- The model is designed to be run on a single processor and cannot currently take advantage of today's multi-core desktop computers to improve run times. Note: July 2011 saw the commercial release of MODHMS 1.0 for purchase and HydroGeoLogic provided a timeline for a multi-core solver to be added to the model in late 2011.

2.6.5 ParFlow

The most advantageous features of ParFlow are modularity and that the model was, from the beginning, designed as a parallelized model that is able to take advantage of modern, multi-core desktop computers. Additionally ParFlow utilizes very robust numerical techniques to decrease simulation times. ParFlow has also been linked to a number of other codes, including two separate atmospheric models that enable ParFlow to simulate the entire hydrological cycle within a single numerical framework.

Some of the drawbacks of ParFlow include:

- ParFlow is primarily a research code that requires 3rd party software (that is also freeware and open source) to visualize most of its output. The model also does not have a GUI to help the user preprocess data for input into a simulation;
- The model is not flexible in terms of representing various hydrological processes at different levels of complexity;

- ParFlow simulations cannot incorporate hydraulic structures (e.g., dams, weirs, etc.).

2.7 Selected Modelling Codes

Based on the evaluation the selected integrated modelling codes GSFLOW, HydroGeoSphere and MIKE SHE were selected for further evaluation in a case study application. MODHMS was not selected for further evaluation because at the time this study was initiated it was not commercially available. It has been subsequently released for purchase in North America in June of 2011. ParFlow was not selected for further evaluation because of the moderate documentation of the model as well as the relative difficulty of application.

3. Case Study - Subwatershed 19 (Credit River Watershed)

While model evaluation matrices are useful for examining the features of specific models, they cannot predict the ease of use expected during development and application of the model in a real case study that is common between them, nor can they verify the results of such case studies. Rigorous model reviews include the application of differing modelling codes for the same watershed. Therefore, three integrated model codes were chosen for a case study for Subwatershed 19 of the Credit River. The selected model codes were; GSFLOW (Markstrom et al., 2008); HydroGeoSphere (Therrien et al., 2009); and MIKE SHE (Graham and Butts, 2005; DHI, 2009a,b). Model development using the three models and the application of the models to assess water resource impacts are discussed in the following section.

3.1 Subwatershed 19 Background

Subwatershed 19 (**Figure 3.1**) is located at the headwaters of the Credit River Watershed and encompasses the Towns of Orangeville, Caledon, Mono and the Township of Amaranth and East Garafraxa. Subwatershed 19 was selected as a case study because it has been well characterized through previous studies including a completed Tier Three Water Budget Assessment and Local Area Risk Assessment (AquaResource, 2011). In that assessment, detailed surface water and groundwater models were constructed and calibrated for the assessment using HSPF and MODFLOW, respectively. A digital elevation map of Subwatershed 19 (**Figure 3.2**) illustrates the topography of the area, with streams in the uplands regions (i.e. the Orangeville Moraine), which converge towards the Credit River.

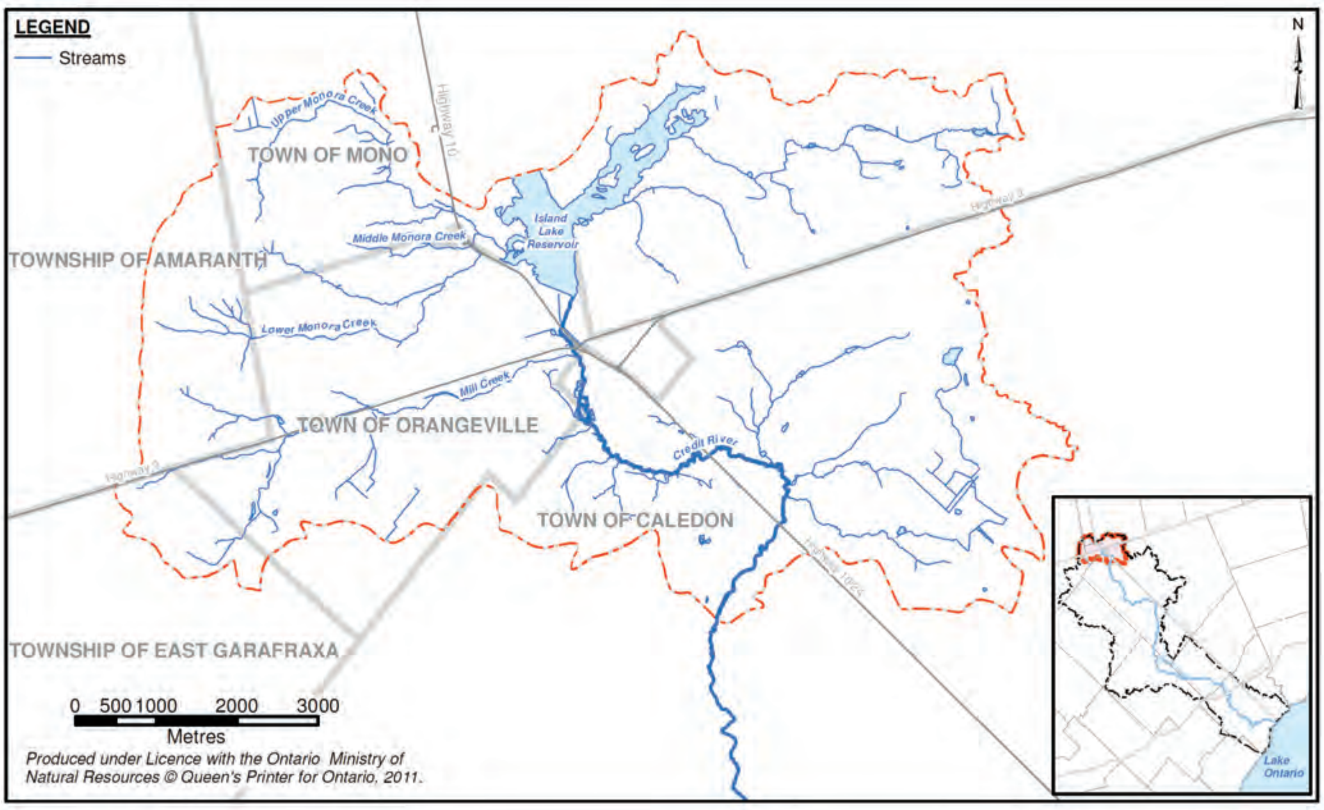

Figure 3.1 Subwatershed 19

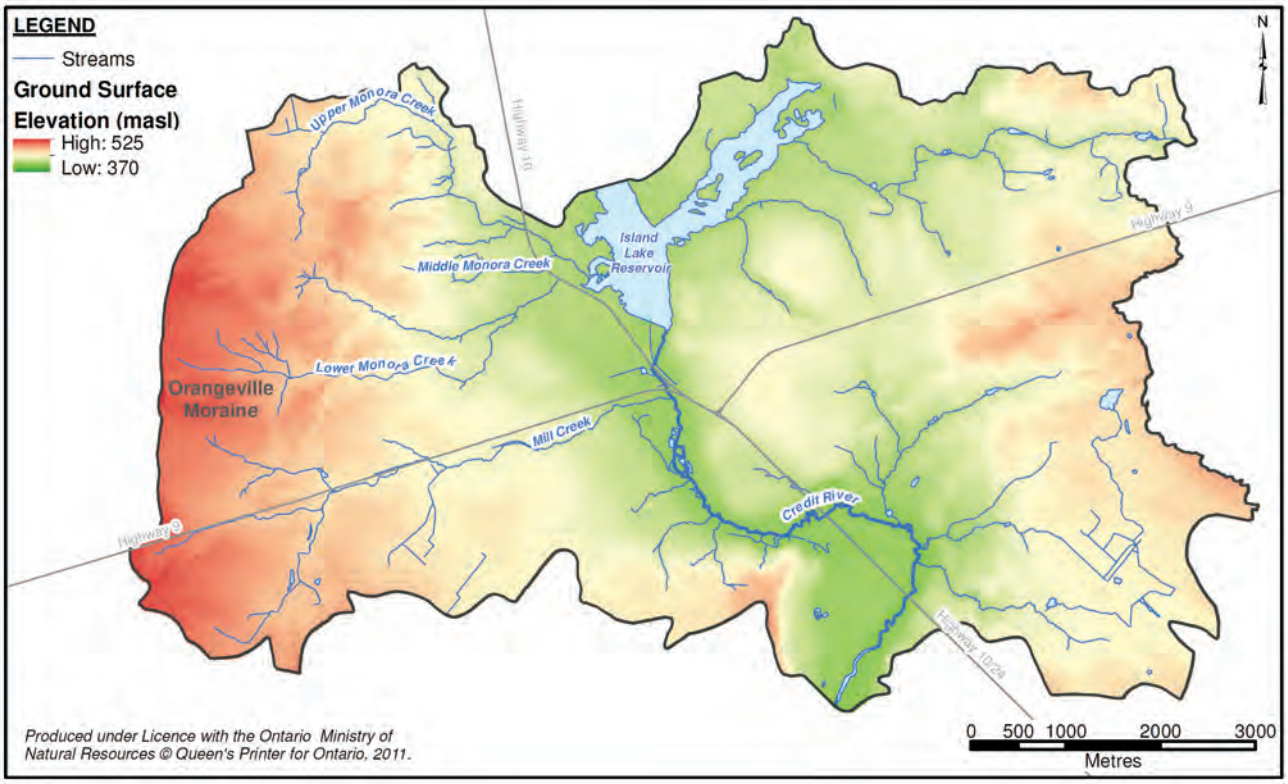

Figure 3.2 Subwatershed 19 Digital Elevation Model

3.1.1 Land use

Land use within Subwatershed 19 includes various natural heritage features (wetlands, greenlands, etc). The urban areas within the town of Orangeville are predominately residential, with some commercial properties. The areas outlying the Town of Orangeville are a mixture of agriculture and forest as well as some aggregate extraction. **Figure 3.3** illustrates the land use within the subwatershed, as mapped in the Tier Three Water Budget Study (AquaResource, 2011a).

3.1.2 Bedrock Geology

Limestone and dolostone bedrock, associated with the Amabel Formation, is the dominant uppermost bedrock unit within Subwatershed 19 (**Figure 3.4**). Bedrock associated with the Clinton-Cataract Group is also present, located along the axis of the Credit River valley. Bedrock outcrops within the subwatershed are minimal, and mainly limited to the Credit River valley in the southern reaches of the subwatershed.

Table 3.1 summarizes each of the bedrock units encountered beneath Subwatershed 19 along with the approximate range of thickness of each bedrock unit.

Table 3.1 Bedrock Geology Underlying Subwatershed 19

Group	Formation	Lithology Description	Approx. Thickness (m)[1]
	Amabel	Eramosa Member: argillaceous dolostone and shale; fine-grained and highly bituminous	10
		Blue-grey thick-bedded dolostone with porous, fossiliferous reefal zones	13 - 40
Cataract	Cabot Head	Maroon to green-grey non-calcareous shale and interbedded dolostone	10 - 39
	Manitoulin	Grey fossiliferous dolostone with thin dark shale interbeds	0 - 25
	Whirlpool	White-tan quartz sandstone with shale seams near the top of the unit	2 - 9

[1] From Johnson et al, 1992

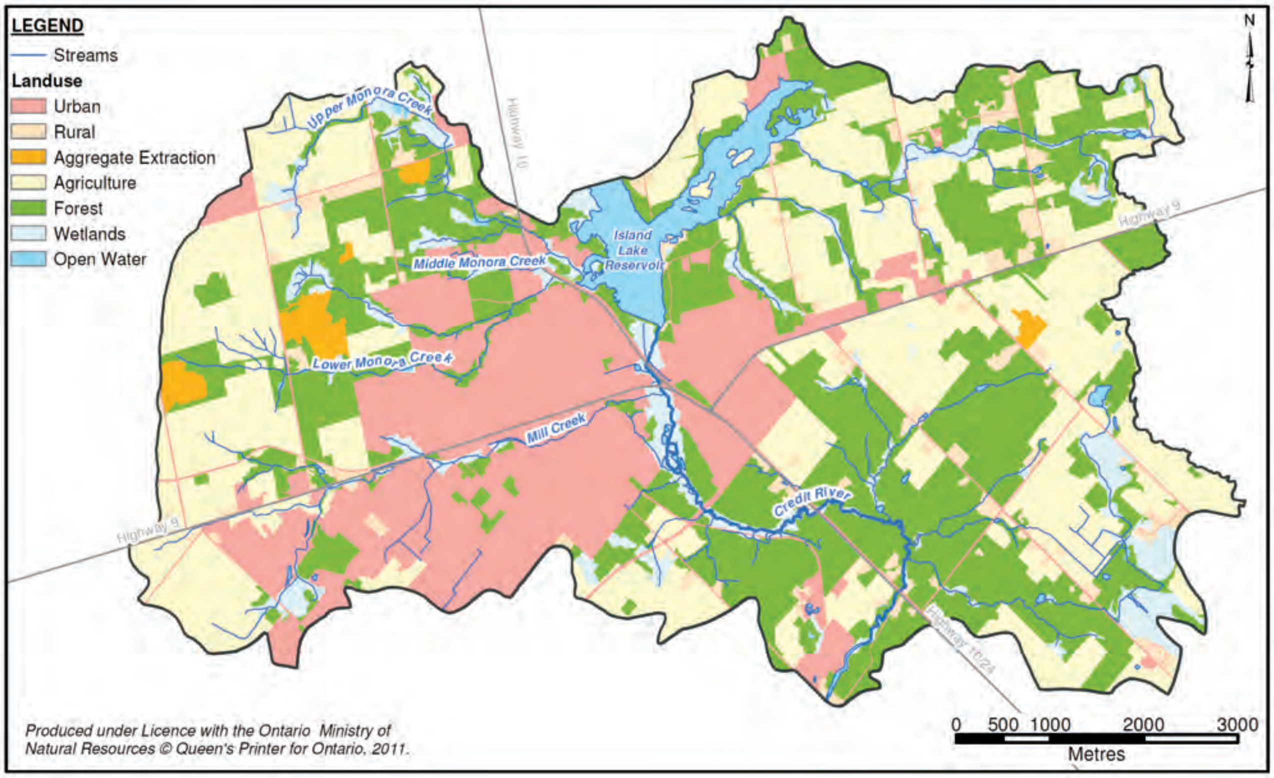

Figure 3.3 Subwatershed 19 Current Land use

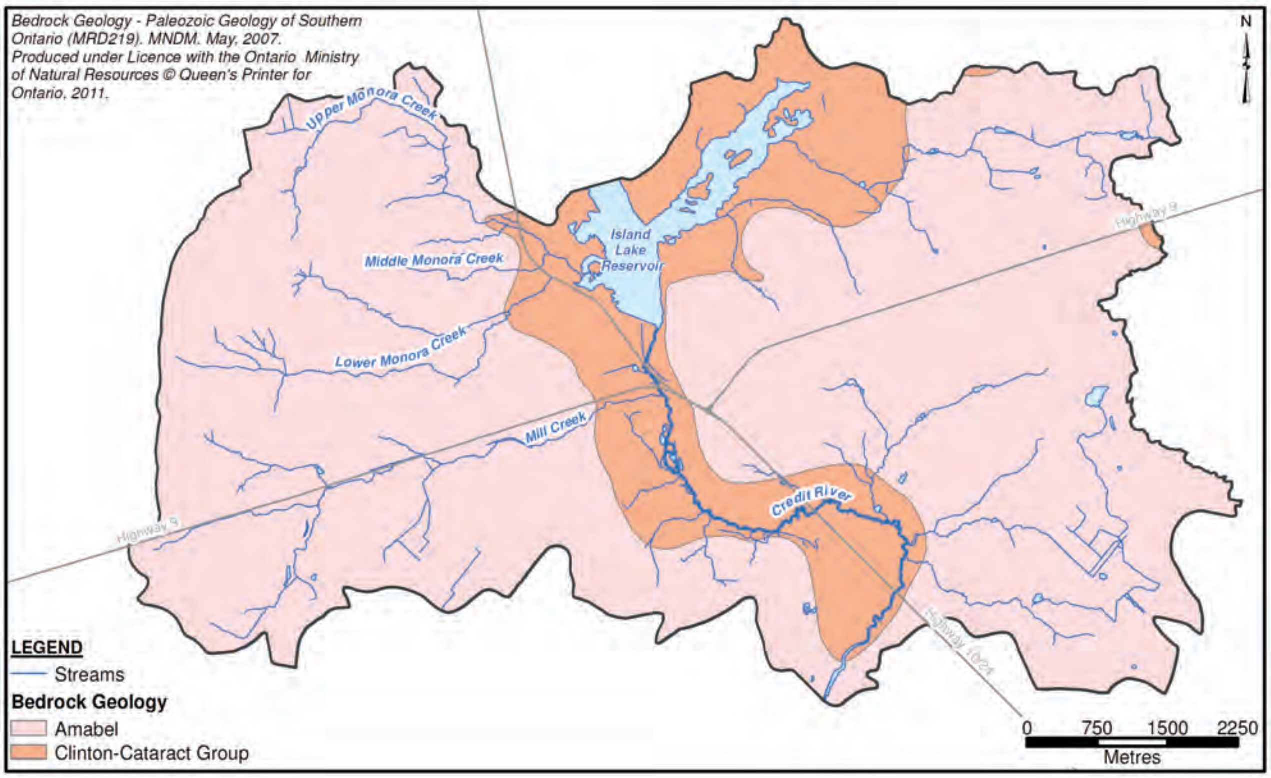

Figure 3.4 Subwatershed 19 Geology

3.1.3 Quaternary Geology

Surficial geology for Subwatershed 19 (**Figure 3.5**) was mapped and compiled by the Ontario Geological Survey (Cowan, 1976; OGS, 2003). Coarse-grained materials associated with ice-contact deposits and glaciofluvial deposits largely dominate Subwatershed 19, with Newmarket, Port Stanley and Tavistock Tills representing the lower permeability materials present. The stratigraphy within the moraine is highly complex due to the variability of glacial processes that were operating within the area at the time of the last glaciation. The resulting deposits, especially within the ice contact environment, are geologically complex and often laterally and vertically discontinuous.

3.1.4 Hydrology

Subwatershed 19 forms the headwaters of the Credit River watershed. The northern portion of the subwatershed contains Upper Monora Creek, Middle Monora Creek and Lower Monora Creek, which all drain into Island Lake Reservoir from the west (**Figure 3.6**). Two unnamed tributaries drain directly into the Island Lake Reservoir from the east.

Outflow from Island Lake Reservoir at the South Dam marks the start of the Credit River. Mill Creek joins the Credit River downstream of the South Dam where the river continues to flow in a southward direction. At the southern end of the subwatershed near Melville, three additional unnamed tributaries located within the Town of Caledon empty into the Credit River. The outlet of the Subwatershed 19 is the Melville Dam.

3.1.5 Hydrogeology

Subwatershed 19 contains both overburden and bedrock aquifers that are utilized for both municipal and domestic water supply. Overburden aquifers tend to be localized in nature and do not extend across the entire Subwatershed. Conversely, fractured-bedrock aquifers, such as the Amabel Formation, are more regional in scale.

Overburden aquifers in Subwatershed 19 include aquifers associated with ice contact deposits, and similar coarse-grained sediments (**Figure 3.5**). These deposits

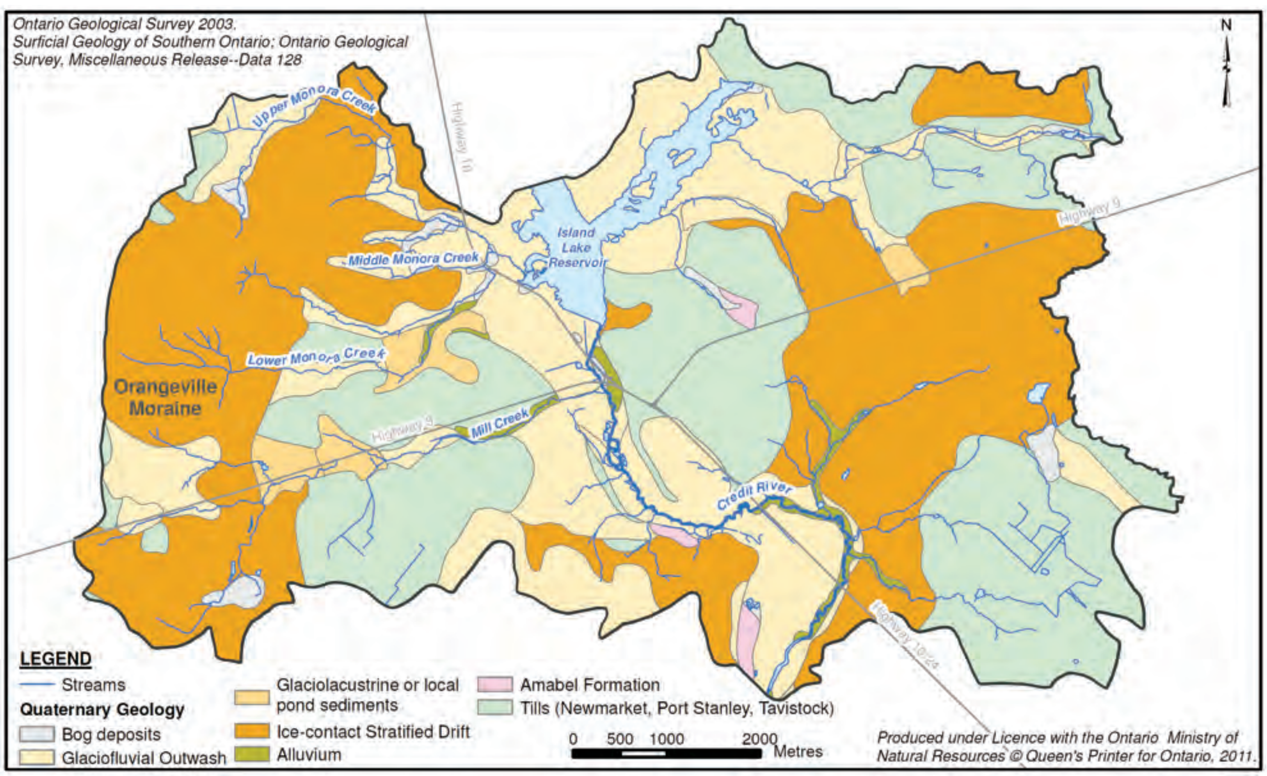

Figure 3.5 Subwatershed 19 Quaternary Geology

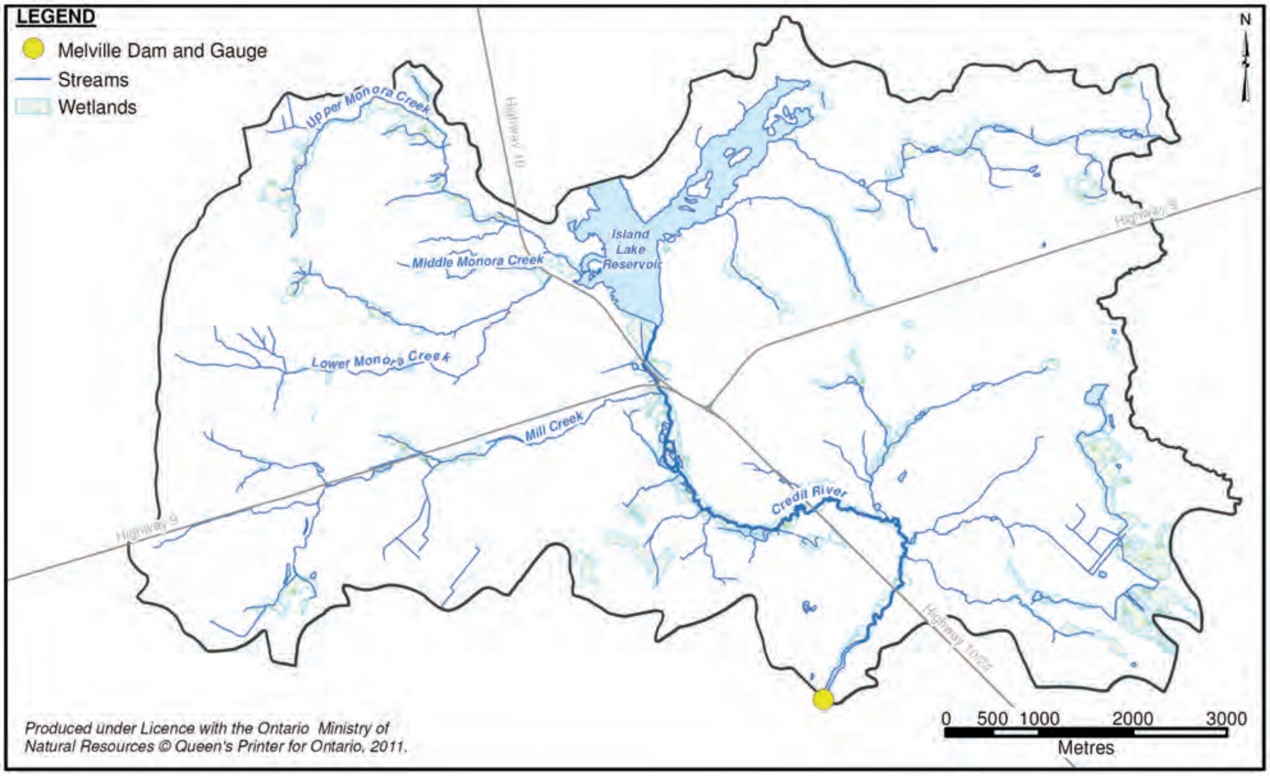

Figure 3.6 Subwatershed 19 Virtual Drainage

create a complex aquifer system within the central portions of Subwatershed 19 (e.g., Orangeville Moraine), and in some areas, the ice contact sands and gravels are in direct contact with the underlying bedrock aquifers (Amabel Formation), leading to thick highly transmissive aquifers.

The carbonate bedrock formations in Subwatershed 19 are highly productive bedrock aquifers. The transmissivity of a bedrock aquifer is highly dependent upon the degree of local fracturing and/or secondary porosity features. The Amabel Formation is reported to have extensive fracturing and secondary porosity features such as solution-enhanced cavities and vugs that increase the transmissivity of the formation (Singer et al., 2003).

3.1.6 Municipal Water Use

The Towns of Orangeville and Mono rely on groundwater for all their drinking water supplies. Most of the water supply wells are completed in the bedrock aquifer referred to as the Guelph-Amabel Formation aquifer; however, a few wells are completed in coarse-grained overburden aquifers. **Figure 3.7** shows the locations of the water supply wells for the two Towns. The 2008 average daily demand within the subwatershed is approximately 6500 m^3/d.

3.2 Existing Models

Calibrated surface and groundwater models have been developed for Subwatershed 19. These models serve as a useful starting point for the development of an integrated model, and are introduced in the following sections. For a full description of the models, please refer to Orangeville Tier Three Water Budget and Local Area Risk Assessment (AquaResource, 2011a).

3.2.1 HSPF

For the Tier Three study, a continuous hydrologic model was applied to estimate groundwater recharge. An existing HSPF surface water model had been constructed and calibrated for the Credit Valley watershed for the Credit Valley Conservation Authority

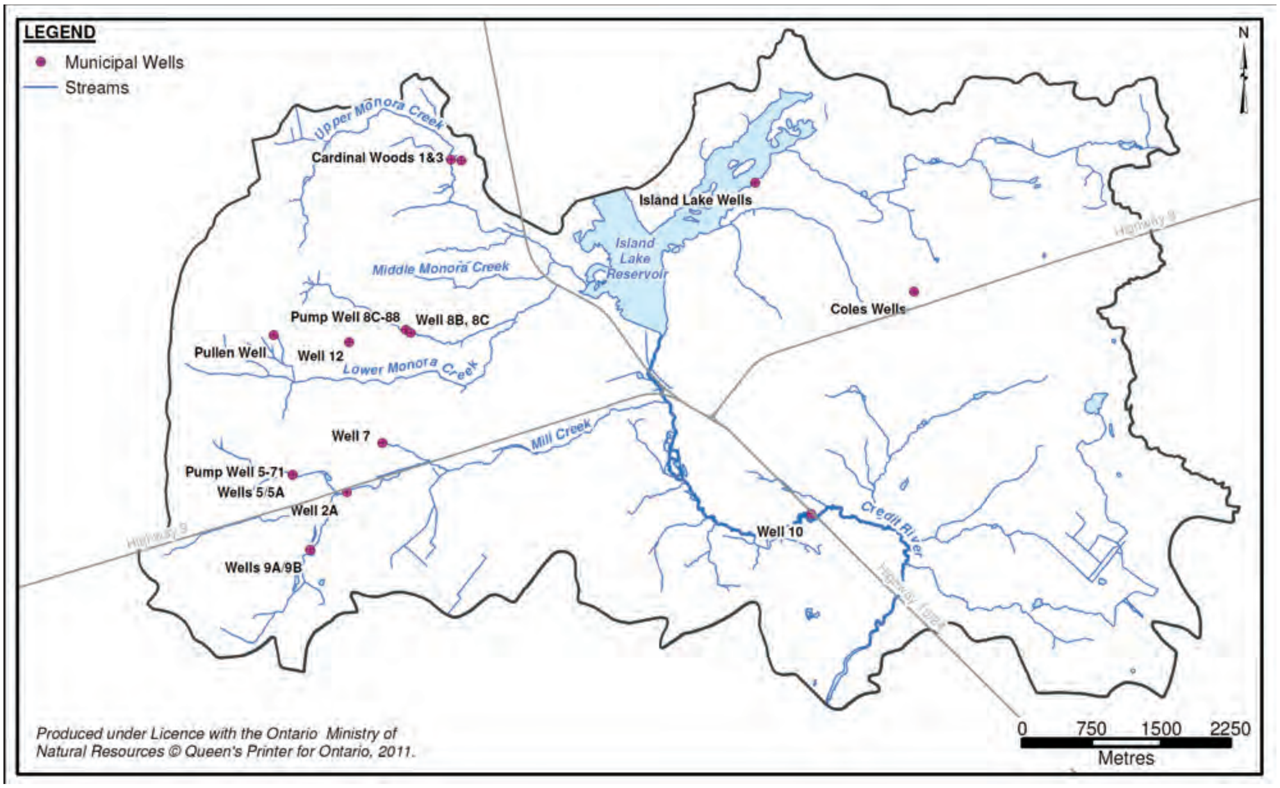

Figure 3.7 Subwatershed 19 Municipal Wells

(CVCA) and was applied for the Tier 2 Water Budget assessment for the Credit, Toronto Region and Central Lake Ontario Drinking Water Source Protection Region. This model was updated and significantly refined for the Tier Three study, with more detailed considerations of hydrologic features within the region.

As with most surface water models, groundwater processes are represented in a relatively simplistic fashion, using a linear reservoir approach. Feedback from the groundwater flow model (e.g., interbasin flow) was manually specified within HSPF.

3.2.2 MODFLOW

As part of the Tier Three study, a detailed 3D groundwater flow model was developed, with a focus on detailed hydrogeologic characterization around each well field. The Tier Three groundwater model was developed using extensive local hydrogeologic data and characterization. The model was calibrated with water level monitoring data collected from the Town of Orangeville's monitoring wells and a long-term pumping test carried out by the Town of Orangeville involving the Transmetro (Well 12), Dudgeon (Well 8C) and Pullen wells. The hydrogeologic representation implemented in the model is described in **Table 3.2**.

Table 3.2 Orangeville Tier Three MODFLOW Saturated Zone Layers

Model Layer	Orangeville Tier Three Model
1	Surficial sands and gravels, clays/ silts/ alluvium, meltwater channel deposits, Newmarket Till (NE), Singhampton Moraine
1	Orangeville Moraine, Spillway/ Outwash Sand Deposits
2	Port Stanley Till, Tavistock Till, unnamed till
3	Catfish Creek Till and coarse grained buried bedrock valley infill sediments
3	Basal aquifer/ bedrock valley infill
4	Weathered Bedrock
5	Guelph Formation
6	Eramosa Member of Amabel Formation
7	Amabel Formation
8	Clinton- Cataract Group
9	Queenston Formation

3.3 Development of Integrated Models

To provide a rigorous review of the three selected integrated codes (MIKE SHE - Section 3.4, GSFLOW - Section 3.5 and HydroGeoSphere - Section 3.6), a model of Subwatershed 19 was developed for each one. The following sections document the experiences and challenges encountered during the setup and development of each model.

3.4 MIKE SHE

The MIKE SHE model developed for this review includes all land areas within the Subwatershed 19 boundary. The model domain is approximately 60 km^2 in area, and was discretized into 50 m by 50 m grid cells for modelling purposes.

The simulation period used for this model is September 1989 to December 1999, while model results are only evaluated for the period from January 1990 to December 1999. The four months prior to January 1990 are included in the simulation period to allow the model a sufficient period of time to adjust from the assumed initial conditions and reach a dynamic equilibrium with the simulated processes and responses (i.e., a "spin-up" period).

3.4.1 Input Data

Climate Data

As with any hydrologic model, climate data is a critical input. Climate data from the Orangeville MOE Environment Canada climate station (AES ID# 6155790) was used to represent the climate for the entirety of Subwatershed 19. This dataset was included in the MNR Ontario In-Filled Climate Data (Land Information Ontario, 2008), and therefore has a continuous period of record from 1950-2005. Available data fields are maximum/minimum daily temperature, daily rainfall, snowfall and total precipitation, as well as hourly rainfall. Hourly precipitation estimates were generated by evenly distributing daily snowfall estimates across the hours of the day and adding them to hourly rainfall data. An hourly temperature series was derived from the daily temperature observations. Hourly temperatures are based on the average of the observed maximum and minimum temperature. Temperature varies about this mean in a sine curve, which assumes a maximum temperature at 3 PM and a minimum temperature at 3 AM.

Daily potential evapotranspiration rates were generated by Jensen potential evapotranspiration method (Jensen & Haise, 1963). This method considers daily temperature maximum and minimum as well as daily solar radiation to compute an estimate of potential evapotranspiration.

Land Surface Data

To represent the hydrology of an area, datasets are required to describe the composition and characteristics of the land surface. These datasets include: topography; land use/cover and associated values of overland roughness, depression storage, vegetation properties; and surficial geology or soils. The required datasets are discussed below.

Digital Elevation Model

Information related to the topography of the watershed is specified through use of a Digital Elevation Model (DEM). DEMs are grids, typically with uniform discretization, that provide the average ground surface elevation within grid cell. DEMs describe the ground surface elevation variation throughout the watershed, which affects a wide range of hydrologic processes. A 5 m DEM is available for Subwatershed 19. This data set was interpolated to the final modelled resolution of 50 m within MIKE SHE.

Land use

Land use is used within hydrologic models to consider the effects of the land surface on hydrologic processes such as overland flow, infiltration, evapotranspiration and unsaturated soil zone processes. The land use mapping shown in **Figure 3.3** was imported into MIKE SHE at a 50 m grid resolution. The grouped land classes utilized in the MIKE SHE model are included in **Table 3.3**.

Table 3.3 Generalized Land use Classes

Category	Description
1	Urban
2	Unknown agriculture
3	Coniferous woodland
4	Swamp forest
5	Cultural plant
6	Deciduous woodland
7	Intensive agriculture
8	Manicured open space
9	Wetland
10	Mixed woodland
11	Non-intensive agriculture
12	Rural development
13	Open water

A spatial distribution defining detention storage was generated on the basis of urban and non-urban land classes. Detention storage is the amount of precipitation that is stored on the ground surface in small depressions, before overland runoff occurs. A value of 2.5 mm was used for urban land classes and 10 mm for non-urban land classes. Literature values for depression storage were used for initial values and were adjusted during the calibration process by matching overland flow contributions to streamflow (Chin, 2006).

Based on the generalized land use categories shown in **Table 3.3**, a spatial distribution of overland roughness was generated (**Table 3.4**). No site-specific coefficients were available, so standard literature values and previous modelling experience from other watersheds were used as the basis for determining the initial coefficient values for each land cover category (McCuen, 2004). These coefficients were then adjusted during the calibration process.

Table 3.4 MIKE SHE Land use Classes

Description	Surface Roughness (Manning's n)
Urban	0.06
Unknown agriculture	0.12
Coniferous woodland	0.71
Swamp forest	0.20
Cultural plant	0.09
Deciduous woodland	0.67
Intensive agriculture	0.36
Manicured open space	0.04
Wetland	0.30
Mixed woodland	0.69
Non-intensive agriculture	0.37
Rural development	0.07
Open water	0.06

Land use data are also used to generate vegetation-specific datasets, specifically the leaf area index (LAI) and the rooting depth. LAI is defined as the ratio of the area of leaves to the area of ground and can vary between 0 and 7 depending on the vegetation type (DHI, 2009b). LAI has significant seasonal variation, and it normally reaches a lower limit during winter time and an upper limit during summer time with full leaf cover. For the coniferous forest land class, LAI remains relatively constant during a year. No specific information is available for LAI in Subwatershed 19, thus values from scientific literature (Scurlock et al., 2001) and professional judgement were used in the model.

MIKE SHE utilizes a rooting depth parameter to represent the maximum depth of vegetation roots. Significant seasonal variations in the rooting depth are typical for annual and deciduous plants, whereas for many perennial and evergreen plants, rooting depth values remain relatively constant throughout the year. The primary function of the rooting depth specification in MIKE SHE is in establishing the depth to which plants can remove water from the subsurface for transpiration. Specific rooting depth values were not available for Subwatershed 19, therefore the values used in the model represent literature values for similar vegetation, climate, and soil conditions (Schenk and Jackson, 2003).

Surficial Geology

The materials present at the ground surface of a watershed play a critical role in partitioning precipitation into runoff and infiltration. To represent these materials, either soils or surficial geology mapping is used in hydrologic investigations. For the Subwatershed 19 MIKE SHE model, surficial geology mapping was used. Surficial geology (1:50,000 OGS seamless) was selected due to the availability of a seamless digital coverage for Subwatershed 19, and is shown in **Figure 3.5**.

Rather than simulating all surficial geology types included in the available OGS mapping, the various geology types were categorized into eight major groups. The response to a precipitation event is assumed to be similar within each group. The groupings are summarized in **Table 3.5**.

Table 3.5 MIKE SHE Simplified Geology Groupings

	Simplified Geology Groupings
1	Diamicton-Sandy Silty Till
2	Paleozoic Bedrock
3	Mixed-Silt, Sand and Gravel
4	Organic Deposits
5	Mixed-sand, gravel
6	Mixed-clay, silt
7	Sand
8	Water

The simplified surficial geology mapping was translated to a grid at a 50 m resolution and imported into MIKE SHE. The required model input parameters for each soil type include the soil moisture content at full saturation, field capacity, wilting point, as well as saturated hydraulic conductivity. Soil properties were taken from literature values based on material description and adjusted during model calibration.

Stream Network

MIKE SHE relies on the MIKE 11 hydraulic model to represent the stream network. The MIKE SHE/ MIKE 11 linkage uses a two-way exchange to collect overland flow, calculate exchange flux between the surface and groundwater systems, and route streamflow downstream. The stream network included in the Subswatershed 19 model was based on the CVC virtual drainage shapefile, and included the major rivers and tributaries. In total, 18 branches are included, and are shown in **Figure 3.8**.

In the MIKE-11 model, hydrodynamic calculations were performed for all included rivers and tributaries. Cross sectional geometry data are required for all hydrodynamic branches where water level is computed by the model. For the majority of the stream network, a simple representative trapezoidal cross section based on stream order, average width and depth was constructed. For branches where complex wetlands are present, cross sections were extracted from the 5 m DEM in order to capture the conveyance of those complexes. In total, 105 cross sections were used in the model.

The southern dam of Island Lake was simulated as a weir within this model. A stage-discharge curve was applied to specify outflow from the lake. A point-source boundary condition was used to simulate the waste water plant discharge into the Credit River.

Subsurface Data

To simulate the groundwater flow system, the properties of the subsurface materials (e.g., hydrostratigraphic layer elevations, hydraulic conductivity distributions) must be specified. As with all other models in this review, all saturated zone properties for the MIKE SHE Subwatershed 19 model were directly taken from the Orangeville Tier 3 MODFLOW model (see Existing Models - Section 3.2). This includes layer elevations,

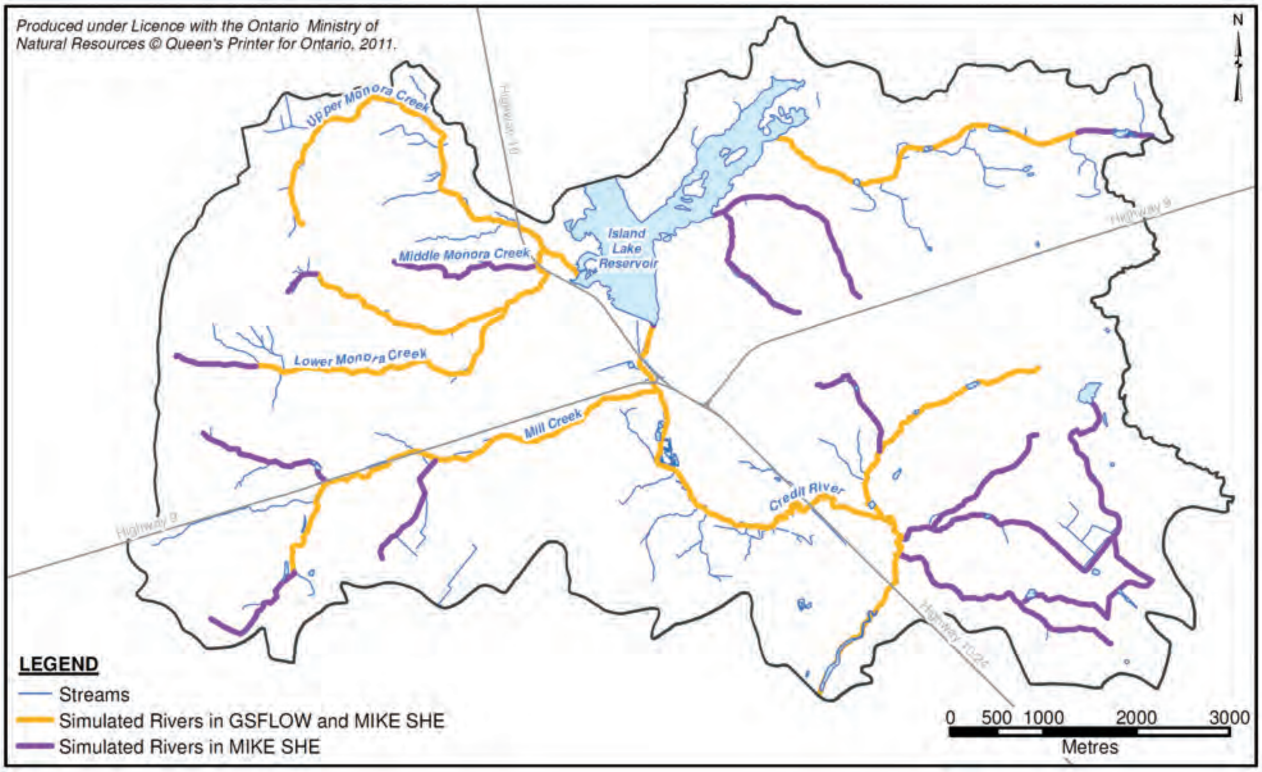

Figure 3.8 Subwatershed 19 Modelled Rivers

hydraulic conductivities, specific storage and specific yield values. Groundwater withdrawals including, location, quantities and screen elevation were also taken from the Orangeville Tier Three Model and used to specify groundwater takings. There are no surface water takings but if there were they would be similarly incorporated into the MIKE 11 model.

To specify initial groundwater heads and external boundary conditions for the MIKE SHE model, groundwater heads were calculated from the steady-state groundwater model. These heads were used as the initial groundwater heads within the model domain and to define fixed-head boundary conditions around the boundaries of the model domain.

3.4.2 Hydrologic Processes

The following section describes the hydrologic processes and approximations utilized in the MIKE SHE model as implemented for this case study. Explanations of these processes are derived primarily from MIKE SHE documentation (DHI, 2009a; DHI, 2009b).

Snow Melt

Snow melt and accumulation is controlled using a degree-day process. The daily temperature variation of the subwatershed is provided using a temperature time series. Freezing or melting of water occurs when the temperature is above or below a threshold temperature. The rate at which snow melt occurs is controlled by a degree-day coefficient (units: mm snow/ day * °C). This parameter can vary spatially and temporally. This coefficient is used often as a calibration parameter to calibrate the snow melt volumes and timing to observed spring runoff. If sufficient snow course data is available, it can be used to calibrate the temporal and spatial variability of the degree-day coefficient. The wet and dry portions of the snow pack also further regulates snow melt. A spatially variable snow melt fraction parameter defines the maximum wet snow fraction. Liquid water is released from the snow pack only when the fraction of wet snow within the snow pack exceeds a threshold value. As with the degree day coefficient, this parameter is adjusted to calibrate to observed snow melt runoff. Snow course data, if available, can also be used to calibrate this parameter.

Overland Runoff

When liquid precipitation reaches the ground surface at a rate faster than the infiltration rate of a grid cell, and the available depression storage is exceeded, overland runoff is generated. Overland flow can also be generated by the water table reaching ground surface and exfiltrating water, which subsequently becomes overland runoff.

The velocity and magnitude of overland flow in the Subwatershed 19 MIKE SHE model is simulated through a diffusive wave approximation of the Saint Venant equations. Numerically, this method is implemented through a 2D finite difference method, and determines which grid cell receives overland runoff generated in an adjacent cell. The amount of overland flow generated and its path are governed by surface topology, depression storage, and surface roughness. Overland runoff can also be reduced due to losses associated with evaporation and infiltration in adjacent cells.

The Subwatershed 19 model also considers overland runoff generated from those grid cells that have impervious land covers associated with them. Land covers which have some portion of impervious land are typically urbanized areas, where the prevalence of asphalt or concrete pavement reduces the land area that can infiltrate precipitation.

Imperviousness in MIKE SHE is handled through a mass balance approach. A paved runoff coefficient is specified for each model cell to represent the fraction of precipitation, after canopy interception, which is directed to streams. The water removed through paved runoff is added directly and immediately to adjacent river cells. This approach assumes that the time of travel for this water to the stream would be less than the time step of the overland processes. The abstraction of water for paved runoff can occur before or after depression storage is considered, depending on model configuration. In the Subwatershed 19 model, abstraction of paved runoff is considered before accounting for depression storage. Values for paved runoff coefficients were derived from scientific literature regarding impervious areas in land use types and adjusted during calibration to match the overland flow portion of streamflow (Sullivan et al., 1978).

Evapotranspiration

Evapotranspiration is represented in the Subwatershed 19 MIKE SHE model using a two-layer water balance model which considers interception, ponding and evapotranspiration. Actual evapotranspiration is computed considering the vegetation parameters and a specified daily potential evapotranspiration rate. In the Subwatershed 19 model, vegetation parameters were assigned to the land cover dataset to specify the leaf area index and the rooting depth. The model attempts to meet the potential evapotranspiration rate through consideration of water availability in the various phases of the hydrologic cycle in the following order:

- Accumulated Snow (if present, through evaporation or sublimation);
- Canopy Interception (through evaporation);
- Ponded Water (through evaporation);
- Unsaturated Zone (through transpiration); and
- Saturated Zone (if water levels extend to the vegetative root zone).

Once all water content in a storage element is evaporated, no further evaporation occurs from that storage element until it is replenished by a precipitation event , overland runoff or though ground water flow.

Unsaturated Zone

The unsaturated zone in Subwatershed 19 is represented using the two-layer water balance method. This considers an upper layer of the unsaturated zone which extends from the ground surface to the top of the capillary fringe and a lower layer which extends from evapotranspiration extinction depth (the maximum root depth + capillary fringe thickness) to the water table. In areas where the water table is above the evapotranspiration extinction depth, there is only one layer. Water that is accessible to vegetation for evapotranspiration is defined by the amount of soil-water content contained within the rooting zone. The soils of the unsaturated zone are described with a spatial distribution and are characterized by a hydraulic conductivity parameter, soil-water parameters (wilting point, field capacity, saturation point) and suction head. Infiltration to the unsaturated zone is calculated using the Green and Ampt method. Limiting factors for infiltration are the soil hydraulic conductivity and the suction head. Soil-water content of the unsaturated zone is maintained on a mass balance basis. When the soil-water content of the unsaturated zone exceeds field capacity, water drains to the saturated zone (percolation). When soil-water content is below field capacity, percolation ceases, with further reductions in soil-water content occurring through evapotranspiration. The Green and Ampt infiltration equation modifies the infiltration rate to account for changes in soil moisture, and when net precipitation falls at a rate faster than the infiltration rate, overland runoff is generated.

Interflow is simulated in MIKE SHE through a head-dependent boundary condition in the saturated zone. Interflow is generated when the water table is above the drain level, a depth below ground surface. The volume of interflow generated is dependent on the water table height above the drain level and a drain time constant. If the water table is below the drain level, no interflow occurs. The drain time constant and depth are calibration parameters which are calibrated to approximate the volume of interflow in streamflow observations.

Channel Flow

The Subwatershed 19 MIKE SHE model is linked to MIKE 11 to simulate flow accumulation and routing to downstream reaches. Channel flow in the Subwatershed 19 model is simulated using a 1D fully dynamic approximation to the St. Venant equation.

Groundwater Flow

Groundwater flow in the Subwatershed 19 MIKE model is represented using the 3D finite difference approach. This approach is very similar to MODFLOW, with the MIKE SHE model using the hydrostratigraphic layer structure and hydraulic conductivity distributions from the Tier Three MODFLOW model.

Summary of Hydrologic Processes

The hydrologic processes represented in and used by the MIKE SHE Subwatershed 19 model are summarized in **Table 3.6**.

Table 3.6 Subwatershed 19 MIKE SHE Process Approximations

Hydrologic Process	Process Approximation
Overland Flow	2D - Diffusive Wave Approximation of the St. Venant equations of flow.
Channel Flow	1D - Fully Dynamic Wave Approximation of the St. Venant equations of flow.
Evapotranspiration	A two-layer water balance model, which applies a simple mass balance approach to predicting ET.
Unsaturated Zone	A 1D, two-layer water balance model. Infiltration based on soil-water content parameters as well as soil conductivity and suction head.
Saturated Zone	3D Finite Difference implementation of Darcy's equation.
Time step	Independent time steps for different hydrologic processes[a]. Time step length is adaptive to dynamics of processes. Small time steps (hourly or finer) for the unsaturated zone, overland and channel flow. Larger time steps for saturated zone.

[a]MIKE SHE hydrologic processes are explicitly coupled such that each process (channel flow, saturated flow etc) can solve with a time step appropriate to the process. Further adaptive time stepping is applied to determine an appropriate time step in each hydrologic process. Time step size is adjusted in accordance with the intensity and duration of hydrologic events. When conditions are changing rapidly within the model, shorter time steps are utilized to capture these processes more accurately. When conditions are relatively stable, large time steps are employed to reduce computational time. MIKE-11 supports both adaptive and fixed time step options.

3.4.3 Numerical Simulation

Average simulation time for the MIKE SHE model is presented in **Table 3.7**. Simulation time is expressed as hours per year of simulated time, and must be considered in light of the spatial and temporal resolution of the model, the size of the model domain, the numerical implementation of the hydrologic processes (e.g., simple empirical processes vs. complex physically based processes) and the computing resources utilized.

Table 3.7 - MIKE SHE Simulation Time

Model Domain Size (km^2)	59.8
Model Elements	247, 510 Finite difference cells - 50 m resolution
Simulation Computer	Intel Core i7 920 (2.67 GHz - Quad-Core)[a], 12 GB RAM, OS: Windows XP Pro x64 Edition Service Pack 2
Simulation Time step	Adaptive & Process Dependent (1 minute ≤ Time step ≤ 12 hours) [b]
Simulation Time (hours / year simulated)	≈1

[a]- While executed on a multi-core computer, the model does not support multi-core execution in the 2009 release of the software. The 2011 release provides support for multi-core processors and the parallelization of many hydrologic processes.
[b]- MIKE SHE utilizes adaptive time stepping to use smaller time steps when conditions are changing quickly, and larger time steps when conditions are stable. Time steps are also variable for different processes. See Table 3.6 for further discussion.

3.4.4 Water Budget

The average annual water budget produced by MIKE SHE is presented in **Table 3.8**. This table shows that on an average annual basis, 880 mm/year of precipitation is received across Subwatershed 19. From that precipitation, approximately 550 mm is lost to evapotranspiration, and just over 200 mm becomes groundwater recharge. Approximately 250 mm of streamflow is generated from Subwatershed 19, with approximately 70 mm of water leaving Subwatershed 19 through groundwater outflows.

Table 3.8 MIKE SHE Water Budget

Period	Precipitation	Evapo-transpiration	Groundwater Recharge	Streamflow	Groundwater Outflow	Pumping	Storage Change
	(mm/yr)						
1990-1999	880	546	205	253	68	36[a]	-22

[a]- Note that pumping is lower than prescribed rate due to certain wells turning off during simulation due to water level fluctuations.

The water balance was evaluated on the external boundaries of the model (**Equation 3.1**). Groundwater recharge occurs across and internal model boundary and is thus neglected in this balance and all terms are in units of mm/year. MIKE SHE reported a 1 mm/year error term.

Equation 3.1: MIKE SHE Water Balance

$$\Delta S = P - ET - Q_{SW} - Q_{GW} - PU + E$$
$$\Delta S = 880 - 546 - 253 - 68 - 36 + 1$$
$$\therefore \Delta S = -22 \frac{mm}{year}$$

ΔS - Change in Storage
P - Precipitation
ET - Evapotranspiration
Q_{SW} - Streamflow or Surface Water Flow
Q_{GW} - Groundwater flow
PU - Pumping
E - Error

The predicted spatial distribution of average annual evapotranspiration is presented in **Figure 3.9**. Estimated average annual evapotranspiration rates range from less than 400 mm/yr to more than 700 mm/yr. Generally, upland areas have estimated

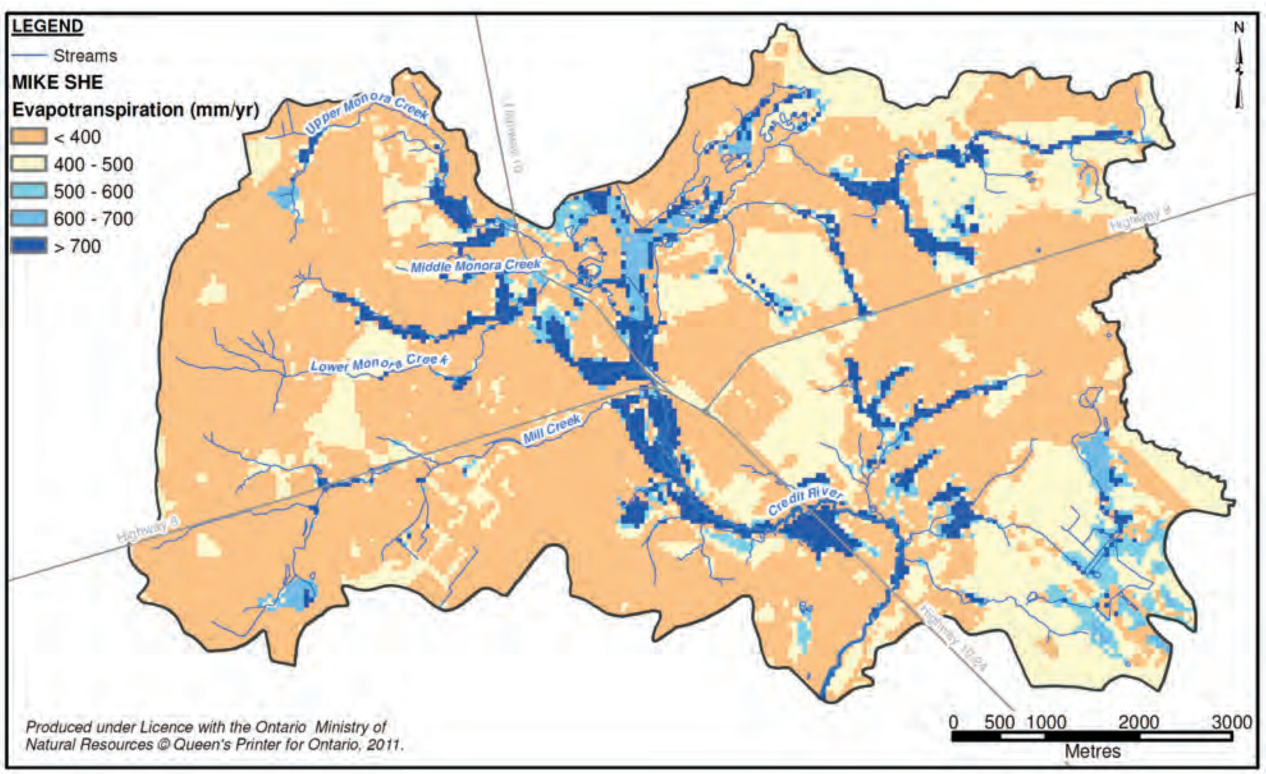

Figure 3.9 MIKE SHE - Subwatershed 19 Average Annual Evapotranspiration

evapotranspiration rates of 400-500 mm/yr, while the river floodplains and wetlands have rates greater than 700 mm/yr. Floodplains and wetlands are able to sustain higher than average evapotranspiration rates because they are discharge areas for the groundwater system. As the vegetative root zones in these areas are constantly being supplied by water from the groundwater system, evapotranspiration is not limited by water availability, which results in high evapotranspiration rates.

Figure 3.10 displays the spatial distribution of predicted groundwater recharge across Subwatershed 19. Groundwater recharge estimates range from less than 100 mm/yr to greater than 400 mm/yr. The impact of the Orangeville urban area is evident by the area of reduced recharge in the central portion of Subwatershed 19. Areas of reduced recharge are predicted alongside stream corridors, where the proximity of the water table to ground surface is limiting the downward movement of water. In these areas, upward gradients are promoting precipitation to be converted to overland runoff rather than infiltration, resulting in reduced groundwater recharge.

Figure 3.11 displays the average annual groundwater discharge predicted by the MIKE SHE model. As would be expected, the majority of groundwater discharge occurs in proximity to watercourses. Large amounts of groundwater discharge are predicted on the main branch of the Credit River, the Lower Monora Creek, the lower reaches of Upper Monora Creek, and on the upper reaches of Mill Creek. The areas of groundwater discharge typically relate to areas of higher evapotranspiration (**Figure 3.9**) and lowered groundwater recharge (**Figure 3.10**).

3.4.5 Modelling Experience

The modelling team found one of MIKE SHE's primary advantages to be a well-developed graphical user interface that strongly aids in model construction, debugging and calibration phases as well as ongoing pre and post processing of model data during these phases. The ability to import input data as GIS surfaces or shape files directly into the model greatly expedites the model construction phase and reduces the possibility of data conversion errors. As input

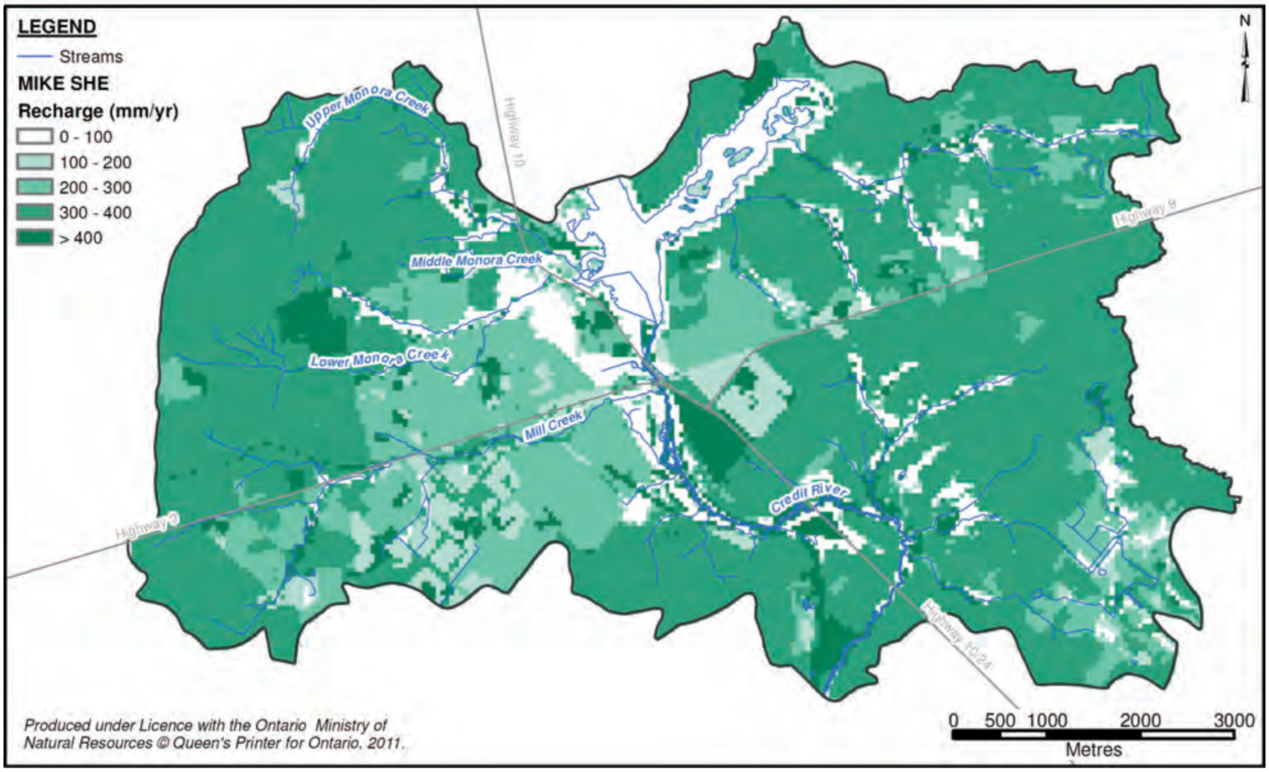

Figure 3.10 MIKE SHE - Subwatershed 19 Average Annual Groundwater Recharge

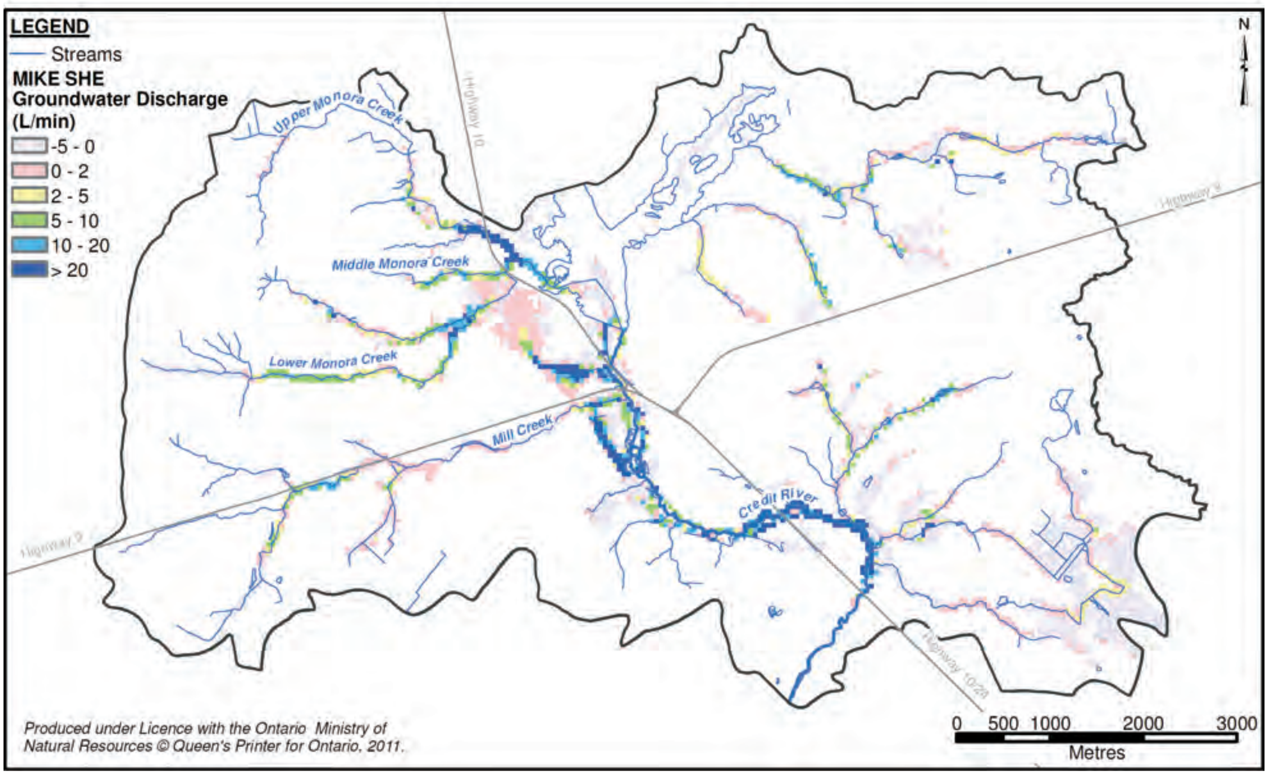

Figure 3.11 MIKE SHE - Subwatershed 19 Average Annual Groundwater Discharge

datasets are stored within MIKE SHE, in their native resolution, with the translation of datasets to the final spatial resolution just prior to performing the simulation, the user can effectively modify the spatial resolution of the model “on-the-fly”. With this ability, the user can complete initial calibration runs at a large spatial scale (e.g., 200x200 m) relatively quickly, before progressing to simulations with a finer spatial resolution (50x50 m) which can be slower. Having the ability to address initial model issues at a large grid scale prior to running the model at a high resolution is a key advantage that allows the modeller to manage computation time, and arrive at an acceptable calibrated model in a shorter period of time.

MIKE SHE also has the advantage of being extremely flexible in terms of having multiple algorithms available for each major process. The modelling team found this to be a key advantage, as it allowed certain processes to be simplified, and allowed the modeller to focus on properly representing other processes. Depending on the study objective or the phase of calibration of the model, the modeller may choose a simple or complex algorithm to represent a specific process. Having the flexibility to select the level of complexity is an important consideration when trying to manage computation time associated with the simulations.

A limitation of MIKE SHE is its uniform grid. By not being able to increase the spatial resolution locally within areas of interest, the modeller is forced to increase the resolution globally. This increases the level of complexity throughout the model, and adds considerably to the computational requirements. The proprietary source code of MIKE SHE is also a limitation in that users cannot examine or modify the source code of the model.

3.5 GSFLOW

The GSFLOW model developed for this review is similar in spatial extent as the MIKE-SHE model. The model boundary is the same as the Subwatershed 19 boundary, approximately 60 km^2 in area, and utilizes a 50m by 50 m grid discretization for modelling purposes. The time period simulated within the GSFLOW model is 1990-1995.

PRMS utilizes an HRU-based discretization of the surface whereas MODFLOW utilizes a finite difference (cell) based discretization of the subsurface. A linkage is made between MODFLOW and PRMS made by mapping the HRUs to MODFLOW grid cells. To streamline the process of coupling the two models, the PRMS HRUs were created at the same grid scale as MODFLOW (50 m). By discretizing the PRMS HRU boundaries to the same grid scale as the MODFLOW cells, it allowed PRMS HRUs and MODFLOW cells to line up directly, and removed a potential source of mass balance error.

3.5.1 Input Data

Climate Data

As was the case with the MIKE SHE Orangeville model, climate data from the Orangeville MOE climate station were used to represent climate within Subwatershed 19. Because GSFLOW is only capable of daily time steps, hourly precipitation data were not required and the daily precipitation rates were used.

Potential evapotranspiration rates were calculated internally by GSFLOW using the modified Jensen-Haise method option (Jensen et al., 1969). In this method, potential evapotranspiration is calculated with consideration of air temperature, solar radiation, a monthly air temperature coefficient computed globally, and a fitting coefficient for each HRU. The calculation of the coefficients considers regional air temperature, altitude, vapor pressure and plant cover (Jensen et al.,1969). Daily solar radiation was estimated using a modified degree-day approach which considers the relationship between maximum air temperature and degree day (Leaf and Brink, 1973).

Land Surface Information

To describe the land surface of Subwatershed 19, many of the same datasets that were used in the MIKE SHE Subwatershed 19 model were used within the GSFLOW model.

Similar to the MIKE SHE model, a 5 m DEM from CVC was used to specify the ground surface. The DEM was sampled to obtain average elevation, aspect (horizontal direction slope faces) and slope for each HRU within GSFLOW.

Land use data, as shown in **Figure 3.3**, were used to define land-cover types within Subwatershed 19. The land use categories were aggregated to four simplified classes: exposed rock or aggregate extraction; forest and wetland; agriculture; and open grass. Each of the land use classes were used to specify the appropriate land cover type on an HRU basis. GSFLOW has predefined parameter sets for four land-cover types: bare soil; grasses; shrubs; and trees. Associated with each plant type are summer and winter canopy densities and storage terms to define canopy interception. A constant rooting depth is associated with each plant type and helps define the water accessible by vegetation for evapotranspiration. Lastly, an imperviousness factor was applied to HRUs according to urban and rural development and based on literature values. These values were adjusted during model calibration.

The spatial distribution of soils was defined by surficial geology layer (OGS, 2003), and is shown in **Figure 3.5**. The current release of GSFLOW is only able to represent three simplified soil classes: sand; loam; and clay. This may be a limitation in areas with high levels of heterogeneity associated with surficial materials. Empirical values were assigned to each class to describe unsaturated zone properties.

Stream Network

The drainage features for PRMS were defined by the 13 stream segments included in the existing Orangeville Tier Three MODFLOW model. As GSFLOW has limited ability to represent hydraulic sturctures, the southern dam in Island Lake was not simulated. The modelled rivers are illustrated in **Figure 3.8**.

Subsurface Information

As with the MIKE SHE model, the saturated zone properties and water takings were taken directly from the MODFLOW model, used in the Orangeville Tier Three study (AquaResource, 2011a).

3.5.2 Hydrologic Processes

The following section details the hydrologic processes and approximations utilized in GSFLOW as implemented for this case study. Explanations of these processes are derived primarily from the GSFLOW documentation (Markstrom et al., 2008).

Snow Melt

Snow accumulation and depletion in each HRU is computed using a two-layer system. The upper layer represents the top 3-5 cm of the snow pack, while the lower layer represents the remainder of the snowpack. The snowpack system is maintained using water balance as well as an energy balance (layers are considered as dynamic heat reservoirs). The energy balance provides a thorough consideration of the various mechanisms of heat transfer to or from the snow pack through radiation, convection, conduction, phase transition, and thermal deposition (rainfall). Snowmelt calculations are computed with consideration through the use of a snow-cover aerial depletion curve.

Overland Flow

GSFLOW does not explicitly simulate overland flow processes; rather, it uses a cascading-flow procedure to direct overland flow and interflow to downstream HRUs or stream segments. For each HRU, the modeller specifies upstream and downstream HRUs, downstream stream segments, as well as the portion of flow from upstream HRUs contributing to downstream HRUs or stream segments.

In the Subwatershed 19 GSFLOW model, cascade connections were set up to provide surficial runoff and interflow directly to the sub-catchment's stream segment. As GSFLOW does not represent overland flow processes, no specific datasets related to overland flow (e.g., roughness coefficients, time of concentration) are required.

Detention storage is not explicitly simulated within GSFLOW. The GSFLOW manual recommends increasing the available storage in the soil layer beyond the available porosity to allow an implicit consideration of depression storage. This was not done in the Subwatershed 19 GSFLOW model.

Imperviousness is defined on an HRU basis by a fraction of the HRU defined as impervious and a depth of storage associated with the impervious areas. Runoff will not occur on the impervious portion of the HRU until impervious storage is exceeded. Water trapped in impervious storage may evaporate. An impervious percentage was specified for urban and rural development HRUs.

Soil Zones

The soil zone is the subsurface portion of the PRMS portion of GSFLOW. Infiltration and evapotranspiration are considered within the soil zone, and modelled using a mass balance approach. The soil zone is conceptually represented as three storage reservoirs which occupy the same physical space, and are shown in **Table 3.9**. Depending on the soil-water content of these reservoirs, different unsaturated processes become active. The capacity of the reservoirs is defined in terms of volume per unit area (depth). The capillary reservoir represents processes which occur between field capacity and wilting point. The gravity reservoir represents the processes which occur between full saturation and field capacity. Finally. the preferential flow reservoir is a sub-division of the gravity reservoir and is defined by a preferential flow water content threshold, which is between saturation capacity and field capacity.

Table 3.9 GSFLOW Soil Zone Reservoirs

Reservoir	Soil-water Content Thresholds	Inflows	Outflows
Preferential Flow	Preferential Flow Threshold - Saturation Capacity	Infiltration fraction, gravity reservoir	Dunnian runoff[a], fast interflow.
Gravity	Field Capacity - Saturation Capacity	Capillary reservoir, groundwater discharge	Contribution to gravity and preferential flow reservoirs, interflow, percolation to unsaturated or saturated zone
Capillary	Wilting Point - Field Capacity	Infiltration fraction , upslope Dunnian runoff, interflow	Evaporation, Transpiration and Contributions to the Gravity Reservoir

[a] - Dunnian runoff is defined as overland flow generated through subsurface saturation excess.

GSFLOW represents infiltration as an indirect, non-physical process. The soil-water content from the previous time step is used to determine the HRU's ability to generate overland runoff. As soil-water content moves towards saturation, overland runoff, rather than infiltration, is generated. Water supplied to the HRU ground surface is the sum of rainfall, snowmelt and Hortonian runoff (surface runoff from infiltration excess) from upslope HRUs. The amount of infiltration generated for each HRU is the amount of water remaining after overland runoff is generated.

Infiltration is initially divided into that which enters the preferential flow reservoir for fast interflow and the remainder which enters the capillary reservoir. If infiltration exceeds field capacity, the upper limit of soil-water is the capillary reservoir; it then is added to the gravity reservoir. Soil properties specified in GSFLOW for each of the three soil classes are utilized to represent infiltration.

GSLFOW computes evapotranspiration using a mass balance approach. Potential evapotranspiration rates are transformed into actual evapotranspiration rates by removing water from a series of water storage reservoirs. All water is removed from the first storage element, before water is removed from a subsequent element. The storage elements and the order of which water is removed by evapotranspiration processes are:

- Plant canopy, impervious surfaces and snow sublimation;
- Evaporation from the soil zone and transpiration from vegetation; and
- Evaporation from the saturated zone, where rooting depths extend to the saturated zone.

Evaporation is limited by the amount of water available in the storage reservoirs. Once available soil-water reaches zero, evapotranspiration will cease until such a time that a precipitation event replenishes one or more storage elements.

Unsaturated Zone

The unsaturated zone of MODFLOW couples to the soil zone represented in PRMS. Flow within the unsaturated zone is simulated using a 1D kinematic wave approximation to Richard's Equation.

Channel Flow

Channel flow in the Subwatershed 19 model is handled through a continuity, mass balance approach. The outflow of a stream reach is set to the inflow from an upstream reach plus the sum of Hortonian runoff, Dunnian Runoff, interflow, groundwater discharge and stream leakage within the stream reach.

Saturated Flow

Saturated groundwater flow within GSFLOW is simulated using the USGS groundwater model MODFLOW. As such, a 3D finite difference solution of groundwater flow is applied using Darcy's equation.

Summary of Hydrologic Processes

The hydrologic processes considered by the model were approximated using the methods summarized in **Table 3.10**.

Table 3.10 - GSFLOW Process Approximations

Hydrologic Process	Process Approximation
Overland Flow	A cascade flow procedure routes flow from the HRU's to the nearest adjacent stream segment. No overland routing occurs in this process.
Channel Flow	A simple continuity expression is used to govern channel flow. Manning's equation is utilized for channel depth.
Evapotranspiration	ET is computed using a water budget-type additive model. This process tries to meet potential ET by supplying water through the various water storages within the model.
Unsaturated Zone	The unsaturated zone is handled in two segments. A soil zone segment in the PRMS portion of GSFLOW uses a linear reservoir type model. The unsaturated zone segment in MODFLOW is approximated using a 1D Richard's equation model.
Saturated Zone	3D Finite Difference implementation of Darcy's equation.
Time step	Daily

3.5.3 Numerical Simulation

Average simulation time for the GSFLOW Subwatershed 19 model is presented in **Table 3.11**. Simulation time is expressed as hours per year of simulated time, and must be considered in light of the spatial and temporal resolution of the model, the size of the model domain, the numerical implementation of the hydrologic processes (e.g., simple empirical processes vs. complex physically based processes) and the computing resources utilized.

3.5.4 Water Budget

The average annual water budget produced by GSFLOW is presented in **Table 3.11**. Evapotranspiration is approximately 65% of the received precipitation, with streamflow comprising the majority of the remainder (34% of precipitation). The remainder (14 mm/yr) is groundwater outflow from Subwatershed 19. Groundwater recharge is estimated to be 170 mm/yr across Subwatershed 19.

Table 3.11 GSFLOW Simulation Time

Model Domain Size (km^2)	59.8
Model Elements	3150 HRUs, 216,081 Finite difference Cells - 50 m resolution.
Simulation Computer	Intel Core i7 920 (2.67 GHz - Quad-Core)[a], 12 GB RAM, OS: Windows XP Pro x64 Edition Service Pack 2
Simulation Time step	Daily
Simulation Time (hours / year simulated)	≈5

[a] - While executed on a multi-core machine, GSFLOW does not currently implement parallelization of its hydrologic processes.

Table 3.12 GSFLOW Water Budget

Period	Precipitation	Evapo-transpiration	Groundwater Recharge	Streamflow	Groundwater Outflow	Pumping	Storage Change
	(mm/yr)						
1990-1995	902	587	170	304	14	20[a]	-23

a - Pumping term is less than prescribed due to certain wells turning off during simulation due to water level fluctuations.

The water balance was evaluated using the external boundaries of the model (Equation 3.2). Groundwater recharge occurs across and internal model boundary and therefore is neglected in this balance and all terms are in units of mm/year. A error term of zero mm/year was observed for this balance.

Equation 3.2: GSFLOW Water Balance

$$\Delta S = P - ET - Q_{SW} - Q_{GW} - PU + E$$

$$\Delta S = 902 - 587 - 304 - 14 - 20$$

$$\therefore \Delta S = -23 \frac{mm}{year}$$

ΔS - Change in Storage
P - Precipitation
ET - Evapotranspiration
Q_{SW} - Streamflow or Surface Water Flow
Q_{GW} - Groundwater flow
PU - Pumping
E - Error

Figure 3.12 shows the spatial distribution of average annual evapotranspiration rates for Subwatershed 19. Similar to the MIKE SHE results, GSFLOW predicts areas of high evapotranspiration along river/creek valleys, where groundwater discharge supports higher than average evapotranspiration rates. Island Lake is not indicated as an area of high evapotranspiration. While the open water surface of the lake was simulated, the dam structure was not and therefore the water available for evapotranspiration was less than would be available in reality.

Simulated groundwater recharge across Subwatershed 19 is shown on **Figure 3.13**. The highest values of groundwater recharge occur outside the Town of Orangeville in areas of sands and gravels at ground surface. Areas with the lowest estimates of groundwater recharge occur in river and creek valleys, where higher water tables are limiting the downward movement of water.

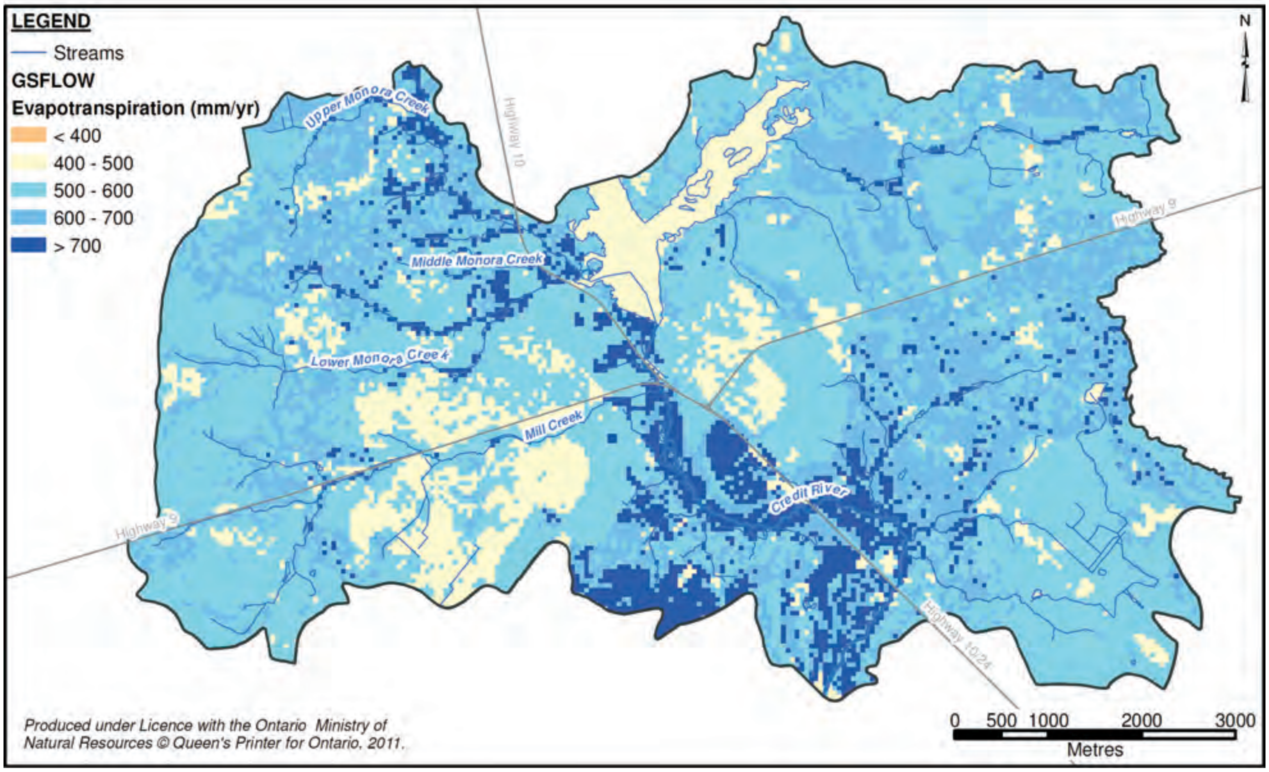

Figure 3.12 GSFLOW - Subwatershed 19 Average Annual Evapotranspiration

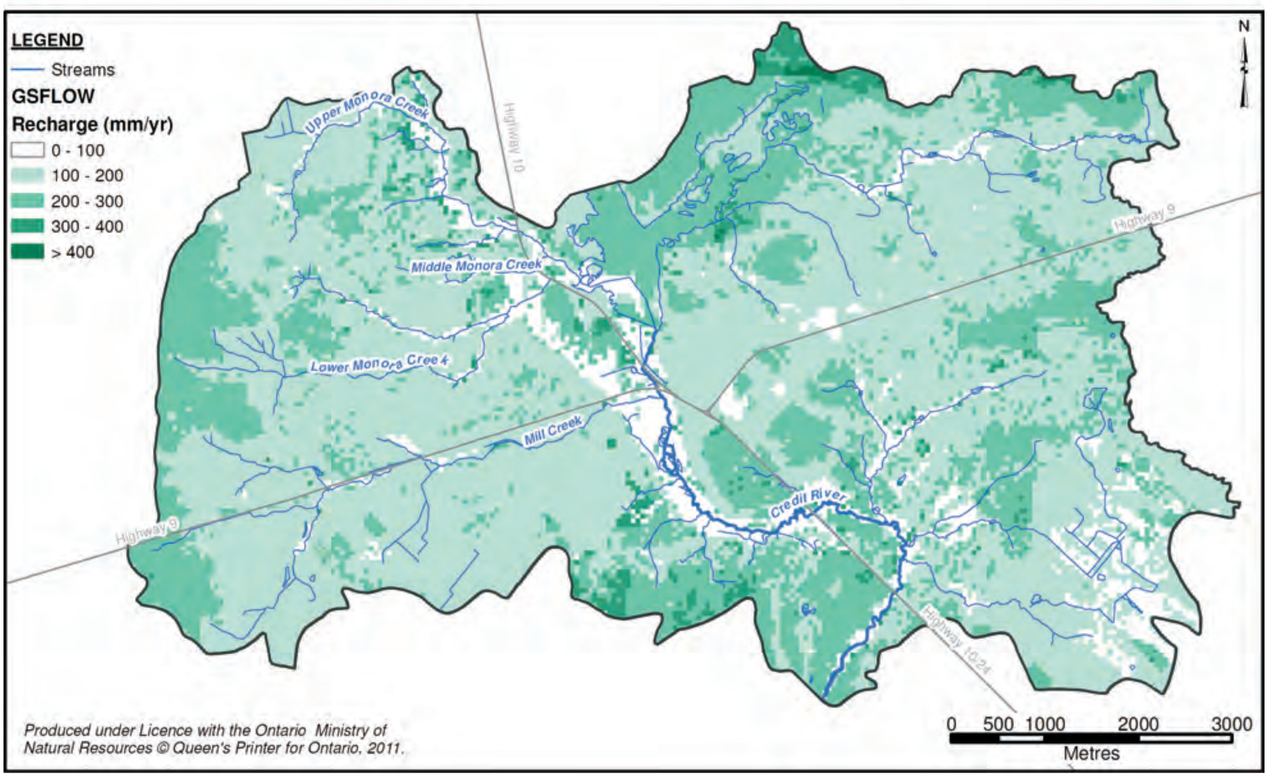

Figure 3.13 GSFLOW - Subwatershed 19 Average Annual Groundwater Recharge

Shown in **Figure 3.14**, expressed in L/min, is the groundwater discharge for Subwatershed 19 as predicted by GSFLOW. As expected, groundwater discharge is found within river and creek valleys, with the highest concentration found within the Credit River valley. The spatial distribution of groundwater discharge appears to be the inverse of simulated groundwater recharge (**Figure 3.13**), which suggests that the upward gradient within the groundwater system is limiting the downward movement of water (e.g., recharge).

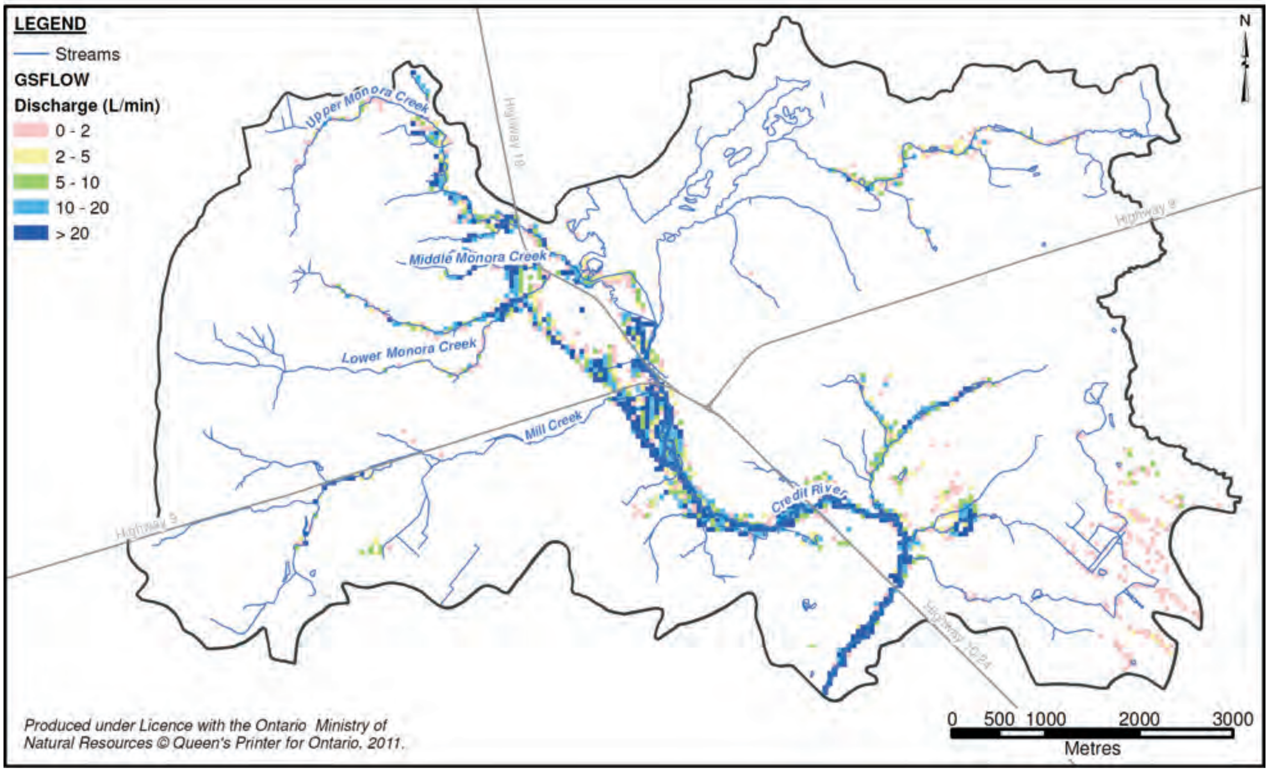

Figure 3.14 GSFLOW - Subwatershed 19 Average Annual Groundwater Discharge

3.5.5 Modelling Experience

The reliability and history of MODFLOW and PRMS, two longstanding model codes supported by the USGS, are advantages to its use within a conjunctive modelling framework. Modellers who have previously developed pre/post processers for MODFLOW/PRMS may find further use of these tools with GSFLOW applications. The publicly available source code for MODFLOW, PRMS and GSFLOW is also advantageous for those who develop software to interact with these models. Another advantageous feature is GSFLOW's ability to support variable grid spacing.

The limitations associated with many of the GSFLOW surface water processes reduce the utility of this software package for surface water applications. These limitations include: simplified soil classes; no consideration of overland flow routing; no consideration of depression storage; simplified channel routing techniques that do not consider the attenuation of waves hydrograph transformation; and a limited ability to represent hydraulic structures. These limitations, in particular, its limited hydraulic capabilities, limit it's usefulness in systems that are highly controlled or contain significant structures or reservoirs. The simple channel flow representation will preclude the applications of this model for floodline or other hydraulic investigations.

Additionally, because GSFLOW cannot utilize sub-daily time steps, it cannot recognize the impact of rainfall intensity on runoff and infiltration processes, and will introduce errors into water budget terms associated with the near-surface. Furthermore, as all processes use the same daily time step, an additional computational burden is experienced relative to other model codes which utilize process-specific time steps. The lack of adaptive time stepping will also contribute to the computational burden.

It is noted that the PRMS portion of GSFLOW is highly empirical, particularly the runoff/infiltration algorithm. This reliance on empirical relationships introduces additional uncertainty when using the model in a predictive fashion for scenarios that are beyond what the model has been calibrated for (e.g., urbanization or climate change impact assessments).

The lack of a graphical user interface, or pre/post processing tools, was a significant hurdle experienced by the modelling team in this study. The absence of a graphical user interface did not facilitate efficient model development or model calibration. Without the provision of such tools with GSFLOW, a modeller must develop data management routines to format GIS and temporal data into the necessary text input files. Further post-processing tools must be developed to assess output efficiently and effectively. Given these challenges, the construction and calibration of the GSFLOW model took a significant amount of time.

3.6 HydroGeoSphere

The model domain used in the HydroGeoSphere model is consistent with the AquaResource, Inc. et al. (2011a) Orangeville Tier Three study. This includes Subwatershed 19 within the Credit Valley Conservation (CVC) area in addition to sections of the Humber River Watershed, Nottawasaga Watershed and the Grand River Watershed. This extension of the domain beyond the boundaries of Subwatershed 19, which is the main region of interest, was performed to minimize any potential boundary effects on flow predictions within the subwatershed. The domain spans approximately 236 km^2. Pumping for the region is approximately 12,000 m^3/d when considering municipal wells and significant non-municipal takings. Whereas pumping for Subwatershed 19 alone is approximately 6,500 m^3/d. The time period simulated in the HydroGeoSphere model is 1995-2005.

A triangular 2D finite element mesh was used to define the model domain and was generated using Grid Builder (McLaren, 2009). To create the 3D mesh, elevation data were mapped onto vertically stacked layers of the 2D mesh generated by Grid Builder. A watercourse overlay was used to generate control points in order to locate nodes along selected stream reaches in the 2D mesh. The mesh was designed such that regions near selected streams reaches have smaller finite elements (~ 30 m spacing), while finite elements further away from the drainage network are larger (~ 150 m spacing). This discretization strategy allows a more refined rendering of the near-stream hydrodynamic processes, while reducing overall computational effort in less active areas. The mesh was also refined around the pumping wells in the study area down to a level of approximately five meters.

3.6.1 Input Data

Climate Data

As was with the MIKE SHE and GSFLOW models, climate data was from the Orangeville MOE climate station. Required datasets included air temperature and total precipitation. As snow processes are not yet included in HydroGeoSphere, snowfall was included as rainfall, using a snow-water equivalent ratio of 10:1.

Land Surface

The Provincial 10 m DEM was used to specify the ground surface of the HydroGeoSphere model domain. The Provincial DEM was utilized rather than the CVC 5 m DEM, due to the HydroGeoSphere model domain extending beyond the CVC boundaries, into the GRCA and NVCA watersheds.

Land use data, as shown in **Figure 3.3**, was used to define land cover types within the HydroGeoSphere model domain. The land use classes were lumped into six distinct land usage categories, as shown in **Table 3.13**. A Manning's surface roughness coefficient was assigned to each land use category and assigned from tables provided in McCuen (1989).

Table 3.13 HydroGeoSphere Land use classes and surface roughness

Land use Class	Surface Roughness (Manning's n)
Streams	0.04
Rural	0.2
Urban	0.012
Forest	0.6
Shortgrass	0.15
Wetlands/Lakes	0.05

Evapotranspiration parameters were assigned to each land use class, as well as the surficial geology type. This included time varying leaf area indices, rooting depths, and evaporative depths (Scurlock et al., 2001; and Canadell et al., 1996).

Surficial Geology

A calibrated surficial geology layer from the existing Orangeville MODFLOW model was utilized to define the first layer of the subsurface in HydroGeoSphere. Calibrated hydraulic conductivities and specific storage values were mapped onto the HydroGeoSphere finite element mesh. Van Genuchten (1980) parameters for unsaturated flow were assigned to the layer based on the sediment type. Infiltration and exfiltration values across the land surface are calculated internally by HydroGeoSphere and do not require parameterization.

Stream Network

Because HydroGeoSphere does not distinguish between overland and channel flow, a stream network does not have to be specified. All flow on the ground surface (overland flow or channel flow) is modelled using a 2D diffusive wave approximation of the St. Venant equations. As overland flow concentrates within low lying areas, and continues downslope, a watercourse is formed within the model. While a stream network is not required as an input dataset, during the grid development process a stream overlay (a GIS layer) was used to locally refine the model grid in areas where channel flow was expected to develop on the ground surface so that the elevations along the expected watercourses have a higher resolution. Smaller finite elements, approximately 30 m, were used in these areas.

The most current version of HydroGeoSphere does not have the capability to simulate hydraulic control structures and therefore the Island Lake dam was neglected. It should be noted that there are plans to incorporate this feature in future versions (Sudicky, 2009).

Subsurface Properties (Groundwater Flow System)

The Orangeville Tier Three MODFLOW model was used as the basis for the HydroGeoSphere saturated zone model. The top surface elevations of each hydrostratigraphic unit from the original Orangeville MODFLOW model were used to form the 3D layering of the hydrostratigraphic model. Consistent with the Orangeville MODFLOW model produced by AquaResource (2011a), the bottom of the model was set to a constant elevation of 240 (masl).

The hydraulic conductivity field used in the HydroGeoSphere model was derived from the calibrated values determined in the Orangeville Tier Three study. As HydroGeoSphere employs a variably-saturated flow formulation in its groundwater flow calculations, it also requires that the wetting and drying properties of each sediment type be defined though the use of a characteristic curve relationship. These characteristic curves define how pressure head and hydraulic conductivity values for the various sediments change as a function of saturation. A Van Genuchten characteristic curve relationship was chosen for use in this study. Because the data required defining the characteristic curves were not available, they had to be estimated (which is commonly the case in most variably saturated flow model studies). This was accomplished by using wetting/drying properties for comparable sediment types reported in Jones et al. (2008) and Schaap et al. (1999).

Subsurface boundary conditions applied in the HydroGeoSphere model were chosen to approximate the regional groundwater flow patterns and the major groundwater fluxes in and out of the study area. Two types of subsurface boundary conditions were applied in the model.

The first type was Dirichlet boundary conditions (Type 1 boundaries). These boundary conditions specify a constant hydraulic head value on a model node, and the amount of groundwater flow through the model element changes to satisfy the specified head condition. Around the model boundary where flow in or out of the study area is predicted (typically by observed water levels and gradients), Dirichlet boundary conditions were used and given values comparable to those reported in the previous Orangeville Tier Three study.

The second type of boundary condition used in the Subwatershed 19 HydroGeoSphere model is Neumann boundary conditions (Type 2 boundaries). These boundary conditions specify a constant flux value across an element face or through a model node. The total hydraulic head at the surrounding nodes or across the face changes to meet the specified condition. Neumann boundary conditions were used to represent extraction wells in the model. The extraction wells were assigned parameters (location, screen elevation and quantity) identical to those reported in the previous Orangeville Tier Three Study (AquaResource, 2011a)

3.6.2 Hydrologic Processes

The following section details the hydrologic processes and approximations utilized in HydroGeoSphere as implemented for this case study. The explanations are adapted primarily from HydroGeoSphere documentation (Thierren et al. 2010).

Overland Runoff

Overland flow is simulated in HydroGeoSphere using a 2D depth-averaged flow model. The diffusive-wave approximation of the St. Venant equations accomplishes this. Surface roughness is considered within these equations and is applied in a spatially distributed manner based on land use classes. Overland runoff does not occur until depression storage has been satisfied. Although depression storage can be defined in a spatially distributed manner throughout the domain based on the land use, for the current application of HGS, the depression storage was assigned a constant value of 1 mm across the top of the model domain.

Evapotranspiration

Evapotranspiration is modelled in HydroGeoSphere using a modified Kristensen and Jensen (1975) approach. Evapotranspiration is modelled with consideration of canopy interception, evaporation from soil, and transpiration. Vegetation is characterized in terms of time-varying leaf area indices and root depths as well as evaporative depth. Transpiration rates are a function of leaf area index values, soil-water content, and root depth. Evaporation for the soil is a function of soil-water content and an evaporative depth. Once soil-water content within the evaporative depth reaches the wilting point, evapotranspiration ceases until the soil-water content is replenished.

Channel Flow

Channel flow is handled in HydroGeoSphere using the 2D diffusive wave approximation of St. Venant equations. It is not numerically distinguished from overland flow.

Subsurface Flow

Subsurface flow, both unsaturated and saturated, is simulated within HydroGeoSphere using a 3D variably saturated formulation of Darcy’s law. Sediment types are charactized for fluid flow with conductivities for all three dimensions as well as specific storage parameters. Infiltration rates are calculated internally by the model using van Genuchten characteristic curves which define how pressure head and conductivity of sediment types vary as a function of saturation.

Summary of Hydrologic Processes

The hydrologic processes considered by the model were approximated using the methods summarized in **Table 3.14**.

Table 3.14 HydroGeoSphere Process Approximations

Hydrologic Process	Process Approximation
Overland Flow	2D - Diffusive Wave Approximation of St. Venant equations of flow.
Channel Flow	2D - Diffusive Wave Approximation of St. Venant equations of flow.
Evapotranspiration	Modified Kristensen and Jensen type ET.
Unsaturated Zone	Variably-saturated flow through a 3D implementation of Darcy's law. Sediment parameters modified by van Genuchten characteristic curves.
Saturated Zone	Variably-saturated flow through a 3D implementation of Darcy's law.
Time step	Variable (Adaptive Time Stepping, monthly climate input used)

3.6.3 Numerical Simulation

Average simulation time for the HydroGeoSphere model expressed as hours per year of simulated time is presented in **Table 3.15**. Simulation time must be considered in light of the spatial and temporal resolution of the model, the size of the model domain, the numerical implementation of the hydrologic processes (e.g., simple empirical processes vs. complex physically based processes) and the computing resources utilized.

The simulation required over 14 hours per year of simulation, which is the largest of all three models compared. It should be noted though, that the spatial area represented in the HydroGeoSphere model was also the largest considered.

To reduce simulation time, the climate input for the Subwatershed 19 HydroGeoSphere model was reduced to a monthly basis. While this improves simulation time, it simplifies many of the surface water processes to a point where they may no longer be physically representative. Using daily or hourly time steps, as were used within the MIKE SHE and GSFLOW models, would perhaps result in simulation times that are orders of magnitude higher than that experienced using monthly time steps. A significant portion of the long run times experienced in HydroGeoSphere may be due to the lack of process-dependent time stepping which would allow large time steps for less dynamic processes and small time steps for more dynamic processes. However, the numerical implementation of HydroGeoSphere (implicit coupling of all hydrologic processes) precludes this approach from being used.

Table 3.15 HydroGeoSphere Simulation Time

Model Domain Size (km2)	236
Model Elements	395,100- Finite Triangular elements of variable resolution: • 5 m near pumping wells • 30 m near streams and • 150 m in regions further away from the stream network
Simulation Computer	Intel Xeon X5355 -x2 (2.66 GHz - Quad Core)a, 8 GB Ram, OS: Windows XP 32 Bit (Only 3GB Ram addressable in this OS)
Simulation Time step	Monthly
Simulation Time (hours / year simulated)	≈14

3.6.4 Water Budget

Table 3.15 presents the Subwatershed 19 average annual water budget for the 1995-2005 period, as predicted by HydroGeoSphere. Evapotranspiration is responsible for approximately 55% (479 mm/yr) of the water budget, with streamflow comprising over 30% of precipitation. Groundwater recharge is estimated to be 355 mm/yr, with 95 mm/yr of groundwater outflows.

The water balance can be evaluated on the external boundaries of the model (**Equation 3.3**). Groundwater recharge occurs across and internal model boundary and is thus neglected in this balance and all terms are in units of mm/year. A small error was observed for this water balance and is included here to balance the equation.

Equation 3.3 - HGS Water Balance

$$\Delta S = P - ET - Q_{SW} - Q_{GW} - PU + E$$

$$\Delta S = 884 - 479 - 280 - 95 - 18 - 1$$

$$\therefore \Delta S = 11 \frac{mm}{year}$$

ΔS - Change in Storage
P - Precipitation
ET - Evapotranspiration
Q_{SW} - Streamflow or Surface Water Flow
Q_{GW} - Groundwater flow
PU - Pumping
E - Error

Table 3.16 HydroGeoSphere Water Budget

Period	Precipitation	Evapo-transpiration	Groundwater Recharge	Streamflow	Groundwater Outflow	Pumping	Storage Change
	(mm/yr)						
Baseline	884	479	355	280	95	18	11

Distributed average annual groundwater recharge is presented in **Figure 3.15**. As was with MIKE SHE and GSFLOW, the majority of recharge is predicted to occur in the upland areas, with minimal to no recharge occurring in the valleys of the main Credit River and its tributaries. Areas of high recharge occur along some sections of watercourses, and indicate reaches where the stream is losing water to the underlying groundwater system.
The spatial distribution of average annual discharge is presented in **Figure 3.16**. The majority of groundwater discharge is predicted to occur along the main branch of the Credit River with other areas of discharge occurring within Monora Creek. This closely matches the discharge pattern predicted by MIKE SHE and GSFLOW.

3.6.5 Modelling Experience

HydroGeoSphere is a rigorous groundwater simulator, which implements an advanced formulation for surface flow and variably saturated subsurface flow. The use of a control volume finite element mesh provides a mesh that may be locally refined around areas of interest, is computationally efficient and retains the superior local mass balance capabilities of the block centered finite difference method.

However, the model has a number of limitations that should be addressed to improve its utility as an integrated model for typical water management investigations in Ontario. Some of these limitations include:

- Lack of winter processes (e.g., snow). This is a significant limitation for Ontario applications;
- An inability to simulate hydraulic structures such as dams and weirs;
- Excessive simulation times are required when the model is operating in a transient mode. To reduce simulation times, modellers are forced to reduce the amount of time steps, increments or reduce the grid resolution, which can introduce errors in near-surface and overland flow processes; and
- Due to the lack of a graphical user interface (GUI), the user most pre-process and post-process model results manually.

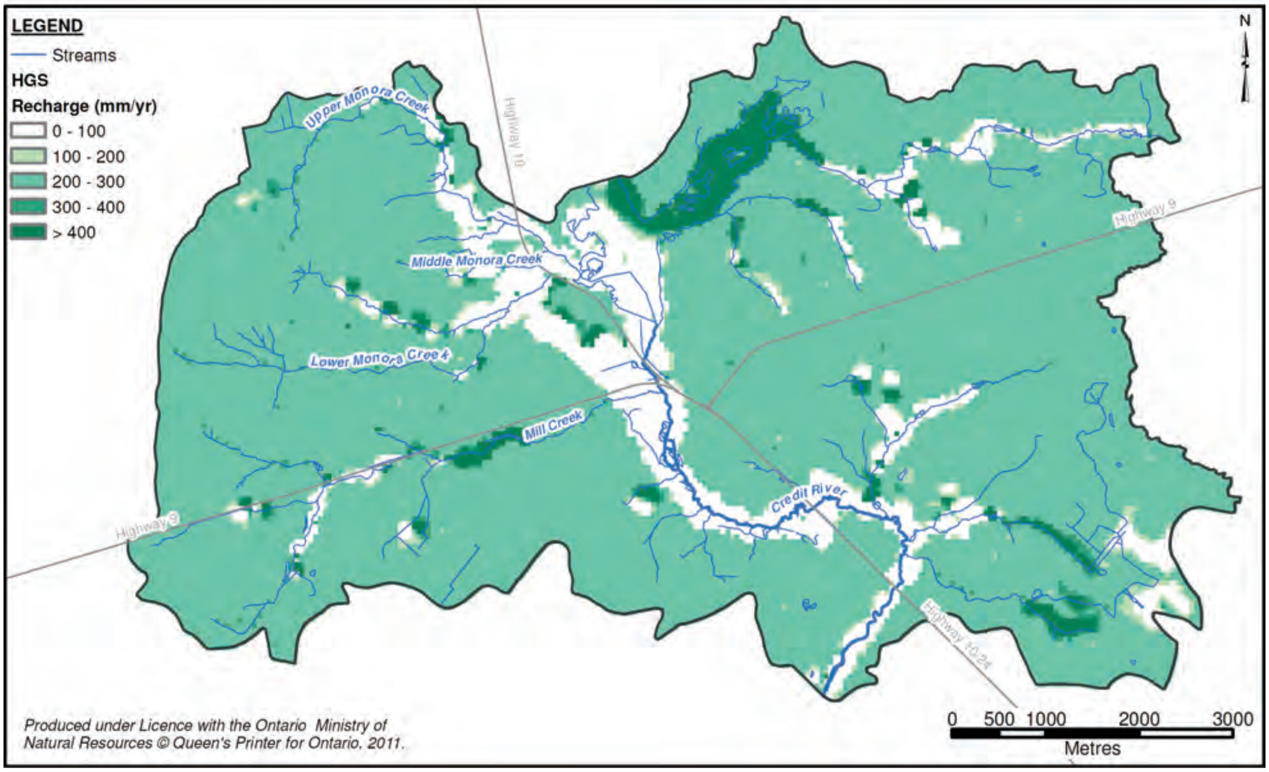

Figure 3.15 HydroGeoSphere - Subwatershed 19 - Average Annual Groundwater Recharge

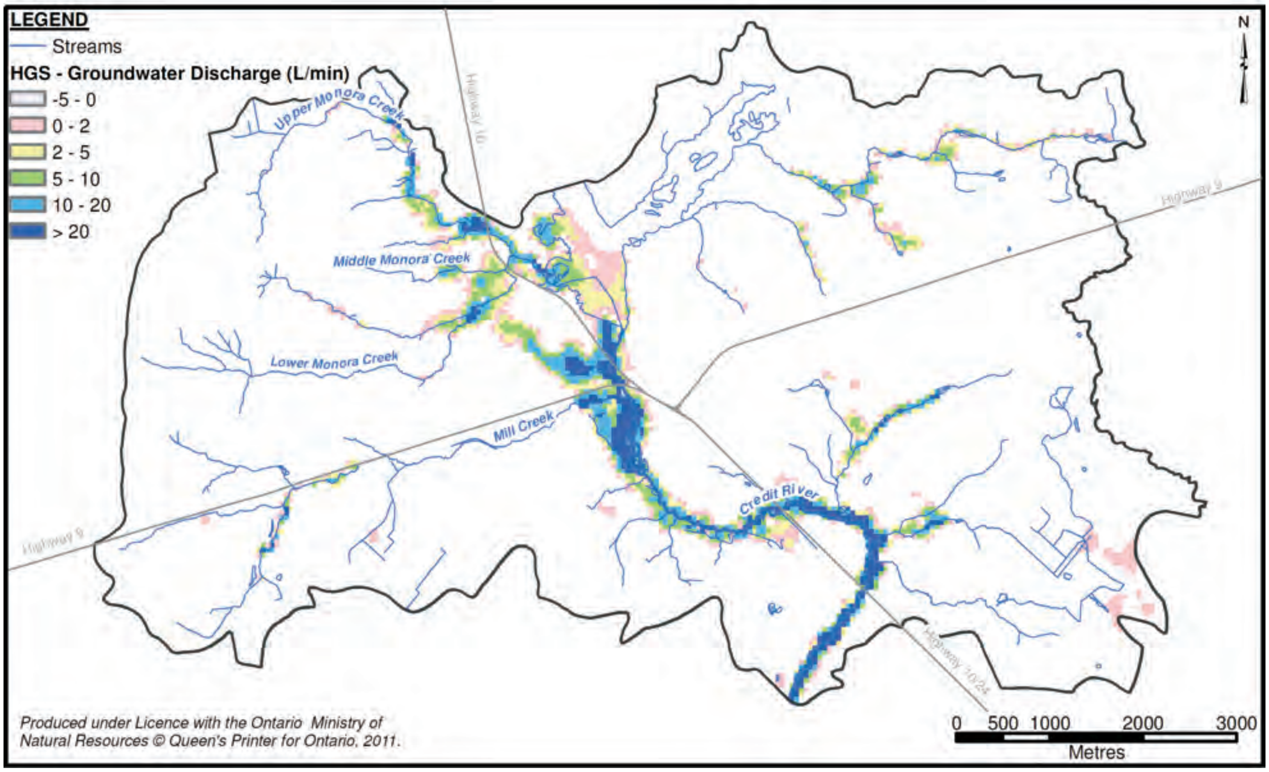

Figure 3.16 HydroGeoSphere - Subwatershed 19 - Average Annual Groundwater Discharge

It is noted that a number of these issues are currently being addressed for future releases of HydroGeoSphere.

3.7 Impact Assessment Scenarios

Beyond understanding and quantifying key hydrologic processes, integrated models can be useful in assessing the cumulative impacts to water resources, and predicting impacts on the surface water system caused by changes to the groundwater systems. (e.g., impacts to streamflow caused by increased groundwater withdrawals). When assessing impacts to groundwater discharge, traditional modelling approaches typically quantify the change in steady-state baseflow, and do not recognize how the impact may vary seasonally or from year to year. This approach is problematic because groundwater discharge or baseflow is not a constant value. Reconciling these temporal changes in steady-state baseflow with an observed (transient) streamflow hydrograph is difficult, if not impossible. Integrated models have the advantage of predicting total changes to the streamflow hydrograph, as well as groundwater discharge, making them an excellent impact assessment tool.

To evaluate the ability of GSFLOW, MIKE SHE and HydroGeoSphere to assess hydrologic impacts, three of different scenarios are evaluated. These scenarios examine groundwater withdrawal increases and land use changes (urbanization) within Subwatershed 19. The scenarios are described below.

- Scenario #1 - Increased Pumping. This scenario evaluates the impact of increasing all groundwater extractions in Subwatershed 19 by 35%;
- Scenario #2 - Land Development. This scenario evaluates the impact of urbanization in the western portion of Subwatershed 19. **Figure 3.17** illustrates the change in land use in this scenario. Imperviousness in these areas was updated to match these values.; and
- Scenario #3 - Increased Pumping & Land Development. This scenario evaluates the impact of both the pumping and land use scenario together.

The impacts related to the three scenarios are assessed in terms of streamflow; both in terms of changes to total annual streamflow and baseflow from baseline conditions. Changes in streamflow are assessed for

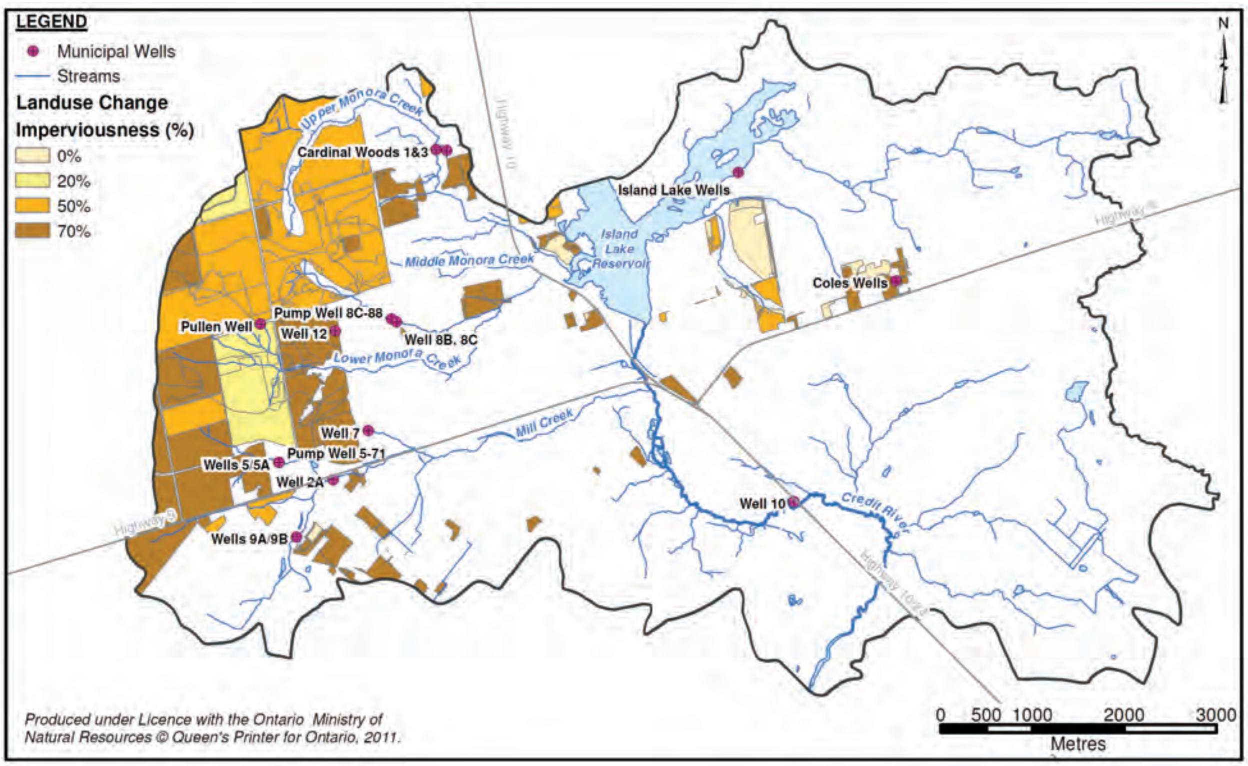

Figure 3.17 Integrated Model Scenarios

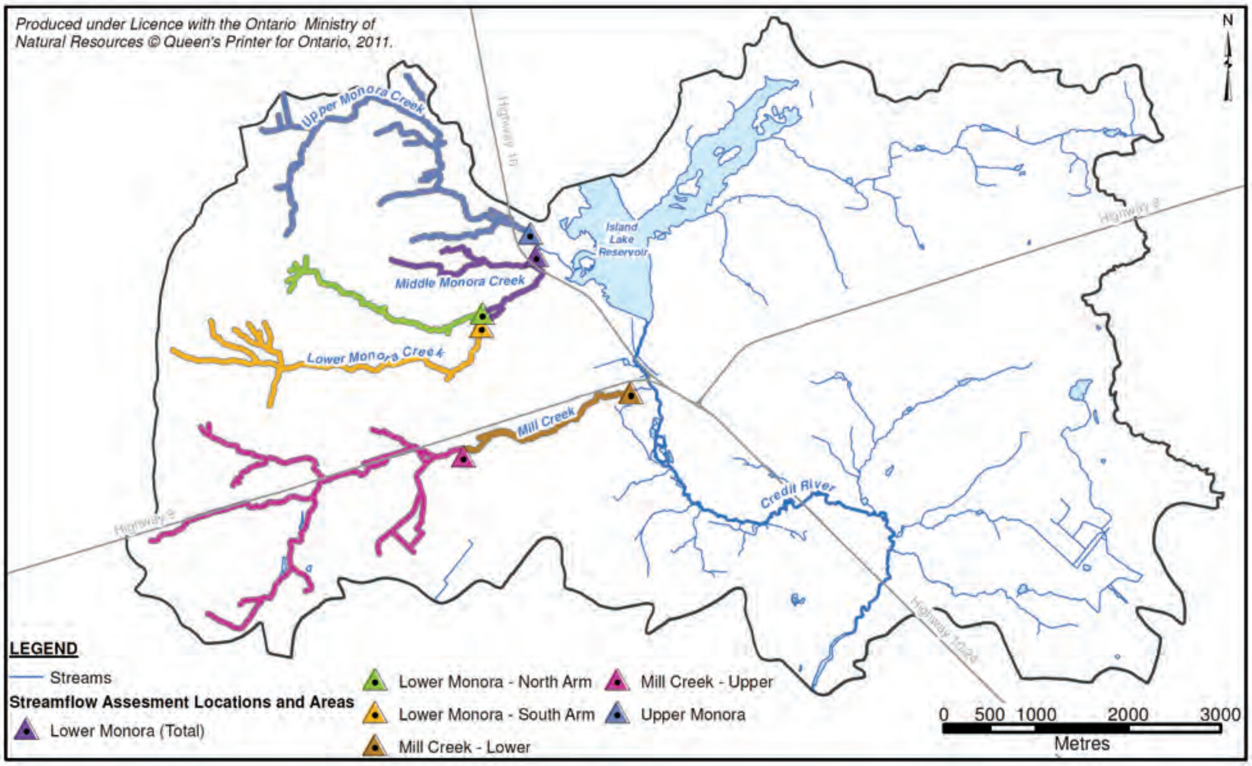

Figure 3.18 Streamflow Assessment Locations

three stream reaches: Lower Mill Creek; Lower Monora Creek; and the Credit River at Mellville (shown on **Figure 3.18**). Lower Mill Creek and Lower Monora Creek represent streams close to the pumping and land use changes, while the Credit River at the Melville gauge station is the outlet of Subwatershed 19. Finally, the seasonal distribution of impacts to streamflow, and impacts to the daily hydrograph are assessed with a number of high and low flow metrics. Due to the HydroGeoSphere Subwatershed 19 simulation implementing monthly climate input, daily hydrographs cannot be output. This precludes HydrGeoSphere output being assessed using daily hydrograph metrics.

3.7.1 Water Budget Effects

The impacts of the scenarios can be assessed at an overall general level by examining the change in the global water budget of the model. At this scale of assessment, some impacts may be subtle as the scenarios simulate impacts localized to specific portions of the model. When comparing results between models it is important to note that the HydroGeoSphere model considered the entire Orangeville Tier Three domain, rather than just Subwatershed 19 and as such the response to the scenarios will be more muted. The water budget impacts for the three scenarios are summarized in the following tables.

Pumping Scenario

In the context of a catchment, increases in pumping should reduce the head levels in surrounding wells and cause a corresponding decrease in groundwater discharge to nearby streams. These reductions in head levels may also promote increased groundwater recharge, as higher water levels can restrict the downward movement of water, depending on the overall gradient. While significant local reductions in streamflow can occur, the effects of increased pumping at the subwatershed scale is typically muted.

In all three integrated models, the increased pumping scenario resulted in certain periods of time where the groundwater system was unable to produce the specified pumping rates. This condition can cause numerical instabilities, and as such these models have numerical procedures to address these instabilities.

Table 3.17 MIKE SHE Scenario Water Budgets (1991-1999)

Period	Precipitation	Evapo-transpiration	Groundwater Recharge	Streamflow	Groundwater Outflow	Pumping	Storage Change
	(mm/yr)						
Baseline	880	546	205	253	68	36	-22
Pumping	880	545	206	250	64	42	-22
Land use	880	502	165	338	45	29	-36
Combined	880	501	165	338	41	36	-36

Table 3.18 GSFLOW Scenario Water Budgets (1990-1995)

Period	Precipitation	Evapo-transpiration	Groundwater Recharge	Streamflow	Groundwater Outflow	Pumping	Storage Change
	(mm/yr)						
Baseline	902	587	170	304	14	20	-23
Pumping	902	587	171	301	11	27	-23
Land use	902	567	163	330	12	20	-27
Combined	902	567	161	327	8	27	-28

Table 3.19 HydroGeoSphere Scenario Water Budgets (1995-2005)

Period	Precipitation	Evapo-transpiration	Groundwater Recharge	Streamflow	Groundwater Outflow	Pumping	Storage Change
	(mm/yr)						
Baseline	884	479	355	280	95	18	11
Pumping	883	476	357	281	95	19	12
Land use	884	474	359	284	96	18	11
Combined	884	486	352	276	94	17	11

When the water table drops below the well screen in MIKE SHE, withdrawals from that well cease. Additionally, a sink deactivation threshold is defined for the saturated zone solver wherein a minimum threshold is set for the depth of water within a cell. If water levels drops below this threshold, all sinks are deactivated to avoid numerical instabilities. In GSFLOW, the Multi-Node Well Package allows for wells to be shut down when the well head falls below a user specified limit or alternatively, wells may be shutdown when well discharge falls below a user specified discharge rate. In HydroGeoSphere automated processes similar to those in MIKE SHE and GSFLOW exist. Wells are deactivated when the water table drops below the well screen.

Both MIKE SHE and GSFLOW predicted slight decreases in streamflow in the increased pumping scenario. This impact is caused by a reduction in groundwater discharge to streams, caused by lower groundwater levels influenced by the increased groundwater withdrawals. HydroGeoSphere predicted increases in streamflow; however, this was to be expected due to well shutdowns required to achieve model stability. All three models predicted minor increases in groundwater recharge.

Land use Scenario

Conceptually, increased imperviousness associated with urbanization should yield a decrease in recharge and increase in overland runoff. With the increase in imperviousness, and corresponding decrease in vegetation, the amount of water lost to evapotranspiration will be reduced.

The effects of this scenario are more significant than those of the pumping scenario. MIKE SHE results show a significant reduction in global recharge (-20%), an increase in streamflow (+18%) and a small decrease in evapotranspiration (-5%). The GSFLOW results show a small decrease in recharge (-4%), a moderate increase in streamflow (+7%) and small decrease in evapotranspiration (-3%). The HydroGeoSphere results illustrate minor changes in evapotranspiration (-1%), streamflow (+1%) and recharge (+1%). Variations in model results are likely a result of differences in the representation of impervious land cover between the models.

Combined Scenario

The combination of increases in pumping and increases in imperviousness can theoretically produce even greater impacts through reduction of groundwater levels from reduced recharge rates and increased pumping rates. In the case of MIKE SHE, similar reductions in recharge and evapotranspiration as the land use scenario (-20% and -5% respectively) are observed. A marginal decrease in streamflow is observed which agrees with the results of the first scenario (pumping increase only). The GSFLOW results show a decrease in recharge of approximately 5%, increase in streamflow of 6% and reduction of evapotranspiration of 3%. In the HydroGeoSphere results, small decreases in recharge and streamflow are observed (-0.8% and -1.4% respectively) coupled with a small increase in evapotranspiration (+1.5%).

3.7.2 Impacts to Total Streamflow

The following sections describe the effects the scenarios have on streamflow and baseflow within the Subwatershed 19. The effects of each scenario on streamflow are summarized in **Table 3.20**, and discussed in the following sections.

Table 3.20 Scenario Impacts - Streamflow and Baseflow alteration

	Location	Flow Component (Mean Annual)	Scenario 1 (Increased Pumping)	Scenario 2 (Land use)	Scenario 3 (Combined Scenario)
MIKE SHE	Lower Monora	Streamflow	-4%	23%	20%
		Baseflow	-5%	-31%	-27%
	Lower Mill Creek	Streamflow	-1%	52%	52%
		Baseflow	-1%	-15%	-16%
	Melville Gauge	Streamflow	-1%	30%	30%
		Baseflow	-1%	0%	-1%
GSFLOW	Lower Monora	Streamflow	-4%	28%	24%
		Baseflow	-6%	-2%	-8%
	Lower Mill Creek	Streamflow	-2%	23%	22%
		Baseflow	-4%	-9%	-14%
	Melville Gauge	Streamflow	-1%	7%	6%
		Baseflow	-1%	-1%	-2%
HydroGeoSphere[a]	Lower Monora	Streamflow	-3%	-8%	0%
		Summer flow[b]	-2%	-5%	1%
	Lower Mill Creek	Streamflow	65%	33%	69%
		Summer flow[b]	88%	12%	49%
	Melville Gauge	Streamflow	1%	2%	2%
		Summer flow[b]	2%	3%	0%

[a]Model instabilities were encountered when running increased pumping rates from wells. Wells causing instabilities were turned off, resulting in increases in flow.
[b]July-August average flows. Monthly Climate input applied in HydroGeoSphere precluded typical baseflow separation techniques.

Scenario #1 - Increased Pumping

Increased pumping should reduce average streamflow and baseflow within the watershed, as groundwater levels are reduced within the well fields. The effects of the increased pumping will be most prominent in those streams immediately adjacent to the wells.

The MIKE SHE results illustrate a small reduction in streamflow of 4% and 1% for Lower Monora and Lower Mill Creek respectively. Baseflow reductions are similar in magnitude at 5% and 1% for Lower Monora and Lower Mill Creek respectively. Streamflow and baseflow at Melville gauge both showed a marginal reduction of 1% each.

In the GSFLOW model, scenario simulations predict a small reduction in streamflow at Lower Monora and Lower Mill Creek of 4% and 2% respectively. Baseflow reductions are slightly larger at 6% and 4% respectively. Streamflow and baseflow at Melville gauge show a marginal reduction of 1% each.

As discussed earlier, numerical instabilities can be encountered in models when the groundwater system is unable to produce specified pumping rates. In the case of HydroGeoSphere pumping rates were reduced to avoid model instability, which caused both total streamflow and baseflow to increase. Given the issue with the results produced by HydroGeoSphere, a direct comparison with the results of GSFLOW and MIKE SHE would not be meaningful.

Scenario #2 - Urbanization

The increased imperviousness in land use should increase streamflow by reducing infiltration and increasing overland flow. Recharge rates should decrease within regions of increased impervious cover, and reduce groundwater heads, causing a decrease in baseflows.

The MIKE SHE results show a significant increase in streamflow of 23% and 52% for Lower Monora and Lower Mill Creek respectively. While these are significant increases in total streamflow, all increases in streamflow are caused by increased overland runoff, produced by the additional impervious areas. The increased impervious areas reduce groundwater recharge, and subsequently groundwater discharge. Recognizing this, MIKE SHE estimates changes in baseflow for Lower Monora and Lower Mill Creek to be -31% and -15%, respectively. At the outlet of the catchment, the increase in streamflow is very evident, at 30%, while the decrease in baseflow is negligible.

In the case of GSFLOW, a significant increase in streamflow is also observed in Lower Monora (+28%) and Lower Mill Creek (23%). However, baseflow for Lower Monora (-2%) and Lower Mill Creek (-9%) is a more muted relative to the scenario than the MIKE SHE simulation. At the Melville gauge a moderate increase of streamflow of 7% is observed, with an insignificant reduction in baseflow (-1%).

Due to the aggregation of climate inputs to monthly increments to manage model run-time, and other limitations associated with output generation, changes to HydroGeoSphere baseflows are assessed by considering the average monthly total streamflow during the July-August period. While this period is typically dominated by baseflow conditions and therefore a good indication of changes to baseflow, increases in overland runoff occurring in this period can mask reductions in groundwater discharge. This is the case in the HydroGeoSphere simulation of the urbanization scenario. Mean annual streamflow, and average July-August streamflows show increases for both Lower Mill Creek and the Melville gauge. Lower Monora Creek is predicted to have slight decreases in both mean annual and mean summer flows.

Scenario #3 - Combined Increased Pumping and Urbanization

The combined effects of increased pumping and increased imperviousness should produce impacts which exceed that of the individual scenarios. However, these effects may not be cumulative given the complex interaction of the hydrologic processes considered within the models.

In the MIKE SHE analyses, a significant increase in streamflow is observed in Lower Monora and Lower Mill Creek at 20% and 52% respectively. These increases in streamflow are equal to, or slightly lower, than those observed in the land use scenario, and are primarily due to increased impervious cover. The baseflow reduction in Lower Mill Creek increases slightly, relative to the land use scenario, to 16%. The combined scenario produces a slightly lower change in baseflow (-27%) than the land use scenario for Lower Monora, and is explained by increased groundwater inflows to Subwatershed 19. At the Melville gauge, the increase in streamflow (30%) is identical to the land use scenario. The reduction in baseflow is the same as that of the pumping scenario (-1%).

The combined scenario in GSFLOW generates smaller reductions in streamflow than the land use scenario for Lower Monora and Lower Mill Creek at 24% and 22% respectively. Increased reductions in baseflows in Lower Monora (-8%) and Lower Mill Creek (-14%) are also predicted, relative to the land use scenario. At the Melville gauge station, a slightly smaller streamflow increase (6%) was observed relative to the land use scenario, with a 2% reduction in baseflows.

As was the case with Scenario #1, increased pumping caused instabilities with the HydroGeoSphere model. As such, the problematic wells were turned off and as would be anticipated, this resulted in significant increases in both streamflow and summer flow.

3.7.3 Streamflow Regime

To further describe the effects of the land use and increased pumping on hydrology of Subwatershed 19, the impacts to the daily hydrographs are evaluated. Monthly climatic data was used as input for the HydroGeoSphere model, therefore daily hydrographs produced by the model would not be comparable to those produced by GSFLOW and MIKE SHE. As such statistics for the HydroGeoSphere model are not included in the following sections.

For the purposes of comparative streamflow analysis only flows for the baseline and combined land use/

pumping scenario are considered for Lower Monora Creek.

Flow Distribution Effects

The streamflow regime describes the variation, magnitude, and seasonality of flow experienced by a watercourse. When simply comparing daily hydrographs, it can be difficult to determine changes in the regime due to the significant variability in streamflow. Statistical measures can summarize daily hydrographs and allow for a more useful comparison between pre- and post-impact flows. Such a measure is shown in **Figure 3.19** (MIKE SHE) and **Figure 3.20** (GSFLOW). These figures illustrate the median, inter-quartile range (25th-75% percentile) and upper/lower decile (90th/10th) flows for each month of the year. Pre-impact flows for Monora Creek are shown on the left, with post-impact flows shown on the right.

Comparing impacts in this way allows evaluation of the impacts within the context of a complete streamflow hydrograph. Both MIKE SHE and GSFLOW show similar patterns: 1) higher peak flows due to impervious land increases; 2) lower extreme low flows due to a combination of lower recharge associated with an increase in impervious land and increased pumping; and 3) a greater spread between the upper and lower decile, which indicates a more variable streamflow regime. MIKE SHE also displays a much more significant downward shift of the inter-quartile range as well as the median flows than GSFLOW. The effects predicted by MIKE SHE and GSFLOW are consistent with the conceptual expectations of impacts to a watercourse related to increased pumping and decreased recharge.

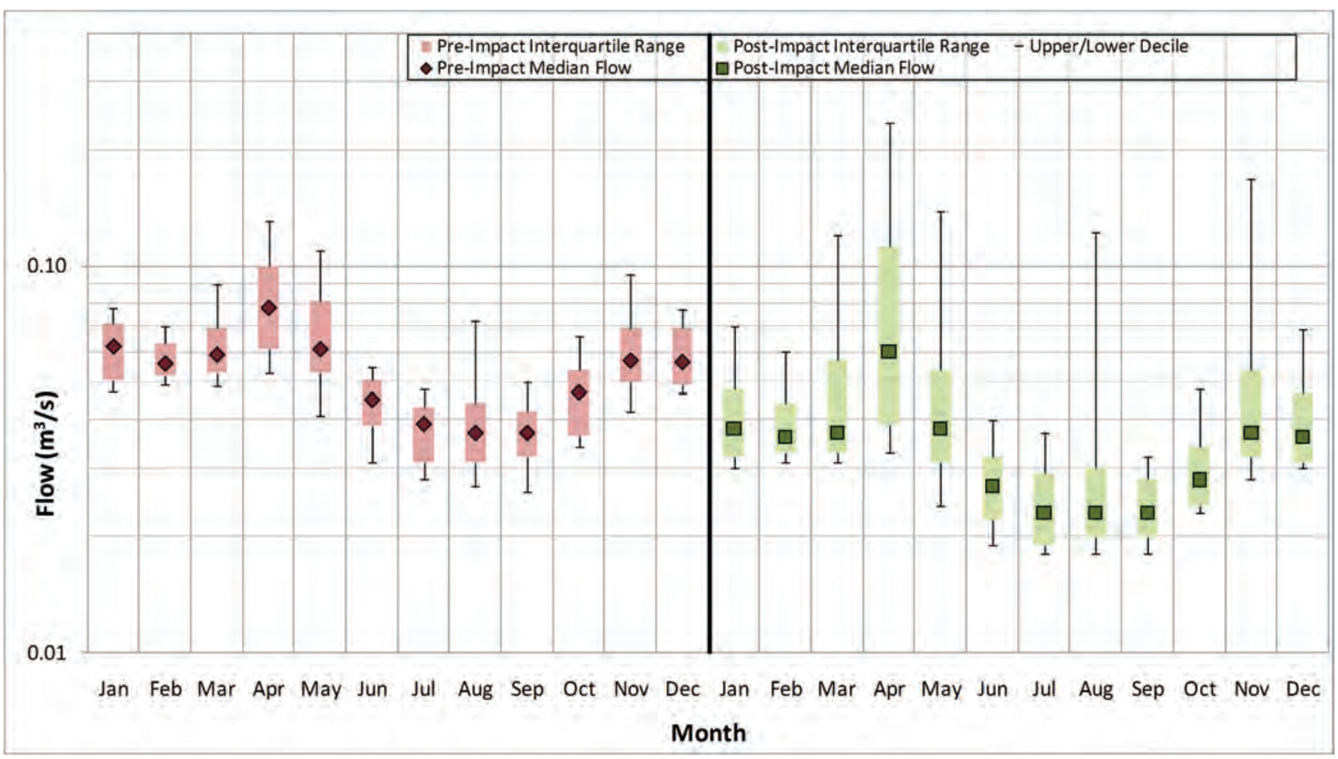

Figure 3.19 MIKE SHE Lower Monora Creek Baseline vs. Combined - Flow Distribution

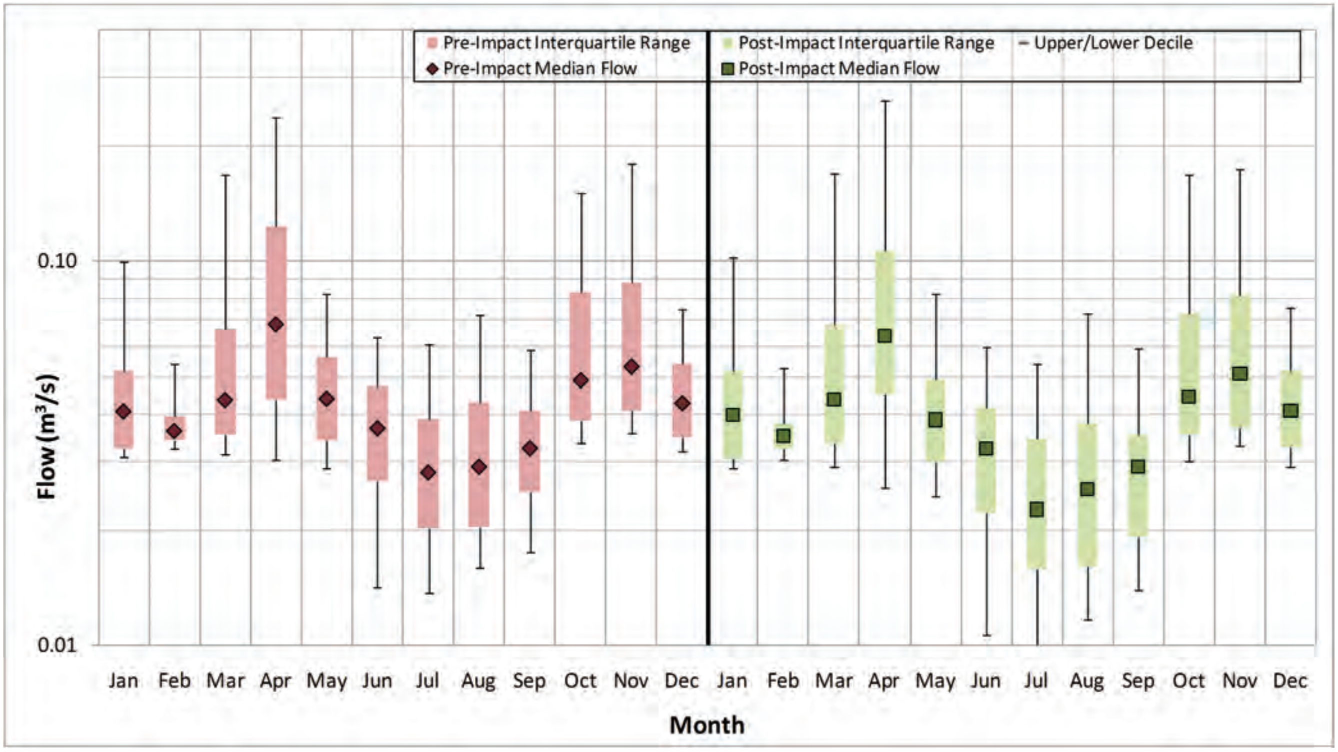

Figure 3.20 GSFLOW Lower Monora Creek Baseline vs. Combined - Flow Distribution Indicators of Hydraulic Alteration

The Indicators of Hydraulic Alteration (IHA) (Nature Conservancy, 2009) is a streamflow analysis tool that is developed and supported by the Nature Conservancy. IHA is an analysis tool that can compare pre- and post-impact flow regimes, and uses an extensive set of hydrologic parameters to evaluate the impact. The parameters considered in IHA include, but are not limited to:

- Annual extreme water conditions - magnitude and duration;
- Seasonal and monthly flow conditions;
- Annual timing of extreme water conditions;
- High and low flow pulses - frequency and duration; and
- Water condition changes - rate and frequency.

For the purposes of this study, a subset of IHA parameters has been selected to examine and quantify the effects of the scenarios on flow regimes for Lower Monora Creek. These parameters include changes in the 30-day minimum flow, and the frequency of two-year flood flows. The parameters selected each describe different aspects of the flow regime that can be affected by land use activities.

The 30-day minimum flow represents the lowest 30-day average of flow within a year and is shown in **Figure 3.21** (MIKE SHE) and **Figure 3.22** (GSFLOW). Comparison of this statistic is an excellent way to assess changes to low-flow conditions within a subwatershed. As would be expected given extensive urbanization and increased groundwater takings, the MIKE SHE model shows a significant reduction in the median 30-day minimum flow of approximately 42%. The GSFLOW model predicts a moderate reduction of the median 30-day minimum flow of approximately 19%. Reduced 30-day minimum flows would affect a variety of uses, including ecological and assimilative capacity uses.

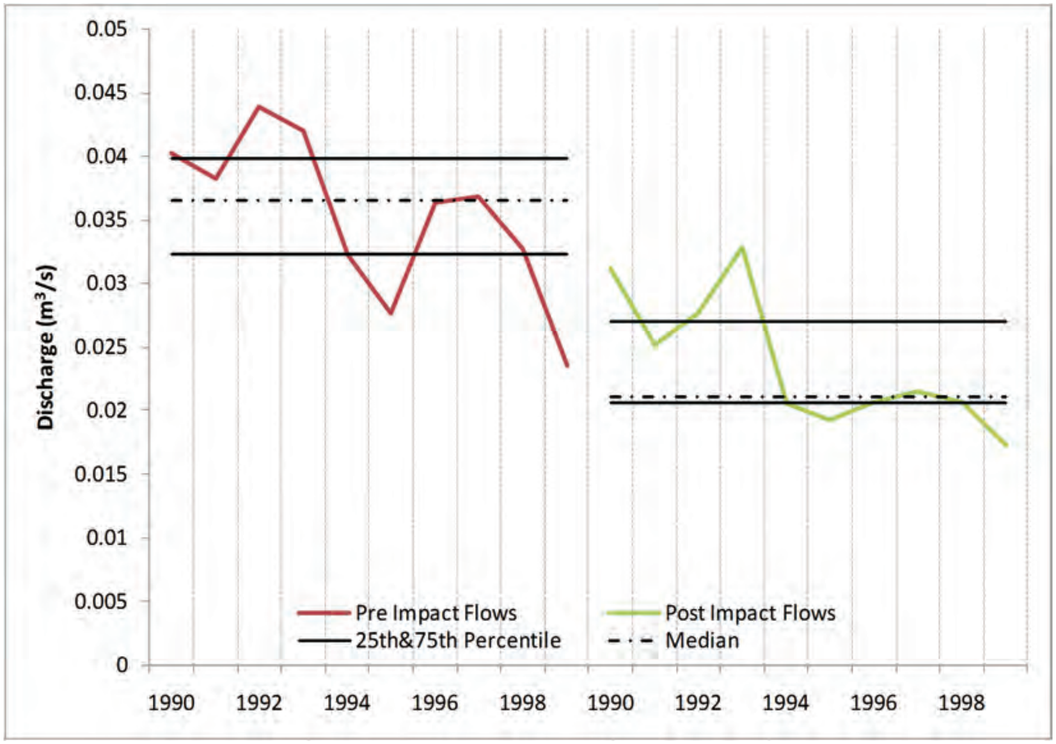

Figure 3.21 MIKE SHE Lower Monora Creek Baseline vs. Combined - 30 Day Minimum Flow

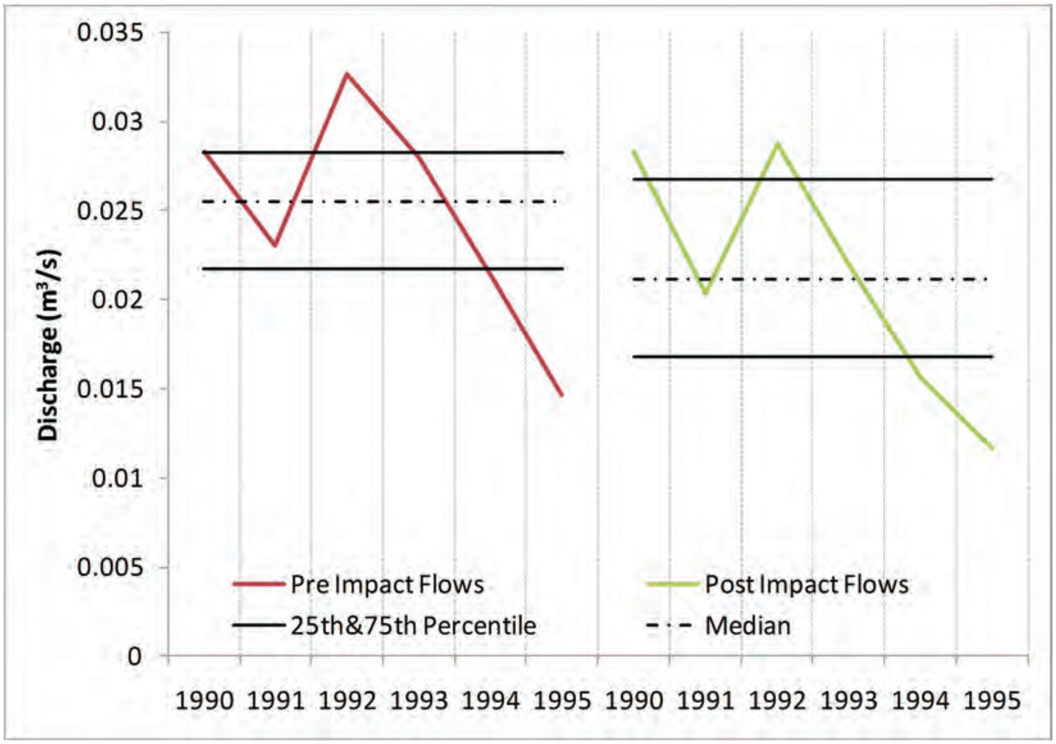

Figure 3.22 GSFLOW Lower Monora Creek Baseline Vs. Combined - 30 Day Minimum Flow

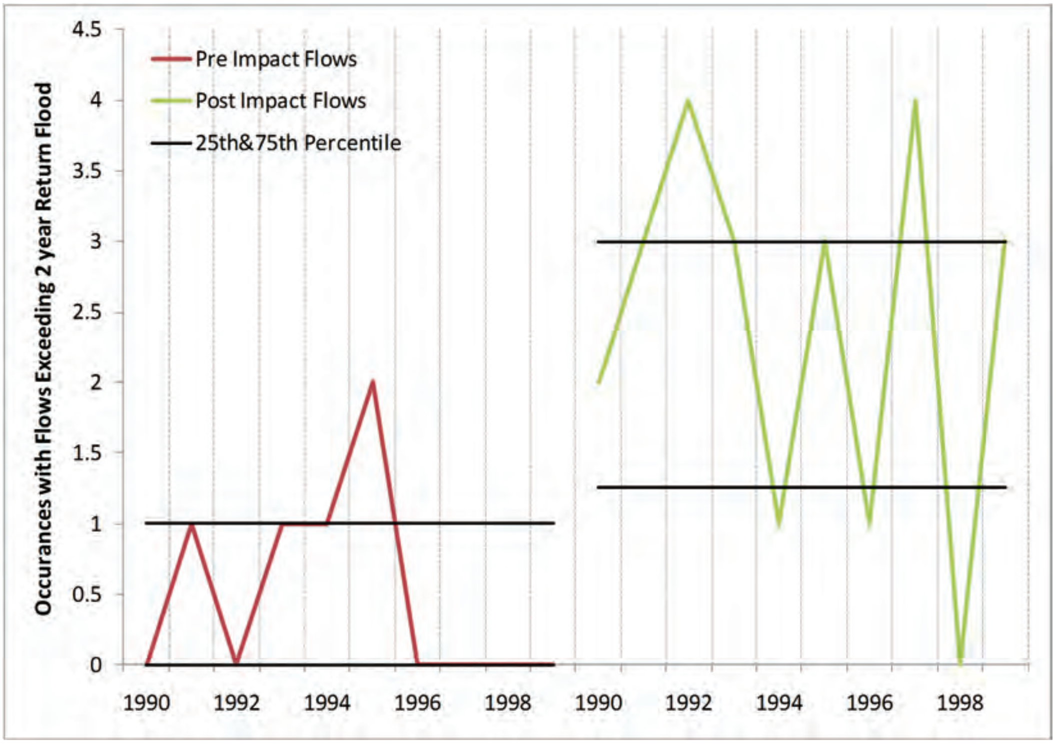

Figure 3.23 MIKE SHE Lower Monora Creek Baseline vs. Combined - 2 Year Flood Frequency

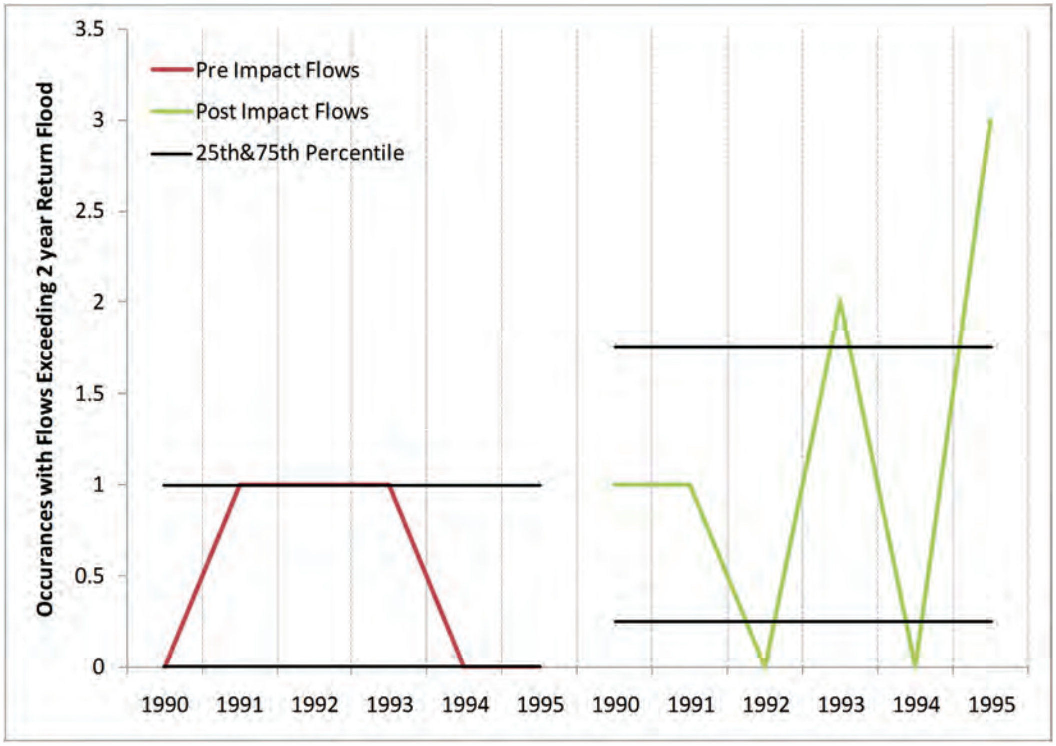

Figure 3.24 GSFLOW Lower Monora Creek Baseline vs. Combined - 2 Year Flood Frequency

Figure 3.23 and **Figure 3.24** show the number of flow occurrences which exceed the pre-impact 2-year flood flow for the MIKE SHE and GSFLOW simulations respectively. This is a useful statistic to assess how the frequency of flood flows may change given urbanization changes to a subwatershed.

Both models show a significant increase in the frequency of flood flows. Peak flows that occur only once every two years under the pre-impact conditions occur almost every year in both the MIKE SHE and GSFLOW simulations, with some years having flow occurrences exceeding the pre-impact 2-year flood flow up to four times. Frequently-occurring high flows can modify the geomorphic characteristics of a channel, possibly causing erosion and downcutting of the channel.

3.7.4 Summary of Impact Assessment

The goal of the impact scenarios was to evaluate each model's ability to predict cumulative impacts (e.g., increased groundwater pumping and land use change) on streamflow. The primary advantage of using an integrated model for such an impact assessment is the ability to evaluate changes in the context of a hydrograph, and as it relates to the streamflow regime of a watercourse. Traditional modelling approaches, either using separate, or coupled, surface and groundwater models are limited in this regard.

MIKE SHE and GSFLOW both predicted similar impacts, albeit with differing magnitudes. Increases in pumping resulted in decreases in streamflow, in particular baseflow, while urbanization resulted in increases in streamflow volume, although concentrated in the high flow portion of the flow regime.

To fully evaluate impacts to the flow regime, analysis of daily hydrographs is required. The use of analytical tools, such as IHA, can aid in evaluating and quantifying these impacts. Integrated model codes that are not able to output streamflow hydrographs at the temporal scale that impacts are evaluated in, are not immediately useful. While HydroGeoSphere is fully capable of running with an small temporal scale (e.g., hourly or smaller inputs), the run-time of the model currently places practical limitations on this ability. Such a limitation was observed with the Subwatershed 19 HydroGeoSphere model where climate inputs were aggregated to monthly increments to provide a reasonable model run-time.

3.8 Review of Models

The following sections discuss differences between the three model codes, as they relate to: model development and calibration tools included with the model; hydrologic processes considered by the model; the spatial and temporal resolution supported by the model; simulation time; and cost of the model. The intent of this section is not to rank models with respect to one another, but rather to discuss the strengths and weaknesses of each model.

3.8.1 Model Development and Calibration Tools

The ease of model development is significantly influenced by the presence of pre- and post-processing tools. These may be standalone utilities or they may be integrated within a user interface. The presence or absence of these tools, and their level of refinement has a great influence on the time spent constructing, debugging and calibrating a model.

There is a large contrast in how these integrated models compare with respect to these resources. MIKE SHE features the most robust set of development tools of all the integrated models considered in this study. It has a fully featured graphical user interface for model development and calibration as well as broad set of pre- and post-processing tools. These tools greatly eased model development and calibration in this case study.

GSFLOW features a very limited set of pre- and post-processing tools from which basic model input and output may be assessed. There is no graphic user interface provided with GSFLOW. A significant amount of time was directed towards creating basic pre and post processing tools for GSFLOW so that it could be utilized in a satisfactory manner. Given the lack of development tools, model construction and calibration assessment took considerably longer in GSFLOW than in MIKE SHE. HydroGeoSphere has a set of basic pre- and post-processing tools at a comparable level of development to GSFLOW.

3.8.2 Hydrologic Processes

The extents of hydrologic processes considered by the integrated models used in this case study are quite similar; however, important differences exist with respect to how these processes are approximated. The hydrologic processes considered within the integrated models are all modelled using either physical or empirical processes. Empirically based approximations may describe a hydrologic process adequately using a set of non-physical or largely non-physical equations at low computational cost. However, because there is no physical basis for the process approximation, there is more uncertainty associated with an empirical approximation of a hydrologic process. Physically based process approximations employ equations based on physical laws and parameters which can, in principle, be measured through laboratory or field work or extracted from generalized literature values. Physically based approximations can describe hydrologic processes with more certainty than empirical approximations; however, physical approximations have substantially higher computational costs and require more data to describe the physical characteristics of the watershed. Without sufficient observation data to parameterize the physical processes the advantages of a physical approach are suspect.

MIKE SHE is able to employ either physical or empirical representations to approximate the various hydrologic processes. A model may be constructed using solely physically based representations, or solely empirical representations, or some mixture of the two. Flexibility in the process representations can be quite beneficial as it allows a modeller to employ a process approximation tailored to the data available for the model.

HydroGeoSphere is the most physically based integrated model considered in this report and is the only model considered which simulates 3D variably saturated groundwater flow. However, HydroGeoSphere currently lacks snow processes. Until such time HydroGeoSphere can represent snow processes, the applicability of HydroGeoSphere to simulate the full hydrologic response of a Canadian watershed will be limited.

GSFLOW provides a mixture of empirical and physical approximation. The empirical processes are particularly prevalent in the overland processes of the model (runoff generation and infiltration). Due to the availability of source-code, modellers may be able to modify GSFLOW to utilize alternative representations for various hydrologic processes.

3.8.3 Spatial and Temporal Resolution

The spatial and temporal resolution employed in integrated models is an important consideration. As model spatial resolution increases, the model's ability to capture spatial variability (e.g., topographic variation) also increases. Increased spatial resolution should lead to refined hydrologic process representation for physically based, distributed processes. The spatial discretization methods of the models vary in their implementation and flexibility. The least flexible of the models is MIKE SHE which employs a block grid system (i.e. rectangular cells) with a uniform resolution, which does not allow the user to refine around features of interest. Rather than refining around specific features, the modeller must increase the discretization of the entire model, which introduces additional computational complexity. However, MIKE SHE does allow flexibility in that the modeller can choose differing grid discretization scales using the same input data. This is an extremely useful feature, as it allows initial coarse model runs to be completed quicker, before moving to a finer, but slower computationally, model.

GSFLOW also uses block grid system (i.e. rectangular cells); however, a variable grid resolution may be utilized. Allowing a variable finite difference grid allows some measure of refinement to be included within areas of interest, however, because the rectangular cells are formed as a grid, horizontal and vertical refinement needed at one discrete location (i.e. a pumping well) are carried through the grid design both horizontally and vertically. This results in additional calculation points in solving the flow system in areas outside of the areas of interest or areas of high flow velocities.

Most flexible of all is HydroGeoSphere which employs a prismatic mesh system (i.e. triangular cells) of variable resolution, similar to the mesh utilized within FEFLOW groundwater flow models. Variable grid or mesh resolution can be beneficial in that it allows the model to resolve greater details in areas of interest (e.g., well fields) while retaining a coarser resolution elsewhere. In addition, this approach is computationally efficient, as the extra calculation points within the flow system are limited only to areas where the higher resolution calculations are needed.

Temporal resolution is also a very important consideration for integrated models. Certain portions of the hydrologic cycle must be considered using relatively high temporal resolution to realistically capture hydrologic processes. Infiltration and runoff generation are important examples of processes where temporal resolution is critical. The amount of rainfall necessary to exceed the infiltration capacity of a given soil and generate overland flow, is substantially different when considered as an hourly process rather than a daily process. A short, intense storm may generate substantial runoff in an hourly time step model, whereas that same storm considered at a daily time step may infiltrate completely and generate no runoff.

The integrated models examined vary significantly with regard to temporal resolution. GSFLOW employs a fixed daily time step which applies to all processes, with no variation for times of changing conditions (e.g., precipitation events or changes in pumping). HydroGeoSphere employs a variable time step which is adjusted based on hydrologic process dynamics. During dynamic periods, when changes occur in the model, increasingly small time steps are used. During relatively static periods, larger time steps are used. The selected time step applies to all processes simultaneously. MIKE SHE also employs a variable time step that is adjusted based on process intensity as well but it is determined independently for each of the hydrologic processes (e.g., overland flow, unsaturated flow, channel flow and saturated flow). This is an important difference compared to the other models. The slowly changing aspects of the model, e.g., saturated flow processes, employ large time steps and rapidly changing aspects of the model, e.g., surface and channel flow processes, employ fine time steps. The independent time stepping used in the various processes of MIKE SHE result in significant benefits with respect to the computational speed of the model.

3.8.4 Simulation Time

The simulation times for integrated models are an important consideration. Simulation times may vary according to the size of the model, the spatial resolution, temporal resolution (time step length) and computer hardware. Simulation times are also very dependent on how hydrologic processes are numerically represented. Certain models implement simplified representations of hydrologic processes whereas others utilize complex ones. A direct comparison of model simulation times may be difficult because of the numerous differences in how the integrated models function. From a practical standpoint, if execution times of the models are too long, it will reduce the amount of time available for debugging and calibration and therefore increase the uncertainty associated with predictions made by the model. Furthermore, long model simulations can prevent the use of model parameter optimization methods which normally require numerous model simulations.

Simulation times for the MIKE SHE model are the shortest of all three models, at just under 1 hour per year of simulation time, compared to 5 hours per year of simulation time for GSFLOW, and 14 hours per year of simulation time for HydroGeoSphere. It should be noted that the spatial extent of the HydroGeoSphere model is approximately four times the area of the MIKE SHE and GSFLOW model domains; however, HydroGeoSphere was run using monthly climate data inputs to reduce simulation times.

It is difficult to make a direct comparison in simulation times between models, as each model does not represent all processes to the same level of detail (e.g., GSFLOW has no overland routing versus MIKE SHE utilized a 2D representation of the St. Venant equation). However, the results of this review suggest that the MIKE SHE model is the most time-efficient integrated model of the three models tested. It is expected that the process-dependant time step feature of MIKE SHE has allowed this to be the case. By allowing shorter time steps for time-sensitive processes (e.g., channel routing, unsaturated zone), and longer time steps for slower-responding processes (e.g., saturated zone), MIKE SHE is able to optimize simulation times, while recognizing the transient nature of certain hydrologic processes. The longer simulation times experienced in HydroGeoSphere are likely due to the model's fully 3D, physically-based representation of saturated and unsaturated groundwater flow as well as the uniform timestep applied to all processes.

3.8.5 Cost

The cost of a MIKE SHE license is higher than other alternatives ($15,000 - $30,000 depending on licence options and a services agreement with DHI), with annual costs of $5000. HydroGeoSphere's cost is significantly less at $3,000. Lastly, GSFLOW is offered at no cost by the USGS. While the license costs of MIKE SHE may increase upfront costs, the time savings and efficiencies introduced by the presence of a well-designed graphical user interface, as well as a robust set of pre- and post-processing tools, may serve to offset the license costs.

4. Case Study - Mill Creek Subwatershed (Grand River Watershed)

4.1 Introduction

Following the review of the abilities of the MIKE SHE (Graham and Butts, 2005; DHI, 2009a,b), GSFLOW (Markstrom et al., 2008) and HydroGeoSphere (Therrien et al.,2010) models in the preceding section; a second case study was developed. The second case study includes an application of a single integrated model code, with the primary focus on the detailed model construction and calibration process. The subwatershed selected for the second case study is Mill Creek, within the Grand River Watershed.

From the results of the two preceding sections, MIKE SHE was selected for application within this case study because it is the most flexible and user-friendly model code of the three models tested within a water budget analysis context.

This section provides a detailed summary of the implementation of a MIKE SHE model for Mill Creek as presented in the following sub-sections:

- Mill Creek Description;
- Input Data;
- Model Setup;
- Model processes and approximations;
- Model calibration; and
- Conclusions and Observations

4.2 Mill Creek Description

The Mill Creek subwatershed covers an area of roughly 100 km^2 and is situated within the Galt-Paris moraine complex. The headwaters of Mill Creek are located southeast of Guelph, where Mill Creek flows southwest, joining the Grand River in downtown Cambridge (Galt). Land cover within Mill Creek is predominantly agriculture, with forests and wetlands comprising the majority of the remaining land area. The surficial geology of the region consists primarily of Wentworth till associated with the Galt-Paris moraines, gravel associated with outwash deposits between the moraines, and some organic deposits. Mill Creek supports cold-water fisheries, and also has extensive aggregate production facilities within the watershed. **Figure 4.1** illustrates Mill Creek and its surrounding features as well as the relative location of Mill Creek within the Grand River watershed.

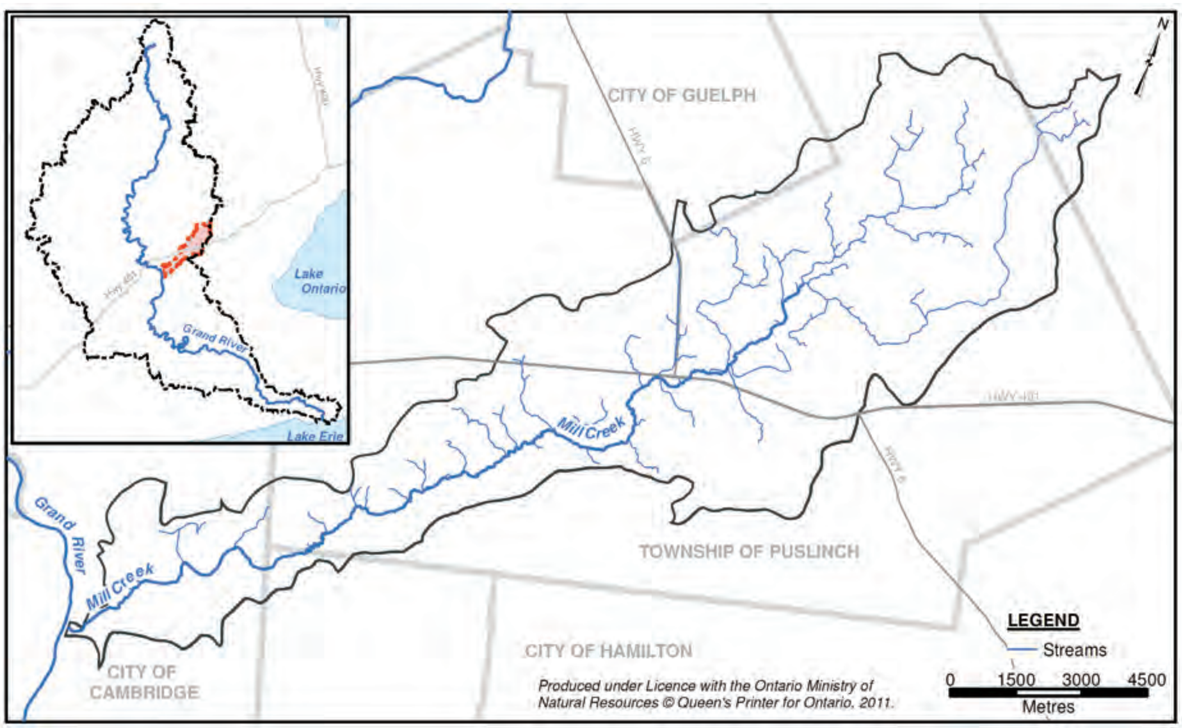

Figure 4.1 The Mill Creek Subwatershed

4.3 Input Data

To represent and quantify the hydrologic processes of a subwatershed, MIKE SHE requires input datasets that describe the makeup and spatial distribution of: geologic materials; land-use; climate conditions; channel characteristics; and topography.

The following sections summarize these inputs into the Mill Creek subwatershed model.

4.3.1 Model Domain and Simulation Period

The model domain delineated for this study is the Mill Creek subwatershed as defined by the Grand River Conservation Authority (GRCA, 2011). The model simulated the period of September 1998 to December 2005. The four months preceding 1999 were used as a model spin up period.

4.3.2 Meteorological Data

Meteorological data for the Mill Creek model include hourly precipitation, maximum daily temperature, minimum daily temperature and solar radiation. These parameters represent the input of water and energy for the subwatershed over time. Precipitation is the fundamental input into the subwatershed and can have a number of different fates such as infiltration into the groundwater system, evapotranspiration or runoff into the local stream network. Daily temperature values are used in the determination of potential evapotranspiration rates as well as snow accumulation and melting processes. Solar radiation was used in determining potential evapotranspiration rates.

Meteorological station data for the period of 1950 to 2005 are available for the Mill Creek model. Daily maximum and minimum temperature values and hourly precipitation rates from the following weather stations were used from the MNR Infilled Climate Database (Land Information Ontario, 2008):

- Guelph Turfgrass (6143090);
- Cambridge Galt MOE (6141095);
- Milton Kelso (6155187);
- Valens (6159127); and
- Waterloo Wellington 2 (6149389).

Additional meteorological data were used from the University of Waterloo weather station. Daily short wave solar radiation data from the station are available for the period of April 1998 - December 2008.

For the Mill Creek subwatershed, input precipitation and potential evapotranspiration time series for the meteorological stations are spatially distributed in the model according to Thiessen polygons that were developed within GIS software external to MIKE SHE (**Figure 4.2**).

4.3.3 Evapotranspiration data

Evapotranspiration is the combined process of water evaporation from interception and from the soil surface as well as vegetation transpiration. Potential evapotranspiration (PET) defines a reference rate of water evapotranspired per unit time, based on a reference vegetation surface with an unlimited supply of water. MIKE SHE requires the PET time series to be entered by the user, which can be generated through an algorithm external to MIKE SHE. For Mill Creek, a PET time series was generated using the Jensen method (Jensen and Haise, 1963), which is available within the Watershed Data Managment Utility time series tool (WDMUtil), which is distributed with the HSPF model. The Jensen method considers daily temperature values and solar radiation values in computing a value for PET. PET values are employed by the MIKE SHE model to calculate actual evapotranspiration (AET) by considering soil parameters, vegetation parameters and water availability.

4.3.4 Topography and Physiography

Topography defines the top elevation of the ground surface, and controls the majority of hydrologic processes, including overland flow routing and the representation of the saturated zone. The GRCA has developed a 1 m DEM for the Mill Creek subwatershed, and supplied it for this project. A 5 m DEM was derived from the 1 m DEM, and was used as the primary input to MIKE SHE, as is shown in see **Figure 4.3**.

4.3.5 Land use

Land use indicates how land areas within the watershed are being used, and determines key hydrologic features of the watershed including vegetation, surface roughness, imperviousness and depression storage.

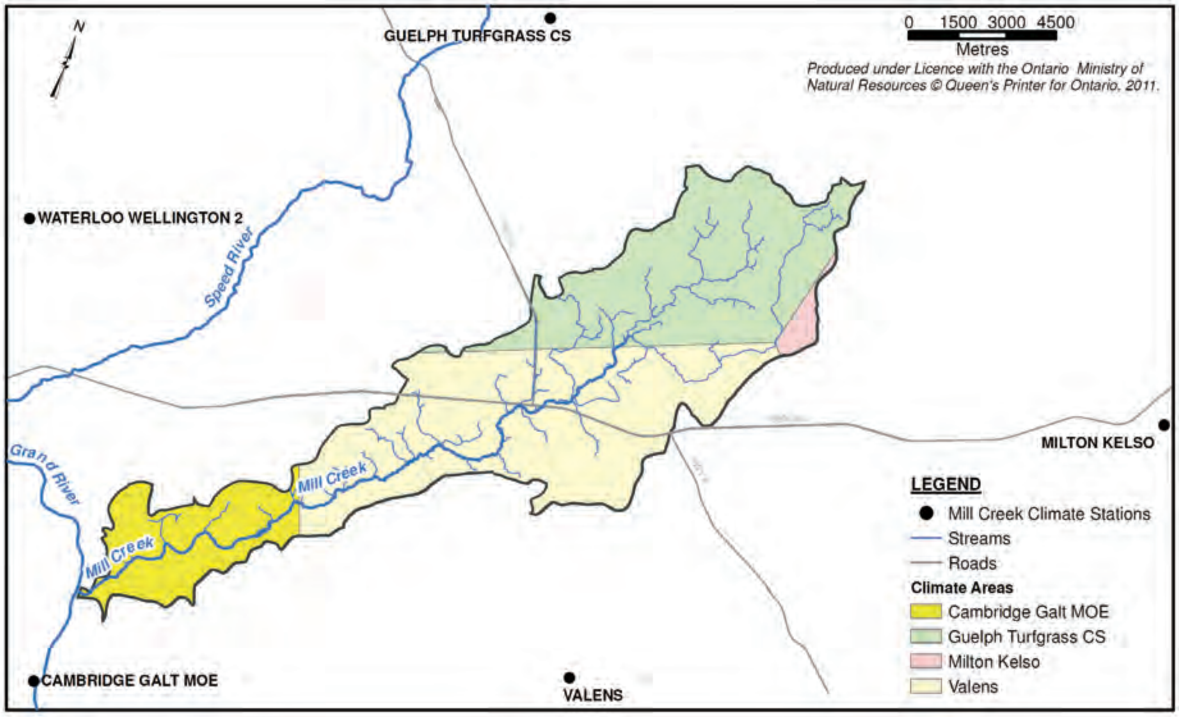

Figure 4.2 Mill Creek Climate Zones

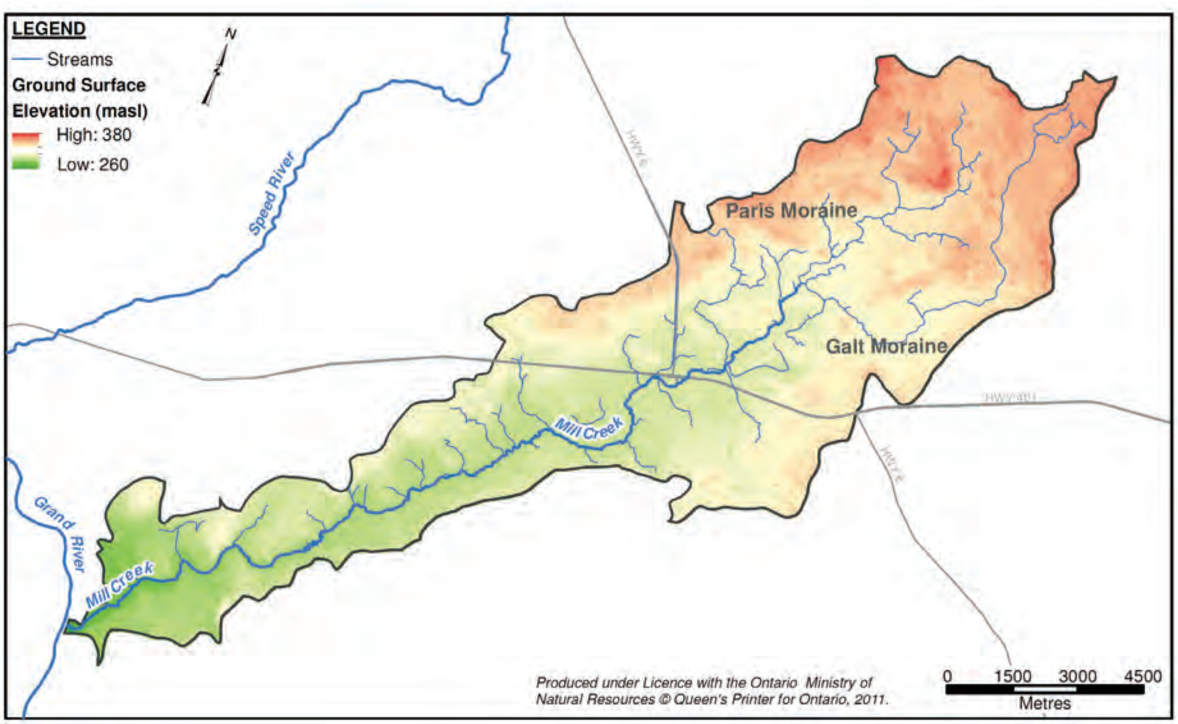

Figure 4.3 Mill Creek Topography

Evapotranspiration processes are affected by the vegetation present in each land class. Surface runoff processes are affected by surface roughness, depression storage and imperviousness associated with a particular land class. **Figure 4.4** illustrates land use classes in the Mill Creek Subwatershed. A 25 m land use grid of the area was provided by GRCA based on a 1999 satellite imagery survey of the region.

The vegetation parameters associated with rooting depth and leaf area index are defined using a time series, allowing the seasonal variation of these parameters to be captured. Values for these parameters are assigned based on the vegetation class assumed dominant in the various land classes. Values for these parameters are based on literature values and adjusted during calibration (Schurlock et al., 2001; Canadell et al., 1996).

Overland roughness is an approximation of surface friction in the subwatershed and governs the speed of surface runoff. The land use classes shown in **Figure 4.4** were assigned literature values for overland roughness, to create an overland roughness grid layer.

Paved areas are generated based on the urban land classes. A paved runoff coefficient is defined for these areas based on literature values and modelling experience, (Chin, 2006).

Depression storage values are based on land use classes and literature values as well as topography. The consideration of topography is important in Mill Creek due to the prevalence of hummocky topography associated with the Galt-Paris Moraine Complex within the subwatershed. Depression storage as a result of this terrain is computed by calculating the volume of depressions which do not drain to watercourses. These data are supplemented with literature values to form a depression storage grid layer.

4.3.6 Watercourses

The river network for Mill Creek is derived from the GRCA virtual drainage layer (**Figure 4.5**). Channel cross sections are indicated on the map and illustrate which streams are modelled in MIKE 11. Cross section elevations were taken from the 1 m Mill Creek DEM, and were cross referenced against orthoimagery to confirm channel location and extent. Due to the relative

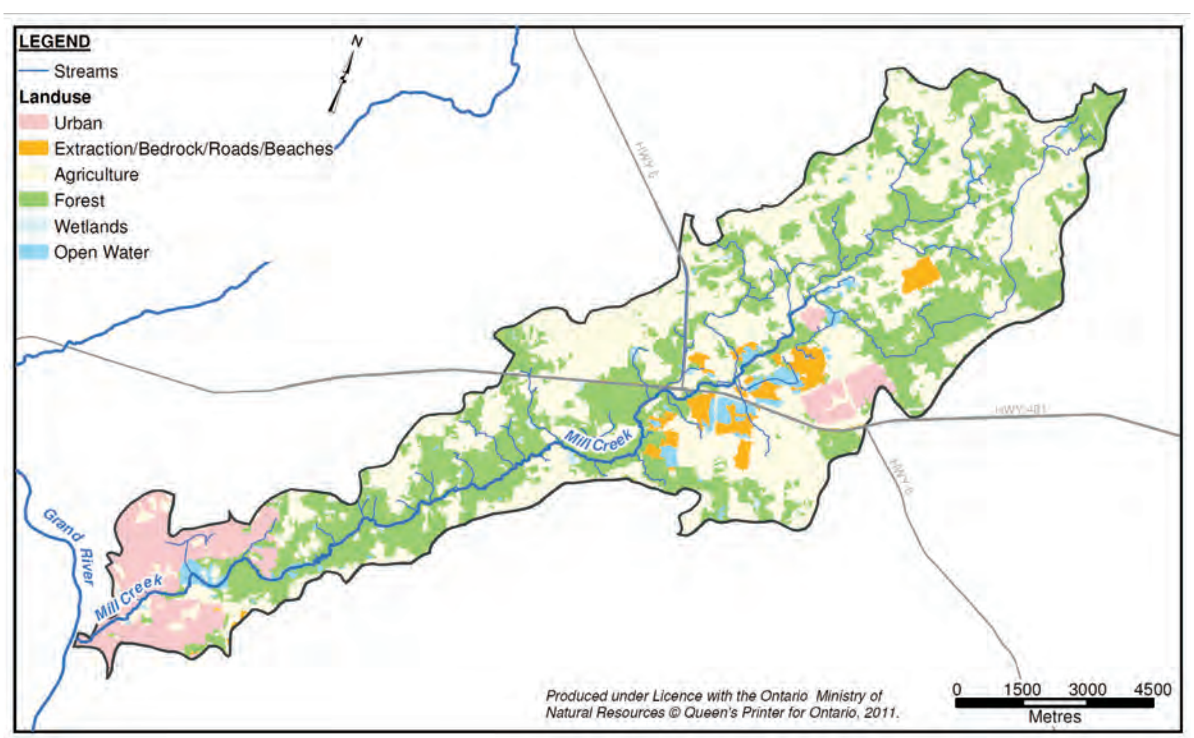

Figure 4.4 Mill Creek Land use

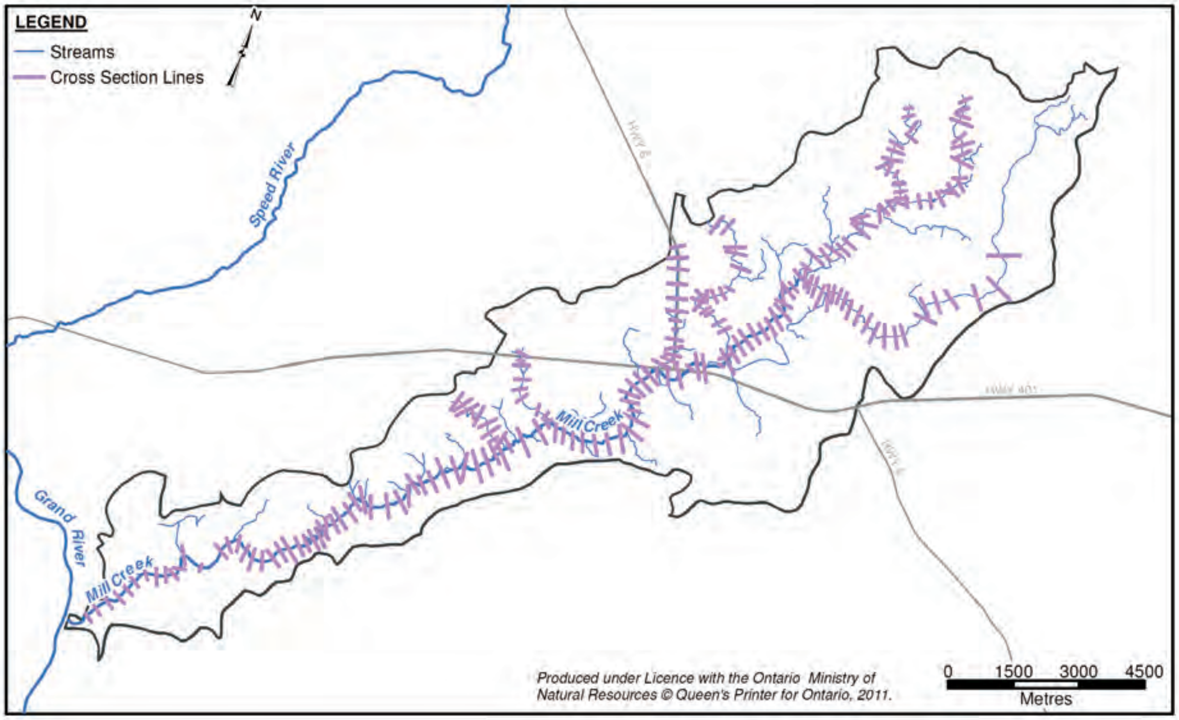

Figure 4.5 Mill Creek Virtual Drainage

coarseness of the distributed model compared to the high resolution data the cross sections geometries are derived from, discrepancies can arise between the ground surface elevations of the distributed model and the bank elevations of the hydraulic model. To address this issue, cross section bank elevations are adjusted to better match the elevations of the distributed model.

4.3.7 Quaternary Geology

Surficial soils and their hydrologic parameters (e.g., hydraulic conductivity, soil-water capacities) are a major factor in determining the hydrologic response of a watershed. The type and nature of soils will determine the proportion of precipitation that is converted to overland runoff versus infiltration, as well as the amount of soil moisture that can be held within the unsaturated zone to sustain evapotranspiration during dry periods.

The distribution of soil types are specified in the Mill Creek model by using the 1:50,000 scale seamless quaternary geology mapping produced by Ontario Geologic Survey (OGS, 2003). To minimize the number of geology types, a simplified coverage of six major geologic classes is created. The six classes are shown in **Figure 4.6**. Hydraulic properties for these general classes are taken from the GRCA GAWSER model (AquaResource, 2008). Literature values are applied for the shale and dolomite regions (Chin, 2006) as there are no matching soil classes in the GAWSER model.

4.3.8 Hydrogeology

To represent the saturated zone, the spatial and hydraulic characteristics of the subsurface materials present within Mill Creek are required to be specified in the MIKE SHE model. In this case, grids representing the elevation of each geologic layer, hydraulic conductivities (K_{xy}, K_z), specific yield, and specific storage are used. Because the entire Mill Creek watershed is contained within an existing calibrated groundwater flow model (City of Guelph Tier Three Water Budget and Local Area Risk Assessment (AquaResource, 2011b)), layers and hydraulic properties could be directly imported into MIKE SHE. The geologic layers used in the Mill Creek model are listed in **Table 4.1**. The conceptual model used is a simplification of actual conditions and is not intended to represent all data or interpretations available within the subwatershed.

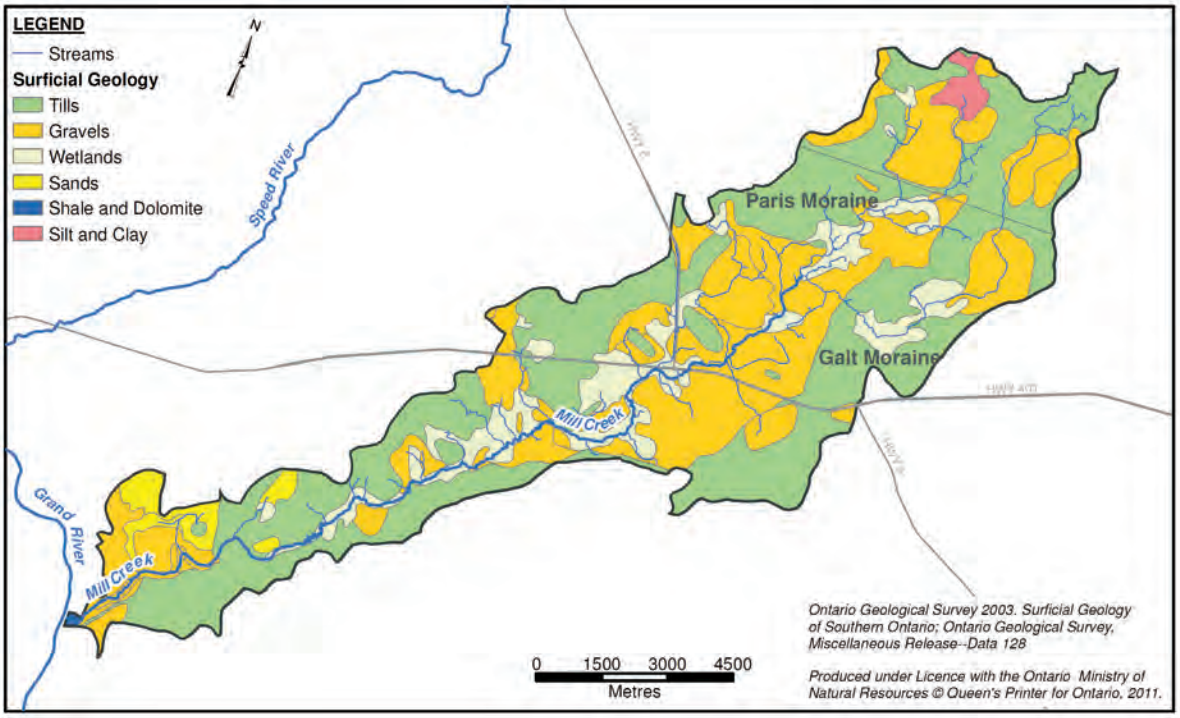

Figure 4.6 Mill Creek Surficial Geology

Table 4.1 Mill Creek Geologic Layers

Layer no.	Name
1	Upper Overburden
2	Lower Overburden
3	Weathered Bedrock
4	Guelph Formation

Initial groundwater heads are based on a steady state solution to the groundwater system. Fixed head boundary conditions are applied to the saturated zone and are based on the results of the steady-state solution.

4.4 Hydrologic Processes

The various algorithms available in MIKE SHE to represent the hydrologic processes have been described in Sections 2 and 3, and as such, will not be repeated here. **Table 4.2** describes the approximation for each major hydrologic process within the Mill Creek MIKE SHE model.

Table 4.2 Mill Creek MIKE SHE Model - Hydrologic Processes

Hydrologic Process	Process Approximation
Overland Flow	2D - Diffusive Wave Approximation of St. Venant equations of flow.
Snowmelt	Degree-day snowmelt processes
Channel Flow	1D - Fully Dynamic Wave Approximation of the St. Venant equations of flow.
Evapotranspiration	A two-layer water balance model, which applies a simple mass balance approach to predicting ET.
Unsaturated Zone	A 1D, two layer water balance model. Utilized Green-Ampt infiltration which considers: soil-water content; soil conductivity; and suction head.
Interflow	Interflow was simulated using the drainage option in MIKE SHE. The drainage code option was selected to route interflow to nearby watercourses based on surface topography.
Saturated Zone	3D Finite Difference implementation of Darcy's Law.
Time step	Variable (dependant on process). Small time steps (hourly or finer) for unsaturated zone, overland and channel flow. Larger time steps for saturated zone.

4.5 Model Development and Calibration

This section details the development and subsequent calibration of the Mill Creek model. The simulated output of the model is compared against observation data and performance metrics are provided.

4.5.1 Model Development Process

An incremental approach was used for the development the Mill Creek model, i.e., model processes are added and verified incrementally. MIKE SHE allows different components of the hydrologic cycle to be developed independently of one another. This ability simplifies the model construction process as the components can be debugged independently and then integrated. The model development process proceeded in the following fashion:

- Construct overland flow and unsaturated zone components (MIKE SHE);
- Construct and integrate river hydraulics component (MIKE 11) ; and
- Integrate saturated zone component (MIKE SHE).
- Incorporate water takings - surface water (MIKE 11) and groundwater (MIKE SHE - Saturated Zone)

These separate components are integrated in two phases. The first phase of integration links the MIKE 11 river hydraulics component with the overland flow and unsaturated zone components constructed in MIKE SHE. This combined model forms an interim stage of the Mill Creek model and the output of this model is analyzed to ensure reasonable model function. Additional testing of the interim model is conducted using a simplified linear reservoir approximation to the saturated zone. In the second phase of integration, the linear reservoir saturated zone model is replaced with the 3D finite difference model saturated zone model. After this second phase, the model for the complete hydrologic cycle is evaluated. This evaluation includes analysis of the overall water budget, stream flow values and groundwater head levels.

Certain model components were augmented or revised during the model evaluation phase. Revisions to overland flow were made with the addition of a distributed surface roughness layer and paved area runoff layer. The subsurface flow model was augmented with the addition of a drainage layer to account for interflow considerations. Revisions to channel flow were made with the addition of flooding considerations and a weir structure to better approximate the hydraulic effects of the Shades Mills dam. Finally, a flood region was delineated to help better approximate evaporative losses from a reservoir created by the Shades Mill Dam.

After these model enhancements were built into the MIKE SHE model, the remaining effort focused primarily on achieving proper water budget proportions and streamflow calibration.

4.5.2 Simulation Time

A challenge throughout the development and calibration of the Mill Creek model has been managing simulation run time. MIKE SHE simulates many hydrologic processes in a fully distributed manner and as a result, the simulation of various combinations of these processes can computationally expensive. Two techniques were used to reduce computational time. These techniques are: performing calibration simulations at a coarser model resolution than the final simulation; and running concurrent model simulations.

MIKE SHE solution time is highly dependent on grid resolution of the model. In the Mill Creek example, the time required to simulate the watershed at the 200 m grid resolution is approximately 30 minutes, whereas simulating the watershed at a 50 m resolution takes approximately 40 hours. To take advantage of the relatively short simulation times associated with the coarse grid resolution, the majority of initial model simulations are completed at this resolution. Initial model simulations are typically focused on addressing major issues (e.g., mean annual streamflow, numerical instabilities), where a coarse model which solves quickly is preferable. Once major issues are resolved at the coarse grid scale, high resolution simulations can be undertaken to refine the calibration. The ability of the MIKE SHE model to quickly shift from one resolution to another is significant benefit for managing simulation time.

The other technique employed to manage simulation run time is the simulation of concurrent models on multi-core computers. The number of total simulations is limited by computational resources and MIKE SHE license restrictions. In the case of the Mill Creek model, up to four simulations were executed concurrently for calibration purposes. The enterprise edition of MIKE SHE provides up to four computational cores for simulation purposes and additional computational licenses can be purchased. The ability to have multiple simulations with differing model parameters, allows the sensitivity of model parameters to be more rapidly assessed than a single simulation.

4.5.3 Calibration Data

To evaluate how accurately the model is replicating the hydrologic regime, simulated output must be compared against observed data. Model processes and parameters are adjusted to minimize differences between simulated and observed values, a process known as calibration. Calibration of the MIKE SHE model relies on two datasets of varying levels of reliability: streamflow observations from Mill Creek stream gauges; and groundwater level elevations contained within the Ministry of Environment water well record database.

The two stream gauges in Mill Creek provide daily streamflow estimates, and are operated by the Grand River Conservation Authority. It is important to note that because these stream gauges are not operated by Water Survey of Canada, they are not corrected for backwater effects due to ice or aquatic plant growth. Backwater effects are particularly noticeable in the winter, with uncorrected streamflow estimates under ice conditions being significantly higher than the actual flow. As a result of the Mill Creek stream gauges not being corrected, winter flows are known to be overestimated. The impact of this on model calibration will be discussed in subsequent sections.

The two stream gauges located on Mill Creek are as follows:

- Mill Creek at Aberfoyle (Period of record November 2002 - December 2009); and
- Mill Creek at Side Road 10 (Period of record August 1990 - December 2009).

For the purposes of this example, comparison of simulated to observed streamflow is shown using data collected at the Side Road 10 stream gauge location, the most downstream stream gauge in Mill Creek.

4.5.4 Calibration Process

Calibration of the Mill Creek model is primarily directed towards matching observed streamflow values while retaining a reasonable annual water budget.

Assessments of initial water budgets produced by the Mill Creek model reveal evapotranspiration values that are outside the range typically expected, and result in annual streamflow values that are much lower than observed. Evapotranspiration rates were reduced during the model calibration process.

Initial simulations also indicated that Mill Creek watercourses receive insufficient overland flow. The primary cause of this was determined to be soil hydraulic conductivities as well as vertical offsets between river bank elevations within MIKE 11 and the ground surface elevation in MIKE SHE. Infiltration parameters were adjusted where required. The elevations of MIKE 11 river banks are adjusted to better match the elevation of the ground surface in MIKE SHE and to support runoff across the landscape into the stream on the 50 m model grid.

Other parameter adjustments include: elevation at which drains become active; the drain constant; Manning's value; soil-water content holding capacities; and the riverbed conductance. Adjustments to these parameters are made to minimize differences in the following streamflow metrics:

- Mean monthly discharge;
- Mean daily discharge;
- Ranked duration plots;
- Residuals in groundwater elevations;
- Statistical comparisons (Nash-Sutcliffe, r, R^2); and
- Stream Flow Hydrographs.

The following section examines the streamflow hydrographs of the Mill Creek model over a number of timescales.

The mean monthly discharge values for the Mill Creek model are presented in **Figure 4.7**. Comparison of monthly hydrograph values provide the ability to assess how well the model is representing the seasonal behaviour of the watershed. Generally speaking, a good approximation of observed values has been achieved, although the effects of ice are apparent in the winter months. The summer flow, in addition to the rise in streamflow occurring through the fall months, is very well replicated. The mean value, in this instance, refers to the arithmetic mean which is the sum of observed values divided by the number of observations.

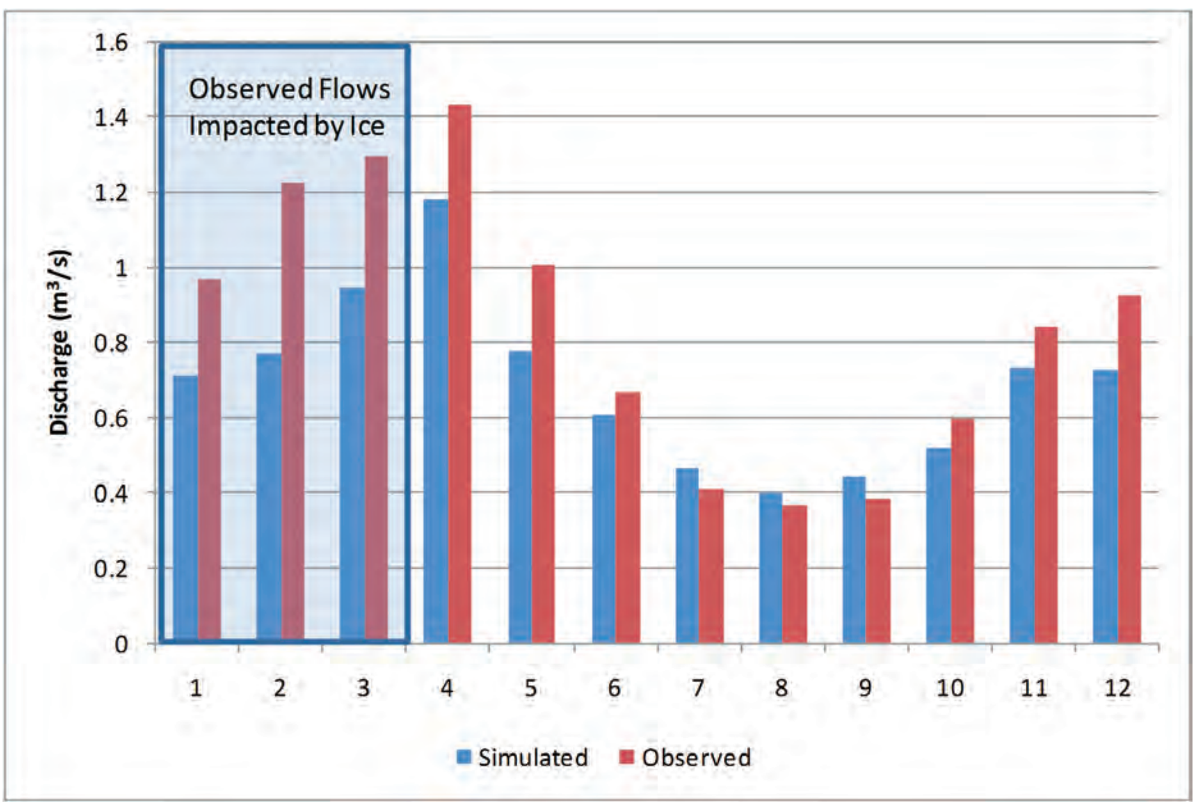

Figure 4.7 Mill Creek - Mean Monthly Flow at Side Road 10

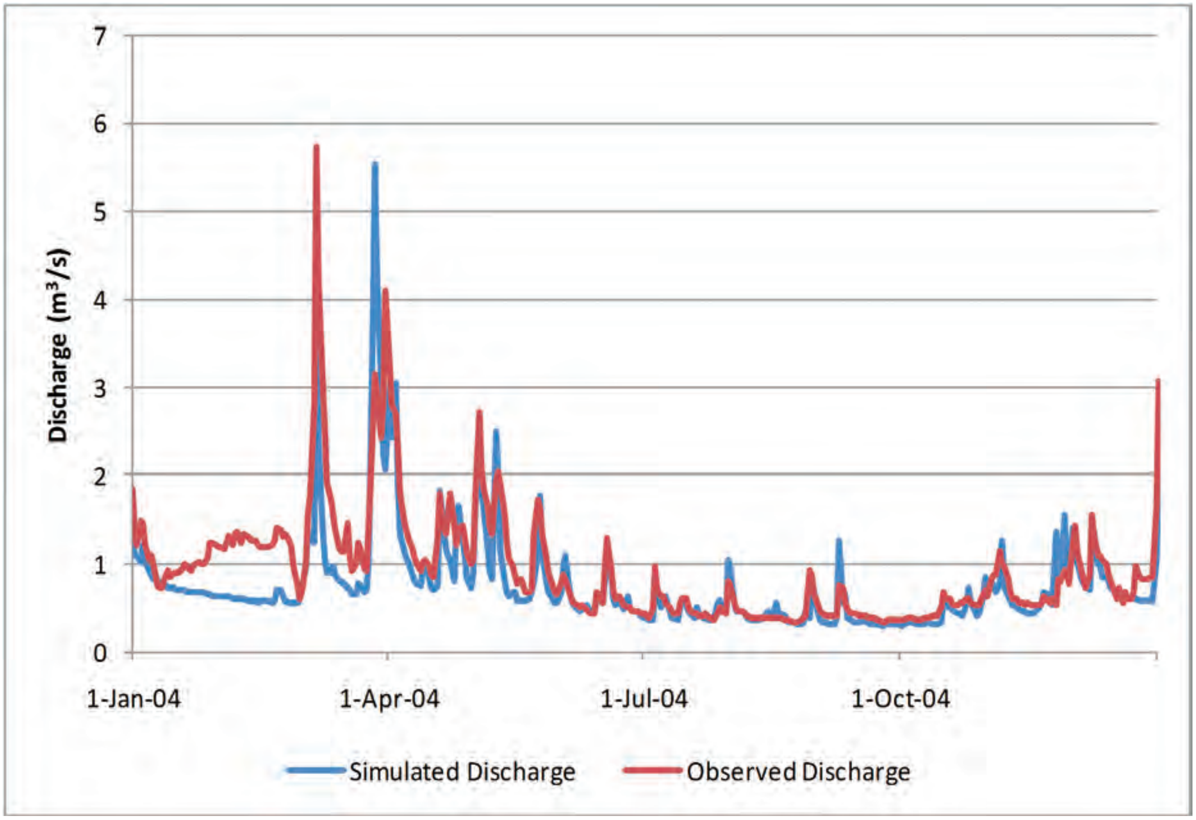

Figure 4.8 Mill Creek - Daily Flow at Side Road 10 (2004)

Mean daily discharge values for the Mill Creek Model in 2004 are presented in **Figure 4.8**. The daily simulated streamflows fit the observed streamflows very well. The timing and magnitude of streamflow increases in response to precipitation are well matched, as are the recession components of the hydrograph. Low summer flows match quite well, indicating that the saturated zone component of the model is reasonably replicating observed conditions. One area where observed and simulated flows do diverge, is in the winter months of January through March. Through this period, a clear upward trend is shown in the observed record, before a significant drop in the month of March. This is indicative of an ice jam building downstream of the gauge, which then breaks with the onset of warmer weather, allowing the backwater to quickly drain out and resulting in a "drop" in observed flows.

Finally a flow duration curve for daily discharge values is presented in **Figure 4.9**. The flow duration curve indicates the time a given flow will be equal or exceeded within the study period. While a good match to large observed flows is occurred, intermediate flows flows are generally under predicted by the model and low flows are generally over predicted.

Simulated streamflow discharge values are evaluated against observed discharge values using the following metrics: Pearson's correlation coefficient (r); Coefficient of determination (R^2); and Nash-Sutcliffe efficiency (NSE).

The correlation coefficient (r) indicates the degree of linear relationship that exists between observed and simulated data. The coefficient of determination (R^2) describes the proportion of variation in the observed data which is explained by the simulated data (Moriasi et al., 2007). The Nash-Sutcliffe efficiency quantifies the difference between observed and simulated streamflow data. According to Chiew and McMahon (1993) and Nash and Sutcliffe (1970), a NSE:

- Equal to 1 is a perfect fit;
- Greater than 0.8 is considered good;

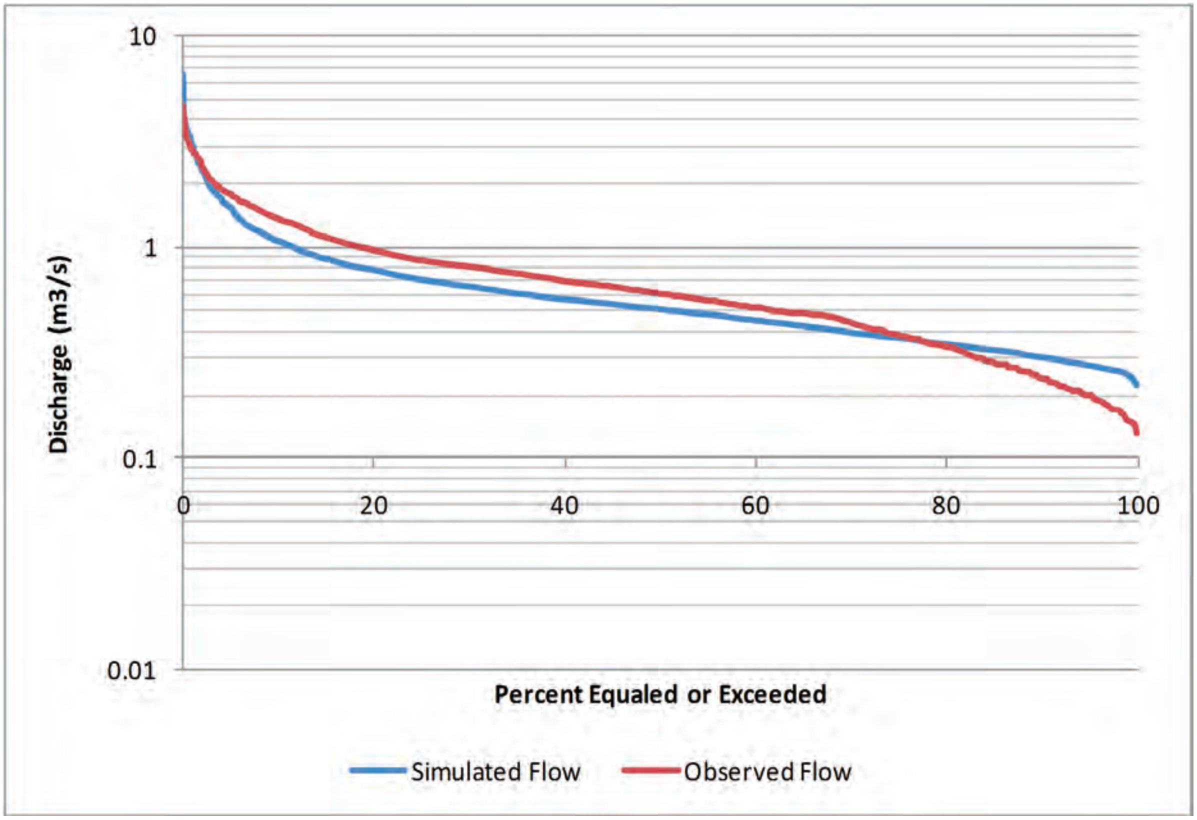

Figure 4.9 -Mill Creek at Side Road 10 - Flow Duration Curve (April - Dec)

- Greater than 0.6 is considered reasonable; and
- Less than 0 is when the observation mean is a better predictor than the model.

A recurring issue in approximating the stream flows of Mill Creek is ice effects on observed discharge values. These effects are primarily evident in the months of January through March. Ice build-up in the river serves to raise the river stage level during the winter months. The observed discharge values for Mill Creek are based on a simple stage-discharge relationship which does not differentiate between increased stage due ice effects and increased stage due to simply increased flow rates. As a result of this insensitivity, discharge levels in winter months are higher than they should be. This effect is illustrated in the observed daily flows visible in **Figure 4.8**. During the period of January through March increasing observed discharge values are reported, a time of year which is not associated with increasing discharge rates. To ensure that calibration metrics are not influenced by this phenomenon, the period of January to March is excluded in the calculation of the performance metrics.

The performance metrics for mean monthly and mean daily discharge are summarized in **Table 4.3**.

Table 4.3 Mill Creek Streamflow Performance Metrics

	Mean Monthly	Mean Daily
r	0.99	0.79
R^2	0.97	0.63
NSE	0.82	0.58

4.5.5 Groundwater

Steady-state groundwater model performance is evaluated using static head levels in water wells within the subwatershed. Approximately 80% of all groundwater head values are within 5 m of observation heads. Performance metrics for the groundwater model are presented in **Table 4.4**.

The normalized root mean squared error (NRMS) provides a goodness-of-fit assessment of a model which can be compared to another model, regardless of the scale. It is generally accepted that a normalized root mean square error (NRMS) of less than ten percent is considered satisfactory (Spitz and Moreno, 1996; Lutz et al., 2007; Gallardo et al., 2005), however the NRMS is dependent on the range of observed water levels and the scale of the model.

Root mean squared (RMS) error provides a measure of the degree of scatter about the 1:1 line of observed and simulated heads. RMS indicates that the majority of simulated water levels would fall within 4.22 m of the observed levels. A plot of simulated versus observed heads for all layers is presented in **Figure 4.10**. Included in the plot is a 1:1 line which represents a perfect match between observed and simulated heads. As well a pair of secondary lines bound the line by 10 meters above and below the 1:1 to provide a graphic reference point. The residuals are plotted in **Figure 4.11**. The statistical metrics, as well as the plot of simulated heads (H_s) versus observed heads (H_o) and spatial residuals (H_o-H_s) suggest that the MIKE SHE model is performing very well at representing the groundwater flow system and that there is no systematic bias or trends among the residuals.

Table 4.4 Mill Creek Groundwater Performance Metrics

Number of Wells	678
Mean Error	0.63 m
Mean Absolute Error	2.86 m
Root Mean Square Error	4.22 m
Normalized RMS	5.76%
Min Head	276 m AMSL
Max Head	349m AMSL

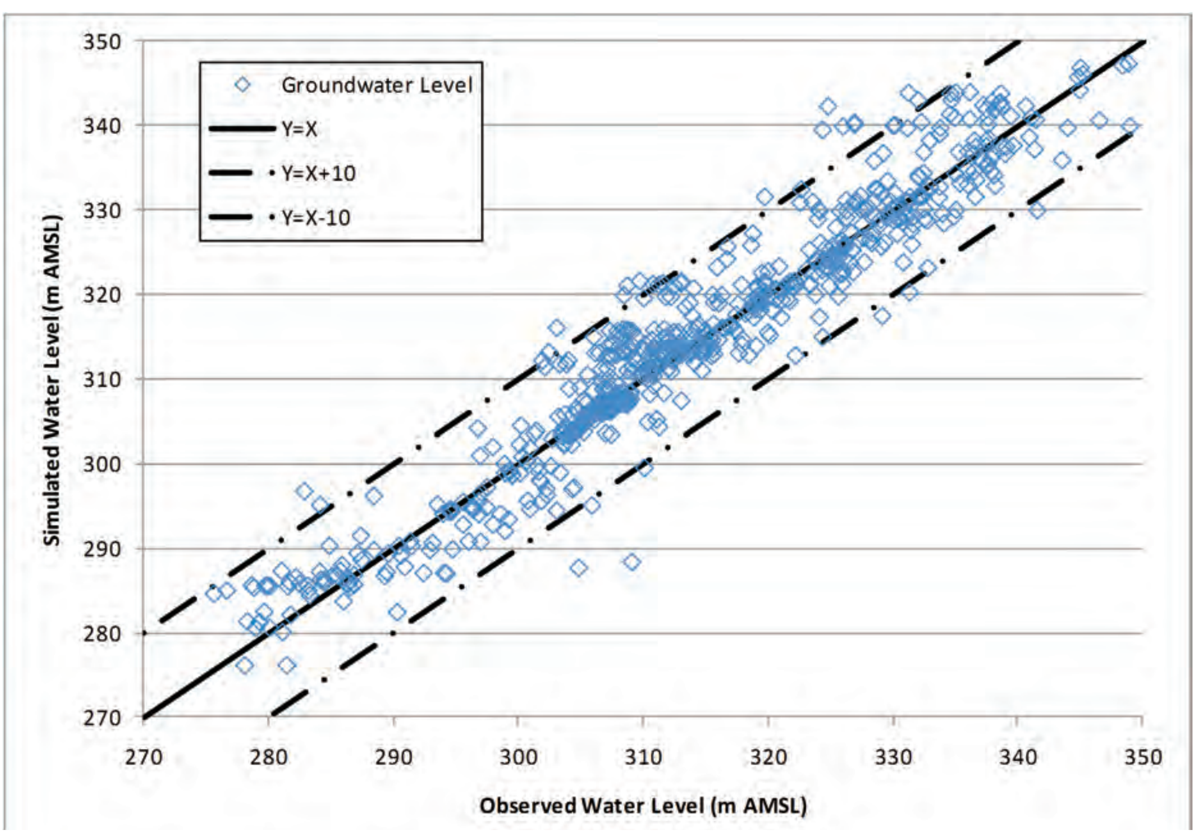

Figure 4.10 Mill Creek - Simulated vs. Observed Heads

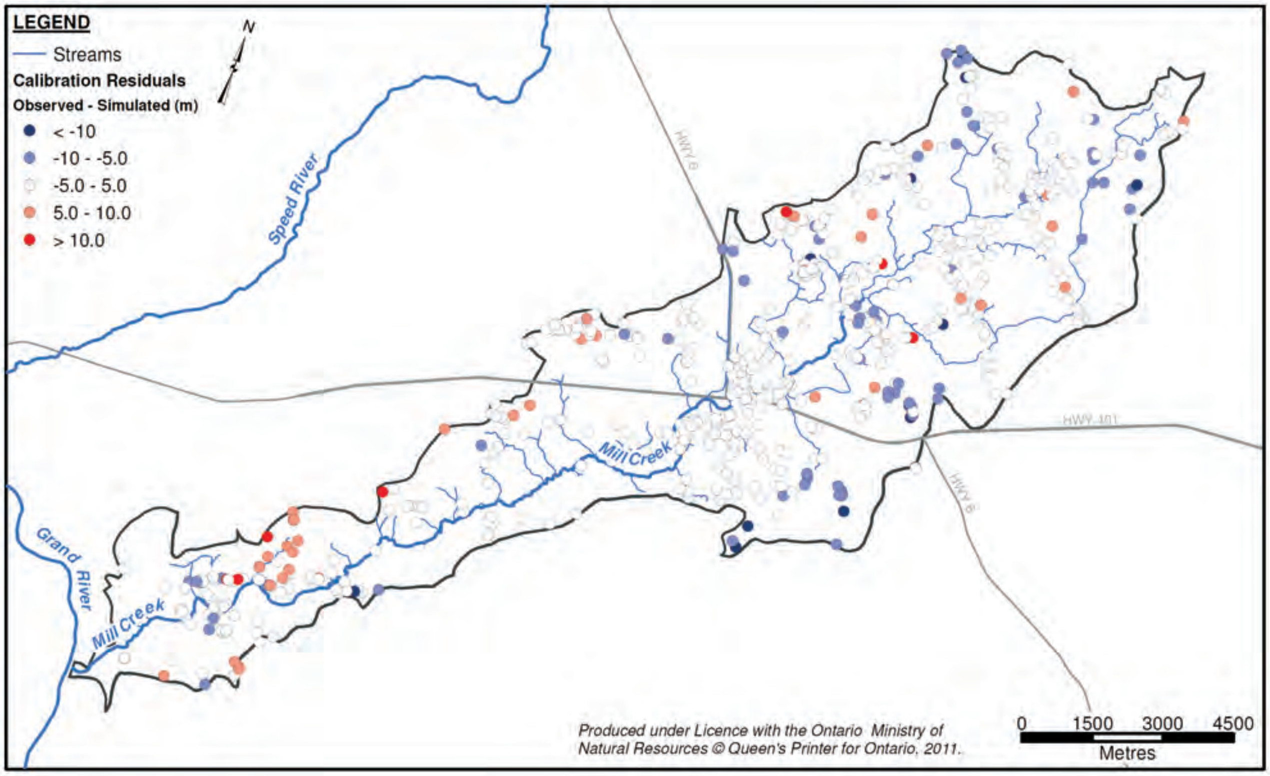

Figure 4.11 Mill Creek Groundwater Head Residuals

4.6 Output

MIKE SHE includes a powerful post-processor that is able to output results for a variety of hydrologic processes, at varying temporal and spatial scales. Results may be computed for the entire watershed; for a subcatchment of the watershed; or for an individual model cell. Temporally, these results may be output for the entire simulation period or for any time period within the simulation.

The following sections present information related to the water budget of Mill Creek both in tabular and graphical forms.

4.6.1 Water Budget Table

Table 4.5 summarizes the annual water budget for the Mill Creek model from 1999 to 2005. The water budget categories are defined as:

- Precipitation - The incident precipitation to the subwatershed;
- ET - Evapotranspiration losses;
- Overland to River - Overland flow that is provided to the river system;
- Drain to River - Interflow to the river system through drainage cells;
- Baseflow - Groundwater flow to the river system;
- GW Inflow/Outflow - Groundwater inflows and outflows to the subwatershed across the groundwater boundary;
- Storage - Water stored within various phases of the hydrologic cycle. This includes the overland regions, unsaturated zone and saturated zone; and
- Error - Water unaccounted for in water mass balance.

Also included in **Table 4.5** are the average annual values for each water budget component.

Table 4.5 Mill Creek Annual Water Budget (mm)

Year	Precip-itation	ET	Overland to River (Runoff)	Drain to River (Interflow)	Baseflow to River	Groundwater In	Groundwater Out	Storage	Error
1999	864	550	144	7	103	280	265	76	0
2000	958	573	185	9	123	274	274	68	0
2001	818	500	188	9	119	273	276	-2	0
2002	821	511	194	10	127	269	281	-32	0
2003	877	521	189	9	115	278	269	51	-1
2004	898	523	223	11	138	292	301	-6	0
2005	902	532	215	10	121	271	276	19	0
Average	877	530	191	9	121	277	277	25	0

We can check the water balance by considering a water balance on the external boundaries of the model (**Equation 4.1**). Note that all terms are in units of mm/year. Due to rounding, there is a slight difference in the calculated storage in the balance and that incorporated into the table.

Equation 4.1: Mill Creek MIKE SHE Water Balance

$$\Delta S = P - ET - Q_{OL} - Q_{DR} - Q_{BF} - Q_{GW-IN} - Q_{GW-OUT} + E$$

$$\Delta S = 877 - 530 - 191 - 9 - 121 + 277 - 277$$

$$\therefore \Delta S = 26 \frac{mm}{year}$$

ΔS - Change in Storage
P - Precipitation
ET - Evapotranspiration
Q_{OL} - Surface Runoff
Q_{DR} - Drainflow (Inteflow) to rivers
Q_{BF} - Baseflow to River
Q_{GW-IN} - Groundwater Flow In
Q_{GW-OUT} - Groundwater Flow Out
E - Error

Evapotranspiration is approximately 530 mm/yr, which is consistent with other evapotranspiration estimates for the area. Annual evapotranspiration totals for individual years vary from 500-573 mm/yr; with the variation primarily due to changes in precipitation (e.g., years with higher precipitation have higher evapotranspiration). Overland runoff (185 mm/yr) is slightly higher than baseflow (120 mm/yr).

4.6.2 Water Budget Spatial Distributions

The following sections present and discuss the spatial distribution of evapotranspiration, groundwater recharge and groundwater discharge throughout the Mill Creek subwatershed. The distributions presented are the average annual values for the 1999-2005 period.

Evapotranspiration

The surface topology, soil layer and vegetation all have important roles in determining the distribution of evapotranspiration within a region. **Figure 4.12** illustrates the spatial distribution of evapotranspiration in the Mill Creek subwatershed. The general hummocky topography of the region creates large stores of ponded water which contribute to evapotranspiration throughout the region. The wetland areas within the watershed have evapotranspiration rates that approach the specified potential evapotranspiration rate. Wetlands are able to evapotranspire this amount of water due to the soil-water content within those model cells being constantly resupplied by groundwater discharge, or overland runoff, from adjacent cells.

Figure 4.13 illustrates the average annual recharge for the Mill Creek Subwatershed. Low recharge values are present in the central wetland regions of the subwatershed, where shallow water tables inhibit the downward movement of water. Ponds resulting from aggregate extraction also act as local groundwater discharge features as predicted by the model. Regions of higher recharge are present within areas that have

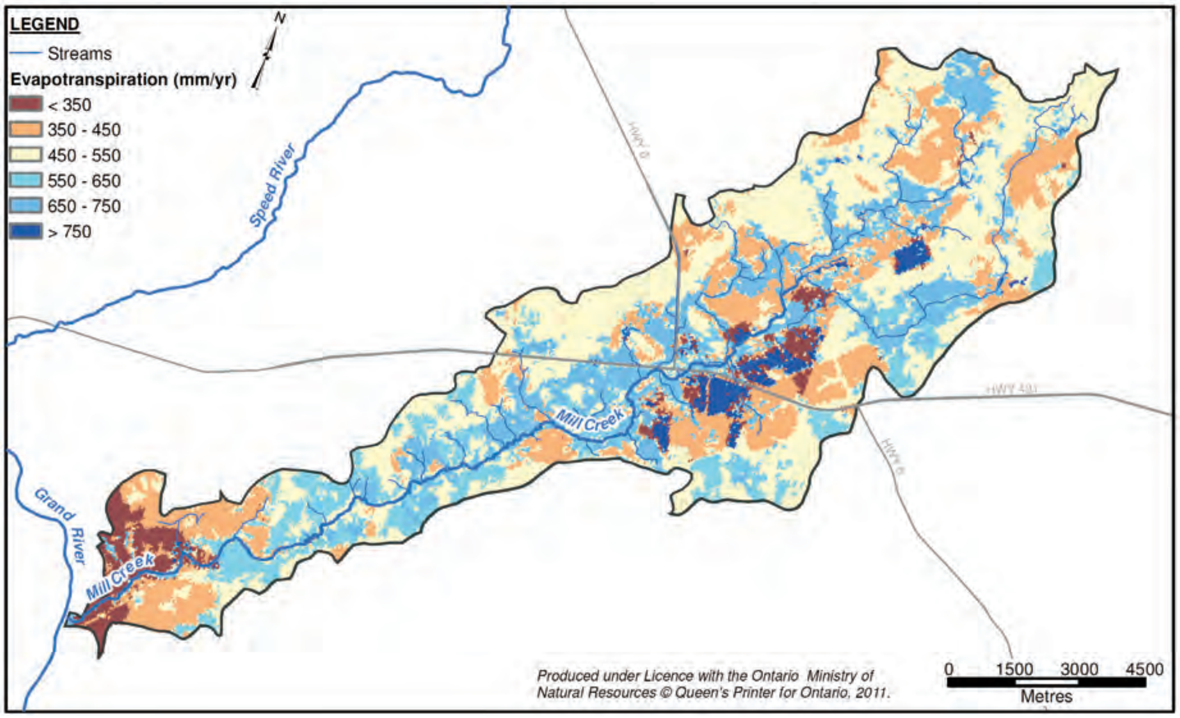

Figure 4.12 Mill Creek Average Annual Evapotranspiration

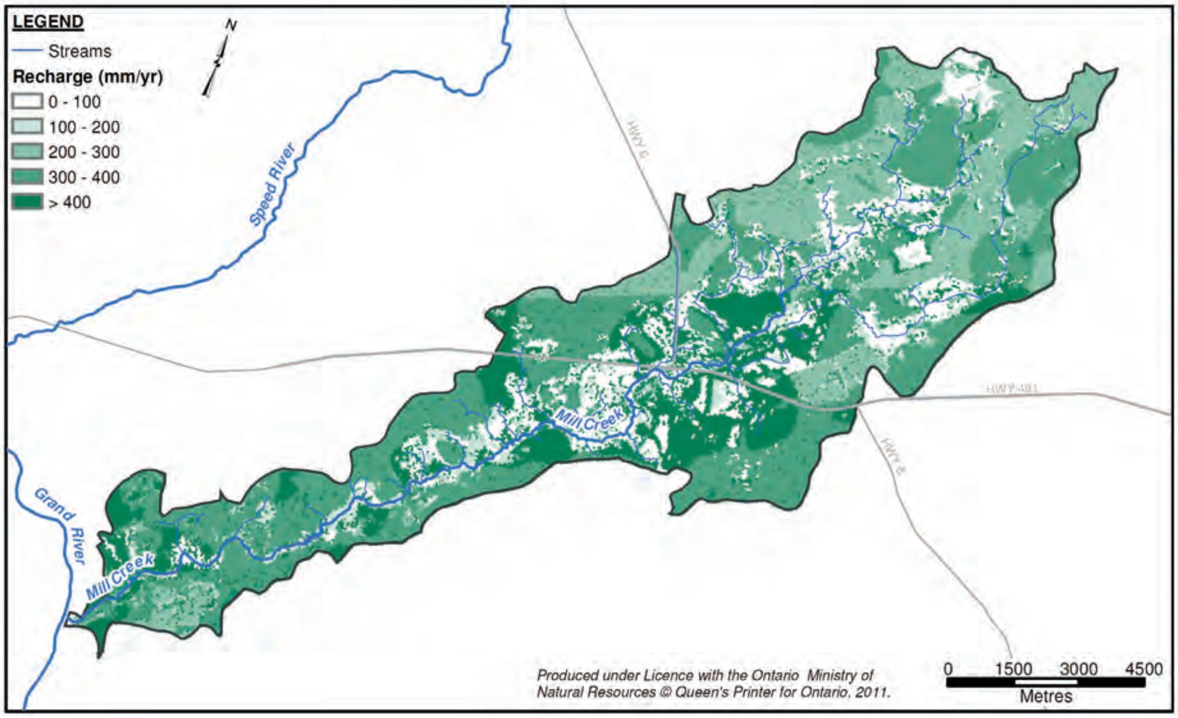

Figure 4.13 Mill Creek Average Annual Groundwater Recharge

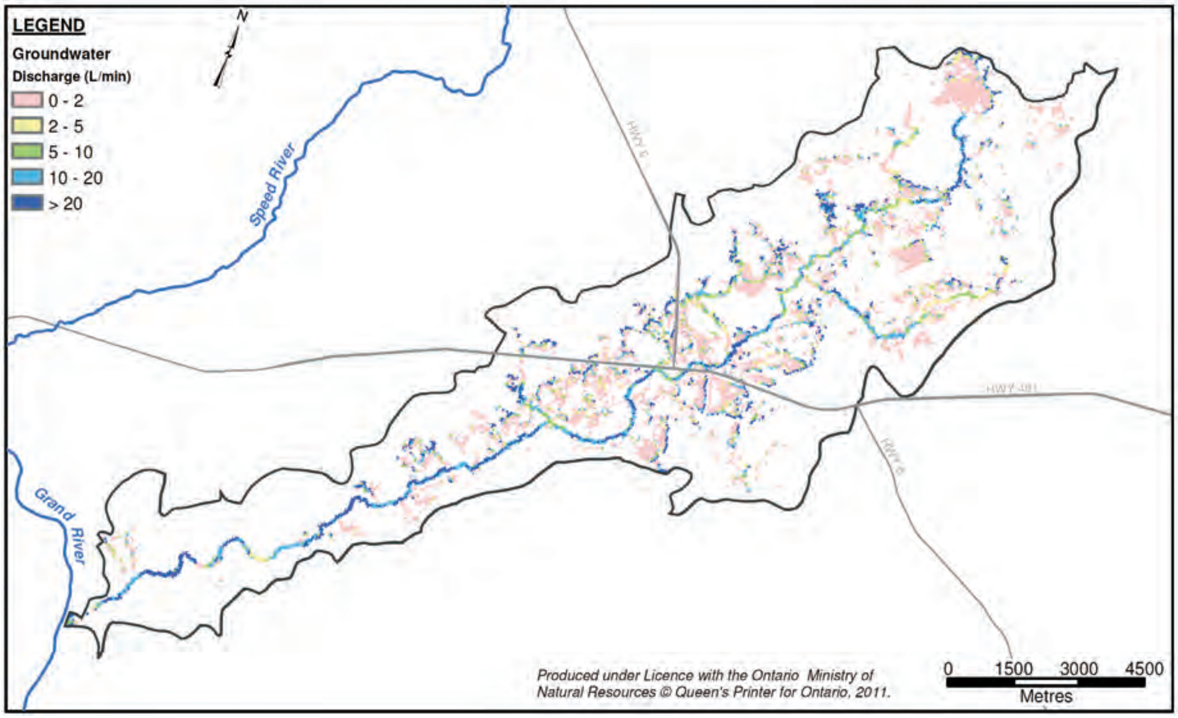

Figure 4.14 Mill Creek Average Annual Discharge

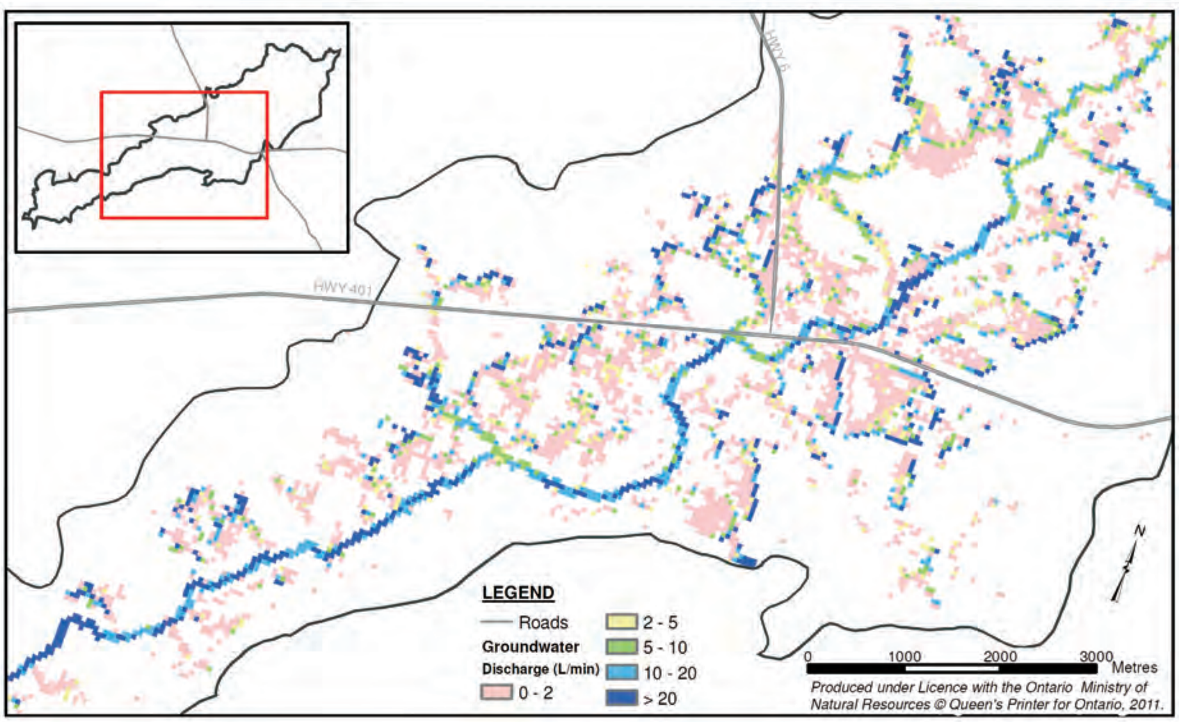

Figure 4.15 Mill Creek Average Annual Discharge - Central Wetland Area

sand or gravel surficial materials and a sufficiently thick unsaturated zone.

Groundwater Discharge and Stream Leakage

Figure 4.14 illustrates the average annual groundwater discharge to streams and overland features. The majority of Mill Creek and its tributaries appear to be receiving groundwater discharge from the saturated zone. Diffuse groundwater discharge is predicted throughout the gravel outwash portion of the subwatershed, particularly within the central wetland areas as well as in the headwaters; see **Figure 4.15** and **Figure 4.16**. Groundwater discharge is also predicted in the area immediately surrounding the ponds created from aggregate extraction activities, which suggests the ponds are discharge features.

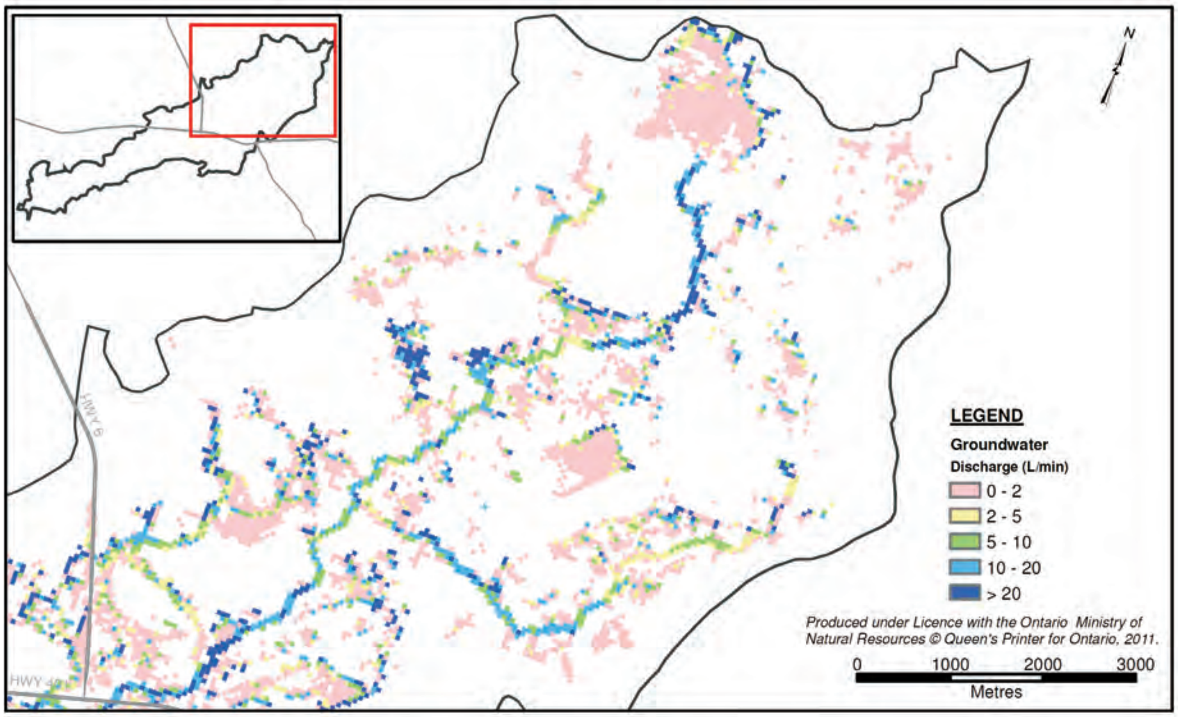

Figure 4.16 Mill Creek Average Annual Discharge - Headwaters Region

4.6.3 Wetland Assessment

Wetlands are commonly characterized as areas with ponded water, or areas that have sufficient soil-water content that allows the point of full saturation to be approached. These conditions are either sustained by groundwater discharging to surface, or overland runoff being captured by surface topography.

Properly simulating the hydrologic function of a wetland requires accurate representation of the extensive surface and groundwater processes that supports the wetland. Integrated models are well suited to this task and provide a large variety of quantitative data which may be used to characterize a particular wetland.

Figure 4.17 and **Figure 4.18** present the soil saturation of a wetland subsection of the Mill Creek at differing times during the year. The mapped values illustrate those areas where unsaturated soil zone deficit is zero (e.g., fully saturated conditions). **Figure 4.17** illustrates the unsaturated soil zone deficit in mid-April. Fully saturated areas are predicted to occur throughout the figure, and generally match up well with the mapped extent of wetland features. As fully saturated conditions will promote overland runoff, rather than infiltration, the ability to reasonably predict the aerial extent of fully saturated conditions will allow the model to more reliably represent the hydrologic response of the watershed. This is key to water budget and risk assessment studies, as impacts of changes within the

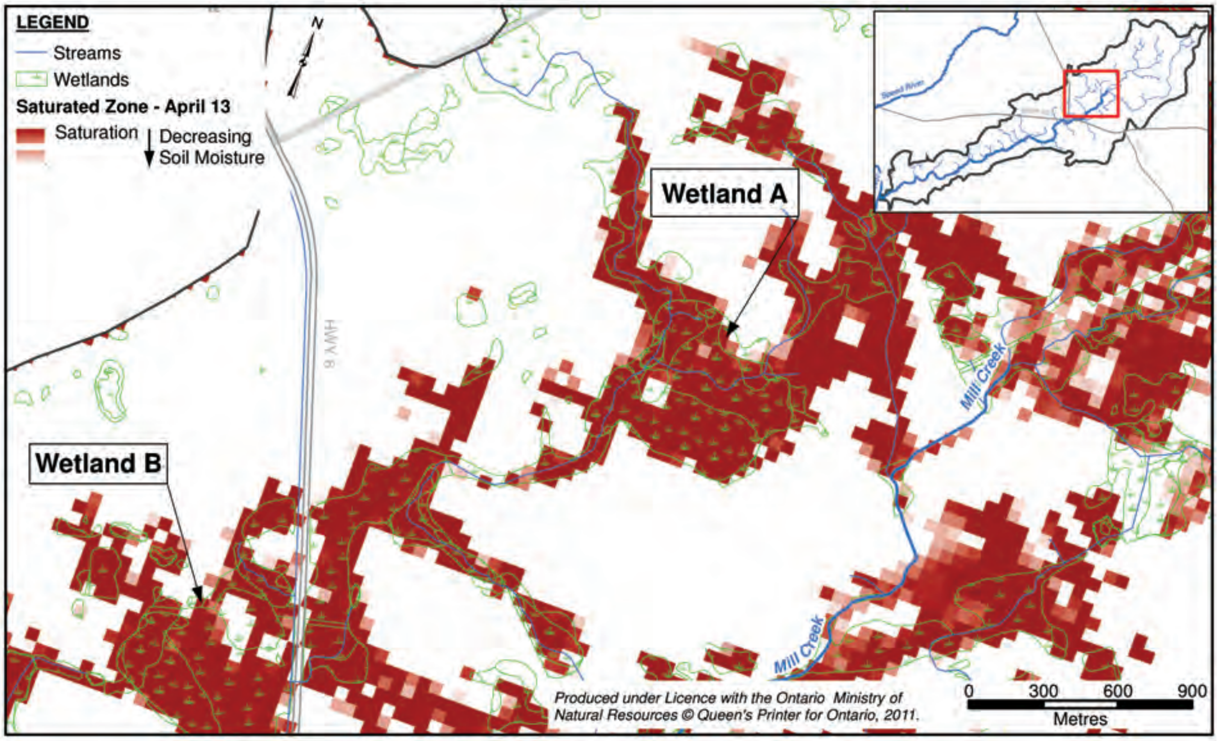

Figure 4.17 Mill Creek Wetlands - Soil Moisture - April 13

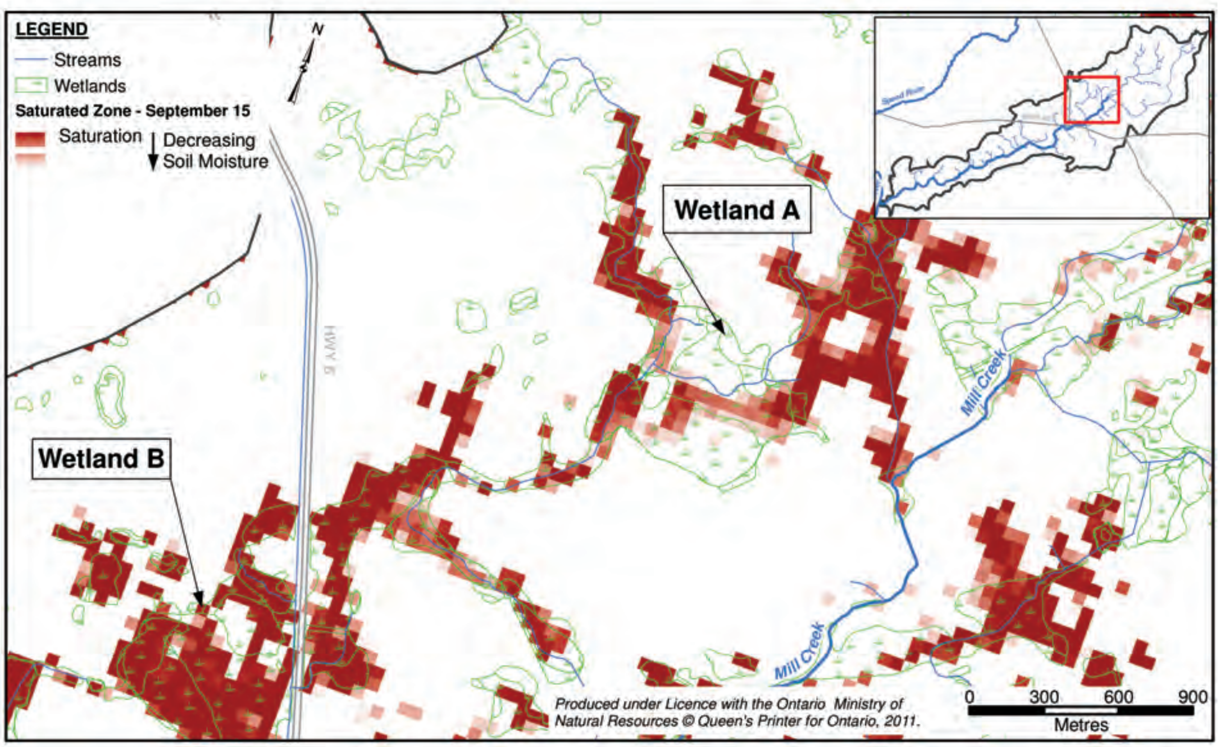

Figure 4.18 Mill Creek Wetlands - Soil Moisture - September 15

groundwater system to wetlands is a key component of these kinds of analyses.

Figure 4.18 illustrates the same dataset as **Figure 4.17**, but for mid-September conditions. As would be expected by the end of summer, the extent of fully saturated conditions is greatly reduced from the spring conditions shown in **Figure 4.17**. Fully saturated areas that are remaining (Wetland B) are likely supported by groundwater discharge, as overland runoff in the summer months is usually negligible. Wetlands supported by groundwater discharge are typically persistently saturated, and likely have vegetation communities that are specific to these conditions. **Figure 4.18** indicates several wetland areas, that were fully saturated during spring conditions, that are now unsaturated (e.g., Wetland A). These areas likely indicate those wetlands that were supported by capturing overland runoff during wet conditions, and are only replenished when overland runoff is generated.

The water budgets for Wetland A of **Figure 4.17** and the Mill Creek subwatershed are presented in **Table 4.6**. As would be expected, evapotranspiration rates are substantially higher in the wetland than for the Mill Creek subwatershed. Inflows to Wetland A include: precipitation (804 mm/yr); overland inflow (1527 mm/yr); and groundwater inflow (576 mm/yr). This breakdown of inflows suggests that the wetland is primarily sustained through overland inflows, and indicates that the wetland may become dry, as overland inflows diminish in the dry season.

In addition to understanding the hydrologic processes that are sustaining a particular wetland, the ability to represent the transient conditions in a wetland more closely replicates the hydrologic response of a watershed. A wetland that is continually fully saturated and unable to take precipitation into storage will produce a significantly different hydrologic response than a wetland that has dried out and has storage available for retention of overland runoff. In watersheds where a large proportion of the total area is wetland, this can be an important consideration.

Table 4.6 Mill Creek Wetland A and Subwatershed Water Budgets

	Wetland Region (mm per unit area of Wetland/yr)	Model Average (mm per unit area/yr)
Precipitation	804	877
Evapotranspiration	667	530
Overland Inflow	1527	0
Overland Outflow	155	6
Overland to River	1790	185
Interflow to River	36	9
Baseflow to River	70	121
GW inflow	576	277
GW outflow	183	277
Storage	6	26
Error	-1	0

4.7 Conclusions

The Mill Creek MIKE SHE model produced streamflows and groundwater head levels which were in close agreement with observation data, while maintaining a well proportioned water budget. These results were achieved after a limited period of model calibration. Monthly streamflow values had an R^2 of 0.97 and a NSE of 0.82. Daily hydrographs matched observed values well in terms of magnitude, timing and post-event recession. Daily streamflows had a R^2 of 0.63 and a NSE of 0.58. The groundwater portion of the model performed very well, with approximately 80% of groundwater head levels falling within 5 m of observed head levels and a NRMS of 5.92%. Based on these model statistics, it can be said that the MIKE SHE model constructed for Mill Creek performed very well at replicating observed hydrologic conditions.

4.7.1 Benefits of MIKE SHE

The Mill Creek case study found the primary strengths of MIKE SHE to be the robust interface, general flexibility and results generation and assessment.

The layout of the MIKE SHE model helps to deliver an intuitive model construction environment. A graphic user interface (GUI) is utilized for all portions of the MIKE SHE environment. This GUI is arranged in a straightforward manner and contextual help is available throughout the interface. The GUI also provides the means to directly edit time series and grid data. Additionally, the interface has some ability to error check the model set up. If model component configuration is incomplete or incorrect, the user will be notified with graphic or text notifications. The pre-processor function of the MIKE SHE model also provides error checking of model components and set up. It should be noted that while a GUI is highly useful it should not be used as a crutch for unqualified individuals to conduct modelling exercises.

This flexibility of MIKE SHE model is present in terms of data inputs, hydrologic process approximations and general model configuration. Data inputs may be provided as constant, spatially uniform values or as complex time varying, spatially distributed values. Hydrologic processes may be approximated through a number of representations of varying complexity levels which in turn require varying amounts of input data. Users may configure a hydrologic process using either a complex model or a simple model and easily switch between the two to evaluate the benefits of either approach. The flexibility of MIKE SHE facilitates the evaluation of modelling alternatives in a quick and straightforward manner.

MIKE SHE provides a diversity of results which may be rapidly generated and assessed. The results editing tools provide good visualizations and are straightforward to use. Results from model runs are available in a very rapid manner and many results may be viewed 'on the fly'. Spatially speaking, model results may be examined for the whole study area, some subsection of the study area or a particular cell within the model. A water balance editor provides the ability to create custom water balance calculations for generating time series or gridded data. The results tools in MIKE SHE provide the means to critically assess model output in an efficient and rapid manner.

4.7.2 Limitations of MIKE SHE

As with all integrated model codes, the primary challenge when utilizing MIKE SHE is minimizing the computation time required for a simulation. The fully distributed, deterministic modelling in MIKE SHE is computationally intense, and often requires a significant amount of time. To minimize simulation time, and maximize calibration efforts, steps were taken to ensure the simulation times of the Mill Creek subwatershed remained manageable during this project. The first step was to build the MIKE SHE model by iteratively adding layers of complexity, rather than attempting to build the fully distributed integrated model at once. The second step was to calibrate the model at a coarse resolution of 200 m. Calibration at coarse resolution provided for run times which were dramatically faster than those of the final, high resolution model (50 m), and allowed for many more parameter realizations than one would be able to consider when only using a high resolution model.

The uniform grid, and the inability to refine around features of interest, is a limitation. While there was no specific need to refine around specific features in the Mill Creek MIKE SHE model, a variable grid that had larger elements further away from watercourses, and finer closer to watercourses, would have reduced the computational complexity of the model, and subsequently, simulation runtime.

5. Integrated Modelling Guidance and Conclusions

Water resources managers in the Province of Ontario have become increasingly aware that the surface water and groundwater components of the hydrologic cycle should be considered as integrated processes (Winter et al., 1998). In the past, assessments of groundwater and surface water interactions have been based on the applications of analytical and numerical modelling techniques that do not fully reflect the complex linkages between groundwater and surface water systems. In many cases, the application of separate groundwater or surface water models can be fully justified. As an example, a model that strictly represents the groundwater flow system may be entirely adequate when delineating capture zones and wellhead protection areas for municipal production wells. Similarly, a model that only represents the surface water flow system may be adequate when simulating a dynamic stormwater drainage network. However, these traditional modelling techniques may no longer be appropriate when evaluating complex groundwater and surface water interactions. For example, predicting the impact of increased groundwater withdrawals on streamflow requires both an assessment of changes to the transient groundwater flow system as well as impacts to surface water features that can vary on an hourly basis. While traditional modelling techniques have a role in identifying potential impacts, they are limited in their ability to represent the interaction of surface water and groundwater.

Integrated groundwater and surface water models have been developed with the goal of being able to represent the complete hydrologic system and simulate the flow of water through and between the groundwater and surface water systems. This document demonstrates that integrated models can be developed and calibrated to Ontario conditions and that integrated models have the potential to provide significant benefits to the water resources community.

The benefits of integrated models, however, cannot be realized without a cost. Integrated groundwater and surface water models are complicated. While practitioners tasked with applying them must have sufficient practical and theoretical background relating to both surface water and groundwater, teams comprised of individual surface water and groundwater modelling experts may be successful at completing integrated modelling studies. Integrated surface water and groundwater models are computationally expensive. Simulation times for fully integrated models may be on the order of days, and as a result, careful planning of model development and calibration activities is necessary to make the process as efficient as possible. Finally, integrated water resources models are more physically-based than traditional models that often rely on empirical formulations. Data collection and model conceptualization efforts may be greater than traditional modelling studies, although integrated models may be more reliable when utilizing the models to quantify changes to the hydrologic system (e.g., climate change impacts).

5.1 Conclusions

5.1.1 General Conclusions

The case studies presented in this document were developed and applied to evaluate HydroGeoSphere (Therrien et al., 2010), GSFLOW (Markstrom et al., 2008) and MIKE SHE (Graham and Butts, 2005; DHI, 2009a,b) under Ontario hydrologic and hydrogeologic conditions. The following general conclusions are made regarding what was learned through conducting these case studies:

Benefits Over Traditional Models

A properly calibrated integrated surface water and groundwater model offer several benefits over traditional modelling approaches, as summarised below:

Realistic Water Budgets. As demonstrated through the case studies, integrated models offer the ability to better represent some hydrological systems and provide more reliable water budgets where those systems are influenced by groundwater / surface water interactions. As an example, actual evapotranspiration rates in wetlands can be better estimated by properly simulating the contribution of groundwater or overland flow to wetlands and the corresponding evaporation and transpiration from the wetlands. Additionally, in areas with shallow water tables (e.g., wetlands, other discharge features), the downward movement of water is constrained by the water table, resulting in reduced groundwater recharge. Constraining groundwater recharge by considering the depth of the water table can be significant in some areas.

Groundwater/Surface Water Interactions. Situations where groundwater and surface water interactions play a significant role with respect to characterization or impact analysis will benefit the most when applying an integrated model. Specific situations where integrated models offer potential benefits are the evaluation of cold water streams and wetlands. Groundwater flow models are useful when trying to look at average or long-term transient groundwater conditions. However, integrated models allow for the assessment of groundwater contributions as part of the overall hydrologic system. Similarly, surface water flow models are useful when evaluating runoff-dominated systems but due to their simplifications of groundwater processes they may misrepresent hydrologic processes in groundwater-dominated environments.

Evaluation of Streamflow Impacts and Hydrographs. The typical method of assessing a hydrologic impact from a groundwater taking or land use change is to examine the change to a streamflow hydrograph. When dealing specifically with groundwater takings, a groundwater model is often used to estimate the change in groundwater levels and average or steady-state impacts to groundwater discharge or baseflow. The problem with this approach is that groundwater discharge or baseflow is not a constant value and it is often difficult to associate an estimated steady-state baseflow estimate with a transient hydrograph. Integrated models provide the advantage of predicting a hydrograph and baseflow change associated with groundwater takings or land use developments.

Limitations of Integrated Models

While they offer a number of significant benefits, there are several limitations of integrated models that should be considered before implementing an integrated model:

Computational Requirements. The computational requirements associated with an integrated model are much greater than typical applications of separate surface water hydrology and groundwater flow models.

Calibration Requirements. Due primarily to longer simulation times, model calibration requirements are greater than those of typical models. Typical models may have simulation times on the order of minutes, and this allows a modeller to evaluate many combinations of model parameters to arrive at sets of parameters resulting in an acceptably calibrated model. The number of processes included in an integrated model also increases the calibration requirements. In calibrating an integrated model, the modeller is tasked with calibrating a hydrologic model, a transient groundwater flow model and a hydraulic model.

Urban Systems. While currently available integrated models can accommodate for the broad hydrologic impacts of urban development, they cannot explicitly represent stormwater conveyance systems. It should be noted that some integrated model codes allow linkages to stormwater models to represent these conveyance systems (e.g., MIKE SHE links to MIKE URBAN).

Experience of Modeller and Learning Curve. All integrated models are complex and require a significant dedication of time and effort to become sufficiently proficient to fully utilize them on a project.

Conceptual Model Requirements

The conceptual model needed to develop an integrated groundwater and surface water model is similar to that needed to develop separate groundwater and surface water models with the exception of some of the features associated with groundwater and surface water interaction. Specification of surface water channel and reservoir profiles and elevations should be as precise as possible, as the computed elevation of water in a surface water feature has a large influence on the flow of water from those features to and from groundwater. While the elevation of surface water features is important in groundwater models as boundary conditions, the shape of those features and the impact of that shape on the conveyance of water is not critical in most groundwater flow models.

5.1.2 When are Integrated Models Most Valuable?

Integrated models offer a physical representation of a hydrologic system and are most valuable in situations where groundwater and surface water interactions play a large role in the hydrologic system. However, the benefits of an integrated model must be balanced with the costs associated with developing and calibrating an integrated modelling approach. Integrated models are becoming more available and their use should be encouraged in situations where: the results of a modelling study rely on proper representation of the complete hydrologic cycle; the data requirements can be sufficiently met; and the model can be constructed with an understanding of the key processes within the restrictions of the study (i.e. budget, expertise, and computer resources). There will also be situations where traditional groundwater or surface water models can achieve the desired project objectives more efficiently than an integrated model. This section describes some aspects that should be considered when selecting the modelling approach.

Integrated models are most appropriate in watersheds that are heavily influenced by groundwater and surface water interactions. These watersheds include extensive wetlands and coldwater streams. By explicitly representing the groundwater system as part of the hydrologic cycle, the model can account for effects of fluctuating groundwater levels on soil moisture and groundwater discharge. This consideration is particularly relevant with respect to simulating low water and drought conditions when groundwater levels may drop below the stream channel, resulting in a disconnection between the surface and groundwater flow systems and a cessation of discharge to the stream. Integrated models are able to simulate this reduced groundwater discharge along with the other components of streamflow, which allows the study team to evaluate the impact of reduced groundwater discharge in context of the entire streamflow hydrograph.

Integrated models may be less applicable in watersheds that are highly runoff-dominated (e.g., urban or clay based). In such watersheds, most precipitation becomes overland runoff, with minimal infiltration and subsequent groundwater discharge. In these systems, there is typically less potential for interaction between the surface and groundwater systems. Groundwater levels, if they are shallow, usually do not significantly modify the hydrologic response of the surface water system due to the low permeability of the watershed. In such systems, a traditional surface water model may provide a reasonable and physically representative simulation of the hydrologic system.

Hydrologic Impact Assessments of Groundwater Takings

The impacts of groundwater takings on surface water flows cannot be well represented using traditional modelling approaches. Surface water models typically rely on the linear reservoir approximation to simulate groundwater systems and cannot physically represent the impact of groundwater takings on streamflow. Typical impact assessments involve steady-state groundwater simulations and assumptions of non-varying surface water body boundary conditions and cannot always replicate the impact to surface water flows on a seasonal and annual basis.

Where there are extensive groundwater withdrawals, and it is expected that surface water flows are impacted as a result of the withdrawals, an integrated model is better suited than a traditional modelling approach, as the model is able to directly simulate the impact of the takings on the streamflow hydrograph.

Wetlands Assessments

The hydrologic processes relating to wetlands are typically poorly represented in traditional modelling approaches. This is primarily due to the intricate groundwater and surface water interactions associated with wetlands. In Southern Ontario, wetlands are usually located within areas of either groundwater discharge, or in depressions where overland flow collects. In such areas, high water tables, supported by the groundwater flow system or overland inflows, affect the hydrology by maintaining soil-water content at, or, near full saturation. Due to the high soil-water content, overland runoff, rather than infiltration, is generated. Evapotranspiration within wetlands is not limited by precipitation received by the wetland, but can be as high as potential evapotranspiration due to the additional supply of water provided by groundwater or overland inflows.

Traditional modelling approaches typically do not represent groundwater / surface water interactions in the vicinity of wetlands as well as integrated models. Integrated models offer an opportunity to better understand water budgets in wetlands both in natural and impacted conditions.

5.1.3 Summary of Integrated Models

Chapter 2 of this document evaluates each of the integrated models with respect to a series of objective criteria. Specific observations and conclusions relating to each of the three integrated models were gathered as part of the case study completion and are provided below.

MIKE SHE

MIKE SHE is a distributed hydrologic model that provides a physically-based representation of all land-based phases of the hydrologic cycle including precipitation, irrigation, snowmelt, evapotranspiration (ET), overland flow, unsaturated flow, groundwater flow, and streamflow as well as the various interactions between these processes. The modelling platform allows for a great deal of flexibility with respect to the level of detail in which each process is simulated.

MIKE SHE has been found to be the most comprehensive and flexible integrated model evaluated and applied to the case studies in this document. Highlights of the model are as follows:

- Surface water hydrology and hydraulics. MIKE SHE's representation of surface water features is flexible and robust. Many options are provided when computing hydrologic processes (e.g., evapotranspiration, snow, runoff, infiltration) and multiple levels of complexity are offered with respect to hydraulic routing as well as the consideration of hydraulic structures through the MIKE 11 model.
- Modular Structure. MIKE SHE has a very modular structure which allows the user to modify the hydrologic and hydraulic routines used for a simulation.
- Grid Flexibility. MIKE SHE maps the input to the simulation grid 'on the fly' and enables the user to begin a calibration effort with a coarse grid and proceed with finer grid resolution as needed.
- Graphical users interface. The MIKE SHE userinterface facilitates the development and calibration of models and also the review and analysis of model output.
- Data Pre-Processing. The users interface aids in the processing of input data and distributes it to the appropriate hydrologic, hydrogeologic or hydraulic modelling components.
- Technical Support. DHI, the authors of the code, are available to provide technical support by telephone or email.

Limitations of the MIKE SHE model are summarized below:

- Uniform Grid Resolution. The overall capabilities of MIKE SHE would be advanced if a variable resolution grid system was present. This would allow grid refinement near features of importance such as wells and surface water bodies as well as regions of highly variable topography. From a computational perspective this would also be beneficial as it would allow more efficient application of computing resources (e.g., fine model resolution within areas of interest and coarse resolution in applied in surrounding regions).
- Source code. The source code is proprietary and not available for examination or modification.
- Purchase price. The purchase price of the code is considered to be high as compared to other alternatives. However, the experience gained when completing the case studies demonstrated that the purchase price of the code can be offset on a single project by the time savings realized by having the user interface available and the overall flexibility offered by MIKE SHE.

GSFLOW

GSFLOW is a coupled groundwater and surface water flow model based on the integration of the U.S. Geological Survey Precipitation-Runoff Modelling System (PRMS, Leavesley et al., 1983) and the U.S. Geological Survey Modular Groundwater Flow Model (MODFLOW-2005, Harbaugh, 2005). In addition to the basic PRMS and MODFLOW simulation methods, several additional simulation methods were developed, and existing PRMS modules and MODFLOW packages were modified, to facilitate integration of the models. Methods were developed to route flow among the PRMS Hydrologic Response Units (HRUs), between HRUs and the MODFLOW finite-difference cells, and between HRUs and streams and lakes. PRMS and MODFLOW have similar modular programming methods, which allow for their integration while retaining independence that permits substitution of and extension with additional PRMS modules and MODFLOW packages. PRMS is implemented in the U.S. Geological Survey Modular Modelling System (Leavesley et al., 1996), which provides input and output and integration functions used by PRMS and GSFLOW modules.

Highlights of the model identified when applying it in the case studies are as follows:

- MODFLOW integration. MODFLOW is the

most widely used groundwater flow model in the world, and its implementation within GSFLOW is advantageous.
- Public domain code. All code relating to MODFLOW, PRMS, and the linking routines, are provided by the developers.

Limitations of the GSFLOW model are summarized below:

- Lack of complete graphical users interface. While processing tools are available for components of the model (e.g., MODFLOW) and the USGS provides data processing tools, there is not a single and complete graphical user interface available for GSFLOW and this will limit its ability to be applied cost-effectively for most applications.
- Empirical water budget formulation. While PRMS includes a variety of methods for simulating surface water hydrologic processes; however, not all of the methods are not enabled for the integration with MODFLOW in GSFLOW. The GSFLOW implementation of PRMS represents water interchange between the surface soil zone using three reservoirs, preferential flow, gravity flow and capillary reservoir. The soil zone exchanges flow with the MODFLOW unsaturated zone. The rate of interchange between these reservoirs is modelled empirically and identification of optimal parameters was found to be difficult when completing the case studies.
- Restricted surface water time stepping and hydraulic routing. The GSFLOW implementation of MODFLOW and PRMS does not allow for time steps in surface water model to be less than one day. This limitation may influence the simulation of hydrologic processes such as runoff, infiltration and snowmelt, all of which occur during shorter periods within a day. Also, the model cannot represent overland flow routing and complex hydraulic structures, which are important to properly representing surface water flow events that occur during short time periods. GSFLOW may be calibrated to account for longer-term hydrologic trends; however, it should not be considered suitable for many short-term events.

Given the widespread support for MODFLOW and the public availability of source code there is significant long-term opportunity for GSFLOW to evolve as a powerful integrated groundwater and surface water model. However, its limitations relating to the implementation of surface water flow processes should be considered when selecting the model to ensure that the modelling approach can meet all objectives.

HydroGeoSphere

HydroGeoSphere is a physically-based and distributed groundwater - surface water interaction model that has been produced by a consortium of researchers at the University of Waterloo in Ontario, Université Laval in Quebec and HydroGeoLogic, Inc. in Virginia. The surface flow module of HydroGeoSphere is based on the Surface Water Flow Package of the MODHMS model, and was fully-integrated into the 3D variably-saturated groundwater flow model FRAC3DVS (Therrien et al., 2004).

Highlights of the HydroGeoSphere model identified when applying it in the Orangeville case study are as follows:

- Strong theoretical basis and numerical formulation. HydroGeoSphere implements an advanced formulation for surface water flow and unsaturated and saturated groundwater flow. The model also provides a number of features such as contaminant and thermal transport not evaluated as part of this study.
- Irregular mesh support. The implementation of a control volume finite element approach that makes its numerical meshes more amenable to systems with irregular geometries.

Limitations of the HydroGeoSphere model are summarized below:

- Computational Effort. HydroGeoSphere's simulation times may be on the order of weeks for a single scenario and this is not practical for many applications.
- Surface water hydrologic processes and features. HydroGeoSphere does not fully account for hydrologic processes such as snowmelt and hydraulic structures. If these processes were accounted for, shorter climate input (e.g., hourly precipitation) would be required to simulate surface water conditions and this would lengthen computational times considerably.
- Lack of a graphical user interface. While processing

tools are available for components of the model (e.g., finite element mesh), there is not a single and complete graphical users interface available for HydroGeoSphere and this will limit its ability to be applied cost-effectively for most applications.

With respect to integrated groundwater and surface water modelling, HydroGeoSphere is perhaps the most advanced model from a scientific basis. This study, however, evaluated HydroGeoSphere strictly for its ability to address water quantity management issues in Ontario and found the model to be limited in this regard. HydroGeoSphere, as tested, lacks support for key surface water flow processes needed to properly represent hydrologic conditions in Ontario. It takes a great deal of time, data, effort, and knowledge to run and utilize the model. It may not be immediately practical to apply HydroGeoSphere to typical water resources problems in the province; however, it may evolve over time with the support of additional researcher and advances in computing power.

5.2 Recommended Integrated Modelling Steps

Developing an integrated model is not a straightforward process, and requires the knowledge and input from both surface water and groundwater disciplines. To fully utilize expertise from disciplines, a phased development approach is recommended when utilizing integrated models. This phased approach is illustrated in **Figure 5.1** and discussed in the following sections.

5.2.1 Data Gathering

In general, the data gathering requirements needed to develop and calibrate an integrated model are similar to those needed to develop separate surface water and groundwater models. In addition to typical data collection requirements, the case studies identified the following types of data which are critical to a physically-based model that properly represents the linkages between groundwater and surface water systems:

- Channel cross-sections and elevations. These datasets are required to simulate the water elevation in surface water features which influences the direction and rate of water flow between surface water and groundwater systems; and
- Vegetation and land cover. The modelling objectives associated with an integrated modelling project will likely require a rigorous simulation of water budget parameters including evapotranspiration and infiltration which are influenced by the types of land cover and vegetation.
- Hydraulic control structures. These structures regulate the streamflow regime and influence surface water groundwater interaction. Relevant data may include operational rule curves, outlet characteristics and stage-storage relationships.
- Water Takings. Relevant data may include coordinates of taking, source of taking, quantity of taking. Groundwater takings should include well screen elevation.

5.2.2 Develop Conceptual Model

The conceptual model needed to develop a physically-based integrated model needs to consist of a number of components relating to the groundwater and surface water systems and the linkages between the two as summarized below:

- Groundwater system. The conceptual model relating to the groundwater flow portion of the integrated model should be developed in a manner similar to any groundwater modelling study and will include horizontal and vertical interpretations of hydrogeological units and estimates of hydraulic conductivity for these units. An integrated model simulates the groundwater flow system transiently, and therefore, needs to have estimates of storage parameters (e.g., specific yield and storativity);
- Surface water system. The conceptual model relating to the surface water portion of the integrated model will be similar to that of other surface water modelling studies and will include maps of land cover, imperviousness, soils etc. The integrated model may require the user to specify how and where to direct surface water runoff from impervious areas and this would be interpreted prior to the development of the actual numerical model; and
- Groundwater and surface water interactions. A key objective of the integrated modelling effort will be the simulation of groundwater and surface water interactions, and as a result it is important to identify those areas within a watershed ahead of time where these interactions are known to be important. This knowledge is important as a check and balance on modelling results. As an example, field observations showing that baseflow increases significantly

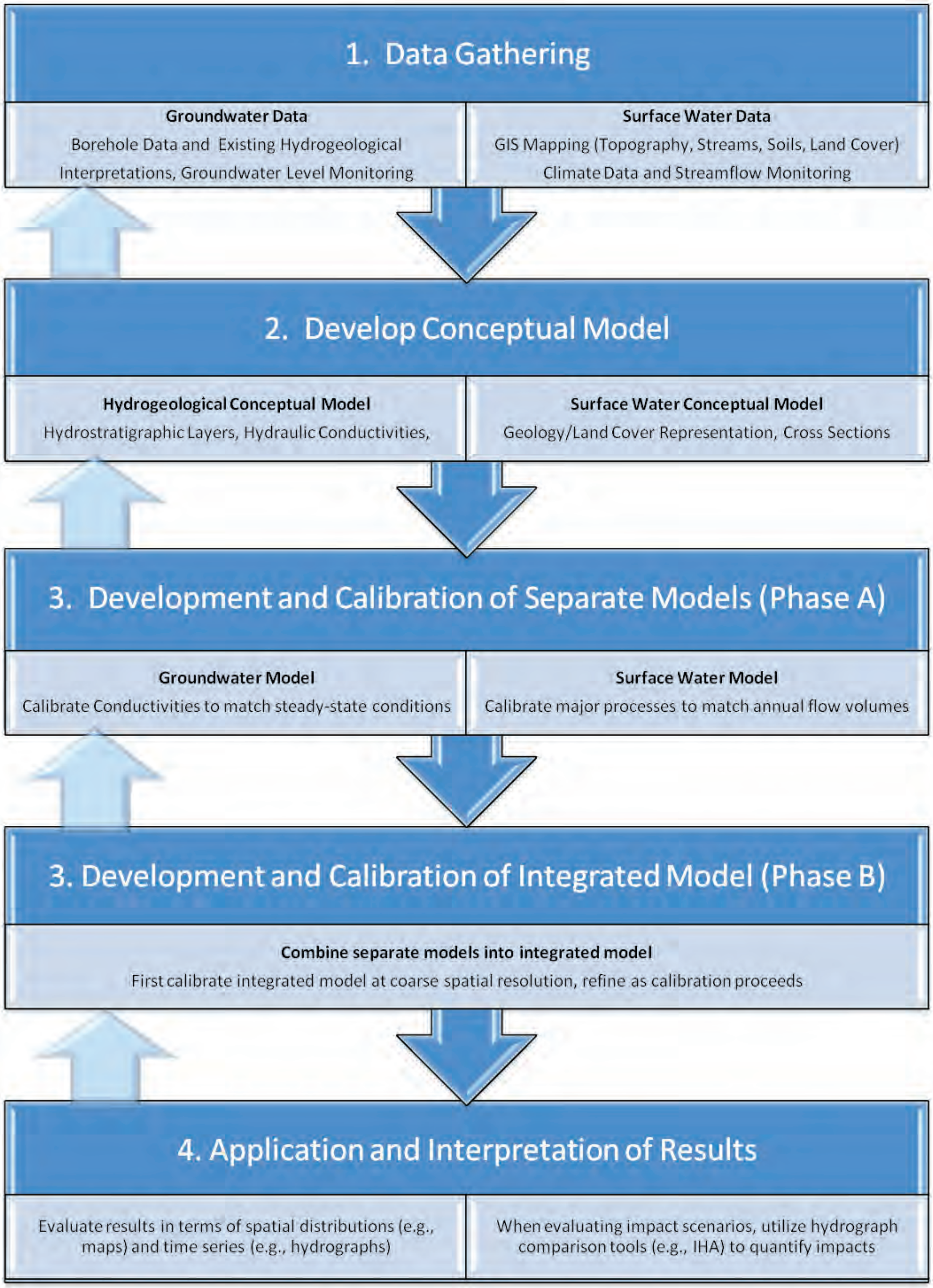

Figure 5.1 Phased Approach for Integrated Model Applications

over a surface water reach should be identified and documented so that this information can be compared to the model predictions.

5.2.3 Model Development and Calibration

A phased model development approach is recommended when developing and calibrating integrated models to best manage the significant computational effort associated with a fully integrated simulation. The underlying concept of phased model development is the incremental addition of model complexity during development. The modelling effort should start simple in terms of spatial discretization and representation of physical processes and becomes more complex as the model is calibrated to represent the simpler conditions.

The following general strategies are employed in the phased development of integrated models:

- Phase A - Initially develop separate surface water and groundwater models. Construct, test and calibrate these models taking advantage of the computational efficiencies available at this level. Potentially have groundwater and surface water models being developed by separate individuals or teams. When these separate process models are constructed, tested and partially calibrated they may be integrated into combined models which surface water, groundwater and river processes together.
- Phase B - Develop, test and calibrate integrated models. Similar to Phase A, start with the integrated model being simplified and test the model to ensure simulations are formulated correctly. Refine the modelling approach through the calibration process.
- During the development of each of the phases, the hydrologic and hydraulic process representations can be varied, starting with simple formulations before ending with the final detailed formulation.
- As the model is calibrated to finer measures the spatial and temporal resolution of the model must increase.

The general benefit of the phased development approach is limiting the scope and the computational complexity of the model. This allows model development to proceed in an efficient manner.

Phase A - Separate Surface Water and Groundwater Model Development and Calibration

The creation of separate models for surface water and groundwater processes serves to limit the scope of the initial models which simplifies their construction, testing and calibration. Additionally these separate models are computationally much simpler than the combined models. A large amount of computational complexity is introduced by coupling surface water and groundwater process models and as such the separate models run much faster. The utilization of simple hydrologic process representations, in place of complex approximations, again serves to limit computational complexity and increase model efficiency. Finally, the spatial and temporal resolution of the model are refined as the calibration of model proceeds from coarse measures to fine measures and as such the computational complexity of the model is limited greatly.

Developing separate models allows both groundwater and surface water modellers to focus on their respective fields, and isolate large scale issues prior to coupling both systems and introducing additional computational complexity. As an example, the surface water modeller can focus on achieving reasonable runoff rates and timing of runoff and river routing. Similarly, the groundwater modeller can calibrate the groundwater model to steady-state conditions and available pumping tests, with the simulations occurring in a time period of minutes as opposed to hours or even days. In some cases pre existing models from other investigations may be used in this phase. Depending on the integrated model code selected, there may be sufficient flexibility to build each model without considering the other system. For example, MIKE SHE can support a surface water model without a 3D groundwater system, or alternatively a groundwater flow model without a surface water system.

Depending on the modeller's ability and available tools, one may find it more efficient to develop a model using a separate code (e.g., FEFLOW or MODFLOW for groundwater) than to develop and calibrate a groundwater model within the integrated model code. It may be entirely reasonable and justifiable to develop the groundwater model using this other code and migrate the conceptual model including layer elevations and hydrogeologic parameters into the new integrated model. In HydroGeoSphere this approach could be applied by considering only saturated groundwater flow within the model initially. Once satisfactory calibration of the groundwater system had occurred the model may be run in integrated mode by enabling variably saturated flow as well as overland flow processes.

It should be recognized that calibrated parameters developed during the Phase A calibration process may require adjustment when moving to the integrated modelling phase. Predicted recharge rates are likely to change, as will simulated hydrogeologic conditions in the vicinity of wetlands or other groundwater discharge features. Similarly, simulated baseflows may not be well represented at this point due to surface/groundwater interactions not yet considered. As a result, the modelling team should be careful not to proceed too far with model calibration before integrating the models in Phase B.

Phase B - Integrated Groundwater / Surface Water Model Development and Calibration

Once the separate surface and groundwater models are developed and are reasonably replicating observed conditions, the two separate models should be coupled within the integrated model code.

In general, the calibration of integrated models should be approached first using coarse temporal and spatial measures then finer measures as the calibration effort proceeds. Initial calibration runs should utilize coarse spatial resolutions and short time periods. Coarse spatial resolutions provide relatively shorter model simulation times. Numerous adjustments to various model parameters and inputs may be required during the initial calibration of a model and therefore short simulation times are useful in expediting the initial calibration process. As the model calibration proceeds the spatial resolution may be refined.

Model calibration efforts for an integrated model are similar or greater than those of a transient water budget model. Initial efforts should first be directed to matching mean annual streamflows and achieving a well proportioned annual water budget. This scale of calibration provides an assessment of the proper functioning of large scale hydrologic processes such as evapotranspiration. Once annual conditions are reasonable, the calibration efforts should be directed towards representing mean monthly streamflows and then potentially median monthly streamflows. The function of seasonal processes may be assessed at this level of calibration (e.g., snow melt). After monthly values are calibrated reasonably, calibration to daily streamflows may follow. This level of calibration provides an assessment of the function of short term hydrologic processes (e.g., stream routing, runoff, infiltration).

5.2.4 Application and Interpretation of Results

Integrated models are able to generate vast amounts of output data, describing hydrologic processes ranging from precipitation to channel flow, and all processes in-between. The study objectives will determine the output datasets required, and may range from a hydrograph for a single point to gridded, time-varying detailed water budget information. For those integrated model codes without interfaces to manage output data, a significant investment in developing data management routines will be required to facilitate the interpretation and presentation of output data.

As a minimum, results should be evaluated in terms of spatial distributions for the primary water budget terms at the average annual scale. These would include evapotranspiration, groundwater recharge and groundwater discharge. Such maps can be used to gain an appreciation of how the model is replicating hydrologic processes, and increase the level of confidence associated with model predictions.

Other output datasets may include transient water levels to infer historical variations within specific wetland complexes, or particle tracking results to link recharge features to a water supply well. Almost all output datasets are transient in nature, allowing the investigator to gain an appreciation of variability within a year, and between years. Some models evaluated as part of this study have interfaces which allow animations of output data, which greatly aids in conveying modelling insights to interested parties.

One of the primary advantages of utilizing integrated models to inform impact assessment exercises is their ability to quantify the impacts of a particular change in relation to the overall flow regime. Changes to the landscape, whether this includes urbanization or increased water takings, rarely affect only one portion of the flow regime. Rather, impacts can be experienced during peak flows, recessions from peak flows and baseflows. The magnitude of impacts can vary month-to-month, as well as between years. Being able to compare hydrographs for both pre- and post impact conditions is critical to being able to better understand the impacts, and the significance of the impacts to the receiving watercourse. Tools such as the Indicators of Hydraulic Alteration (Nature Conservancy, 2009) can be used to compare hydrographs and assess the magnitude of change.

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