Coupled Water Balance and Groundwater Model to Assess the Influence of Low Impact Development Stormwater Strategies on Groundwater Recharge

by

Eva Mooers

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DEDICATION PAGE

The Dance

1. Get the beat.

2. Listen to the wisdom of the system.

3. Expose your mental models to the open air.

4. Stay humble. Stay a learner.

5. Honor and protect information.

6. Locate responsibility in the system.

7. Make feedback policies for feedback systems.

8. Pay attention to what is important, not just what is quantifiable.

9. Go for the good of the whole.

10. Expand time horizons.

11. Expand thought horizons.

12. Expand the boundary of caring.

13. Celebrate complexity.

14. Hold fast to the goal of goodness.

By Donella Meadows

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ABSTRACT

Low impact development has been adopted as a sustainable way of managing stormwater in urbanized catchments. While the effect of LID features on surface water and stream health has been investigated in recent studies, less is known regarding the effect on groundwater recharge. The hydrologic model PCSWMM was coupled with the groundwater model, MODFLOW to assess the influence of LID on groundwater recharge. The coupled models were calibrated and validated using pre-development stream flows and monitored groundwater levels from a predominately forested catchment in which residential development has since taken place. PCSWMM was used to quantify net infiltration rates for conventional and LID stormwater practices. Net infiltration rates were coupled with MODFLOW, which was used to determine aquifer recharge and the availability of the groundwater aquifer to supply the residential development by mean of individual drilled wells. Development was found to decrease net infiltration, and results demonstrated that LID can enhance infiltration.

LIST OF ABBREVIATIONS AND SYMBOLS USED

%	Percentage
Δ	Slope of the vapour pressure curve
λ	Latent heat
ψ_m	Matrix potential of the soil
A_F	Cell surface area
A_{lot} =	Impervious area of the lot
BMPs	Best management practices
CHI	Computation Hydraulics International
CN	Curve number
CWEEDS	Canadian Weather Energy and Engineering Dataset
D	Drainage or recharge out of the bottom of the column
d	Change in the variable
D1	Beginning of time step lower zone depth
D2	End of time step lower zone depth
d_c	Depth of cell
DELT	Time step value
DEM	Digital elevation model
D_R	Depth of rainfall
DTOT	Total depth of upper and lower zone
DWT1	Beginning of time step upper zone depth
ENFIL	Infiltration rate
ET	Evapotranspiration
ETR	Real evapotranspiration
ETU	Upper zone evapotranspiration rate
F_0	Model output also referred to as an objective function
FAO	Food and Agriculture Organization of the United Nations
F_i	The parameter input to the model
g	Gravity, assumed to be 9.81 m/s^2
GIS	Geographical Information Systems
h	Hydraulic head

H^*	Threshold groundwater height
h_0	Initial hydraulic head
H_g	Height of saturated zone above bottom of aquifer
H_{SW}	Height of surface water at receiving node above aquifer bottom
I	Infiltration
k	Soil lateral saturated hydraulic conductivity
$K(\theta)$	Unsaturated hydraulic conductivity which varies as a function of θ, the water content
K_x, K_y, K_z	Hydraulic conductivity in the x, y and z directions
L	½ the subcatchment flow length
LAK3	MODFLOW Lake Package
LID	Low Impact Development
L-THIA-LID	Long-Term Hydrologic Impact Assessment-LID
m	Meter
m^2	Meter squared
m^3	Meter cubed
mm	Millimeter
n	Number of data points in the set
NRCS	Natural Resources Conservation Service
NRMS	Normalized root mean squared error
NSE	Nash-Sutcliffe Coefficient
O	Observed values
P	Precipitation
PAREA	Pervious area divided by total area
PERC	Percolation rate
PT	Priestly Taylor
Q	Constant pumping rate
Q_{gw}	Groundwater flow
q_z	Volumetric flow rate in the z direction per unit cross-sectional area of medium
r	Radial distance from the pumping well
R	Runoff

RMS	Root mean squared error
Rn	Net radiation at the crop surface
R_{off}	Direct runoff from precipitation
Rs	Relative sensitivity
R_{sub}	Interflow or base flow
S	Aquifer storativity (dimensionless)
SCS	Soil Conservation Service
SRTC	Sensitivity-based Radio Tuning Calibration
S_s	Specific storage for the porous material
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	Stormwater Management Model
S_y	Specific yield
t	Time
T	Aquifer transmissivity
TH	Beginning of time step upper zone moisture content
TH2	End of time step upper zone moisture content
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
V_F	Cell volume for required capture depth of rainfall
V_r	Void ratio
W	Aquifer recharge
W(u)	Well function of Theis
α	Recharge ratio.
ΔRAS	Change in the readily available supply of water in soils
ΔS	Change in storage
ρ	Density of water

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CHAPTER 1 INTRODUCTION

1.1 Background

Historically, the primary purpose of stormwater management is to prevent flooding of property and infrastructure as a result of large rainfall events. While typically successful in meeting this objective, conventional stormwater management techniques fail to mitigate the reduced rates of groundwater recharge associated with urban development (Dunne and Leopold, 1978).

Numerical models that represent the storage and movement of water through the landscape are increasingly being used as water resources planning tools. A variety of models are used to predict changes to hydrologic and hydrogeologic processes as a result of changes to the landscape and variations in climate. The motivation behind this study acknowledges that hydrologic and hydrogeologic systems are connected and aims to create a modeling framework which allows existing models to be coupled with the specific goal to determine the influence of stormwater management practices to both surface water and groundwater.

Local water shortages coupled with the fact that approximately half of the population of Nova Scotia uses groundwater as their water supply (NSE, 2014), demonstrate the need for a holistic approach to water management. Starting in 2008, residents of two expanding subdivisions in the community of Beaverbank, Nova Scotia, Monarch estates and Rivendale, serviced by individual drilled wells, began running out of water. After petitioning the city, the water utility, Halifax Water, agreed to extend water services to the communities. This came at the expense estimated to be over $5 million to Halifax Water, and an average cost of $20 thousand to each homeowner for later connection fees (CWRS, 2015).

As a result of short sightedness of the Beaverbank situation, the Government of Nova Scotia passed legislation allowing municipalities to require groundwater assessments for proposed subdivisions as part of the development agreement process. Nova Scotia

Environment has published a guide (NSE, 2011) which can be used by municipalities and developers in the assessment and preparation of such studies.

In partnership with Seven Lakes Development Corporation (a residential developer), the Ecology Action Centre (EAC), and the Nova Scotia Department of Natural Resources (NSDNR), this study is part of a pilot study at a new development in the Halifax Regional Municipality (HRM) known as Seven Lakes. Seven Lakes is located outside of a municipally serviced area in HRM and is planned to have shared wastewater management with some shared and individual wells for drinking water. As per the Seven Lakes development agreement with HRM, the stormwater management plan for each phase may include structural and vegetative stormwater management measures, which may include low impact development (LID) stormwater strategies such as wetlands, vegetative swales, filter strips, buffers and rain gardens.

Hydrometric and groundwater data was collected from the study area in order to construct, calibrate and validate models to assess the effect of the LID stormwater features on the local groundwater system.

1.2 Study Objectives

The overall purpose of the research is to understand the impact of incorporating LID features at the lot level throughout a subdivision on groundwater supplies. This study area offers a unique opportunity to do so because of the availability of monitoring data. Formally, the study objectives are as follows:

- Construct, calibrate and validate a modeling framework which allows the user to determine how stormwater management practices influence recharge rates and groundwater availability, and
- Assess the influence of stormwater management practices on groundwater recharge rates and availability.

CHAPTER 2 LITERATURE REVIEW

2.1 Urban Hydrology

Urbanization has been shown to have a drastic effect on the water balance of a land scape (DeFires and Eshleman 2004) and has made urban catchments hydrologically complex systems (Salvadore et al. 2015). Salvadore et al. (2015) attribute this complexity to the fact that urban areas are highly heterogeneous combinations of natural and artificial land uses. While the definition “urbanized catchment” remains subjective (Elga et al. 2015), Mejia and Moglen (2010) have demonstrated that impervious surfaces change the hydrological response of a catchment outlet. Streams in urbanized catchments are characterized by flashier hydrographs with shorter lag times to peak flows, altered base flows and impaired channel morphology (Schirmer et al. 2013). While leaking potable and wastewater infrastructure can increase recharge to groundwater, Schirmer et al. (2003) and Salavdore et al. (2015) found that infiltration to groundwater in urbanized settings tends to decrease as a result of the increase of impervious surfaces.

2.2 Conventional and LID Stormwater Management

Conventional stormwater management approaches focus on the removal of water from a developed landscape as quickly and efficiently as possible. In a suburban setting this normally takes the form of curb and gutter conveyance systems which direct precipitation falling on impervious surfaces to a stormwater facility. Stormwater facilities are typically designed such that pre- and post-development peak flows leaving a facility are equivalent for specified design storms (Bedient et al. 2013). The main driver behind this design is to protect people and infrastructure from flooding. However, the sole focus on ensuring post-development peak flows do not exceed pre-development peak flows for large rainfall events, overlooks the effects of development on the water balance of a landscape. The unintended consequences of conventional stormwater management have inspired a rethinking as to how stormwater is managed. A new approach, which has gained popularity in the last 2 decades, is referred to as LID.

The design goal of LID stormwater management is to maintain the pre-development water balance post-development. This is achieved by providing opportunities for stormwater generated from small and frequent rainfall events to infiltrate and evaporate at the watershed, neighbourhood and individual lot scales (Stephens et al. 2012). While LID strategies can take many forms, several common LID features and designs for the management of stormwater runoff include (Ahiablame et al, 2012b, and PGCo 1999):

- Management of stormwater as close to the source as possible;
- Focus on prevention rather than mitigation and remediation;
- Integration of stormwater management strategies in the early stage of site planning and design;
- Implementation of infiltration-promoting bio-retention and biofiltration areas, such as rain gardens, vegetative swales, and street runoff collection features (e.g., curb cuts to depressed traffic medians); and
- Lot-scale stormwater management features, such as infiltration galleries and rain barrels.

Beyond management of stormwater volumes, LID has also used to reduce pollutant loading from developments. Common pollutants include sediment, nutrients, such as nitrogen and phosphorus, metals, like lead, copper and zinc, as well as bacteria (Ahiablame et al. 2012b). Dietz and Clausen (2007) found that pollutant export from a subdivision with LID remained unchanged from pre-development levels, while export of total nitrogen and phosphorus from a comparable subdivision using conventional stormwater techniques increased significantly. Ahiablame et al. (2012b) in their review of LID, highlight studies showing the ability of different media within bio-retention areas, to reduce the export of pollutants. Other aspects of LID design which can influence pollutant treatment include: feature sizing, choice of vegetation, siting considerations, and maintenance.

While the effects of LID on surface water systems has been documented, the influence on groundwater supplies is less understood and was absent in recent reviews of current research on LID (Dietz 2007 and Ahiablame et al. 2012b). Both reviews did however recommend future research focus on understanding the effects of LID at different temporal and spatial scales, specifically at spatial scales larger than the lot level. Part of the reason why little is understood regarding the influence of LID on groundwater may be attributed to the challenging nature of analysing interactions between surface water and groundwater. LID features implemented at the lot level tend to be modeled on a time scale of hours, while groundwater systems are modeled at a watershed scale over the order of years (Marchildon and Kassenarr 2013) and quantifying or observing the influence of one system on the other can be difficult.

The following sections include a review of surface water and groundwater models which could be used within a framework capable of assessing the influence of LID on groundwater supplies.

2.3 Urban Stormwater Hydrology Models

There are many different hydrologic models, each with a variety of capabilities, that have been developed to simulate surface hydrology in urban watersheds. Salvadore et al. (2015) in their review of 43 hydrological modeling methods of urbanized catchments found that there is no universal methodology for modeling urban hydrology at the catchment scale. However, the urban hydrologic system is often divided into two main networks, namely: a modified natural set of pathways; and supply-sewerage pathways (Salvadore et al. 2015). The former accounts for changes to movement and storage of water in the natural or vegetated areas of the urban setting while the latter accounts for activities such as piped networks, groundwater extraction and stormwater flows. Salvadore et al. (2015) found that urban hydrology models range in complexity from simple lumped models, to complex distributed models and that data availability tends to dictate which models can be used.

Ahiablame et al. (2012b) conducted a review of modeling techniques used to assess the effectiveness of urban stormwater best management practices (BMP), which includes LID. They found that there are generally two broad ways to represent these practices within hydrologic models. The first approach is to explicitly model the specific processes associated with LID practices, including infiltration, evapotranspiration, sedimentation, adsorption, etc.. The second approach, referred to as the practice representation approach, uses an aggregation method to represent the practices as a whole across an area of interest (Ahiablame et al. 2012b). A common example of the latter, would be to represent the effects of LID using a lumped parameter in order to determine the effect on runoff.

Long-Term Hydrologic Impact Assessment-LID (L-THIA-LID) is a screening tool used to evaluate the benefits of the use of LID that was developed at Purdue University. L-THIA-LID is a spreadsheet model which uses the empirical curve number method to calculate average annual runoff using daily precipitation data and is recommended to be run using 30 years of data.

System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN), is a model used to support the development and implementation of plans for flow and pollution control and was developed by the United States Environmental Protection Agency (USEPA). SUSTAIN has been designed to evaluate the selection and placement of BMPs throughout a development or watershed. SUSTAIN is made up of three primary modules: a BMP siting tool in ArcGIS which includes user defined rules to determine site suitability; a land simulation module that is used to generate runoff time series data; and a conveyance module that provides routing capabilities between land segments or BMPs or both. SUSTAIN computes runoff using algorithms adapted from SWMM5 (Lee at al., 2012) and groundwater flow based on a combination of algorithms adapted from SWMM5 and the Hydrological Simulation Program in FORTRAN (HSPF) (EPA, 2009).

The USEPA Stormwater Water Management Model (SWMM) was originally developed in 1971 and has since undergone many updates. The latest version is called SWMM5. SWMM5 is a dynamic rainfall-runoff model capable of simulating single event and continuous runoff quantity and quality from developed urban and undeveloped or rural areas (James et al. 2010). SWMM5 models surface runoff and infiltration on a continuous basis. Users can select from several different infiltration methods (Horton's Equation, the SCS Curve Number Method, Green-Ampt Method). The model simulates the partitioning of infiltrated water in the subsurface using a two-zone (saturated-unsaturated) mass balance and is able to simulate the contribution of snow and melting. Built in LID features in the latest version of SWMM include (James et al. 2010): bio-retention cells, infiltration trenches, porous pavement, rain barrels (or cisterns), vegetative swales, rain gardens, green roofs, and rooftop disconnection. Zahmatkesh et al. (2014) used EPA SWMM5 to model the potential for LID features to mitigate the impacts of climate change on urban stormwater runoff using New York City as a case study. They predicted that through the use of rainwater harvesting, porous pavement, and bio-retention, the average annual runoff volume was reduced by 41% of the 48% increase due to climate change. Damodaram et al. (2010) modeled a combination of best management practices (BMPs) and LID for stormwater management in a watershed located on the campus of Texas A&M University in College Station, Texas and predicted that the use of LID practices yields significant stormwater control for small events and less control for flood events.

2.4 Groundwater Models

Groundwater-flow models are used to predict an aquifers response, in terms of head and fluxes into and out of an aquifer, as a result of natural and human induced stresses. Recharge rates can be obtained from groundwater flow models if measurements of water levels and groundwater discharges are available (Sandford 2002), however recharge is commonly used as a calibration parameter. The groundwater flow equation (Equation 17, Section 3.4.2) is solved using finite-difference or finite-element methods. Required inputs include hydraulic conductivity, recharge, and other sources and sinks, aquifer geometry, initial head values and boundary conditions (Healy, 2010). Groundwater flow models use different methods for calculating diffuse and focused recharge (Sandford 2002). Diffuse recharge is represented as a constant flux to the top of a model grid, while focused recharge is calculated from specific boundary conditions such as a lake or a stream. The following is a brief description of commonly used groundwater-flow models.

USGS MODFLOW, originally published by the United States Geological Survey (USGS) in 1984, is a three-dimensional finite-difference groundwater model. The latest version of MODFLOW, MODFLOW-2005, simulates steady and nonsteady flow in a confined, unconfined or combination of confined and unconfined. The user is able to define stresses on the groundwater system such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds and lakes (Harbaugh, 2005).

Finite Element subsurface FLOW system (FEFLOW) uses finite element analysis to solve the groundwater equation for flow, mass and heat transport in porous and fractured media (Trefry and Muffels 2007). The model code is proprietary and not feely available however, its use has been widely documented for a range of different types of problems and applications (Trefry and Muffels 2007). The approach of using a finite element method to solving groundwater problems is more complex than finite difference methods but is reported to provide superior solutions for situations with moving boundary conditions, and for coupled problems involving contaminant transport (Fetter, 2001).

Groundwater Modeling System (GMS) is a groundwater modeling tool currently distributed by Aquaveo, LLC, in Provo, Utah, but was originally developed by the Engineering Computer Graphics Laboratory at Brigham Young University and was funded by various US government agencies (Owen et al. 1996). GMS combines a graphical user interface with analysis codes which provides both finite element and difference methods, including the built in use of MODFLOW. Following the same direction as other groundwater models, the latest version of GMS, guides the user through the construction of a conceptual model, grid development, model solution and provide various options for visual representation (Aquaveo 2013).

2.5 Integrated Groundwater-Surface Water Models

Integrated groundwater-surface models consider the entire hydrologic systems and are able to model the movement of water on the surface of the land, the unsaturated and saturated soil zones, and within groundwater aquifers.

Groundwater-water and Surface-water flow model (GSFLOW) developed by the USGS, is used to simulate coupled groundwater and surface water resources. It is an integration of Precipitation-Runoff Modeling System (PRMS), also developed by USGS, and MODFLOW. It is a fully distributed model, meaning that the model accounts for spatial variability throughout the area of study and produces a distributed solution (Markstrom et al. 2008).

GSFLOW does not have a built in ability to model LID features, however Marchildon and Kassenaar (2013) conducted a modeling study in which the GSFLOW code was altered to be able to analyse different LID practices. Marchildon and Kassenaar (2013) modified the GSFLOW code at the sub-cell process level by modifying the mechanisms regulating the storage of water on the surface, namely, evaporative loss, reservoir drainage and excess runoff, to match those at play in a variety of LID features. Adding the use of LID to a fully distributed surface model, provided a means of assessing the local influence of LID on the hydrologic system and allowed the users to assess the placement of LID features among other water management issues.

HydroGeoSphere is a fully integrated, physically based hydrological model. The code on which the model is based, FRAC3DVS, was developed by R, Therrien at the University of Waterloo (Brunner and Simmons, 2012). HydroGeoSphere is used to model variably saturated groundwater flow and advective-dispersive solute transport in porous or discretely fractured porous media and includes a 2D surface water flow and transport component. Finite element methods are used to discretize the surface and subsurface flow equations. What sets this model aside from others is the fact that it is fully integrated, meaning that precipitation is partitioned into all key components of the hydrologic cycle using physically based equations (Brunner and Simmons, 2012).

2.6 Estimation of Groundwater Recharge

Recharge is the downward flow of water reaching the water table, adding to groundwater storage (Freeze and Cherry 1979) and can be expressed as a flux in terms of volume per surface area per unit time, such as mm/year. Recharge can be diffuse, meaning that it is distributed over large areas in response to precipitation, infiltrating the soil surface and percolating through the unsaturated zone to the water table. Or it can be a focused water source, such as the movement of water from surface water bodies such as streams, lakes and wetlands into the groundwater system (Healy, 2010). Humid regions, defined by annual precipitation rates that exceed 1000 mm (Healy, 2010), are typically characterized by shallow water tables and gaining streams. In these regions groundwater from aquifers is usually discharged through evapotranspiration and baseflow to streams, and diffuse recharge is dominant (Scanlon et al. 2002).

Not all water arriving at the water table is considered recharge because a portion may leave the saturated zone as lateral groundwater flow to streams or as evapotranspiration. Therefore, the term recharge is further divided into net infiltration and aquifer recharge (Rivard et al., 2014). Net infiltration refers to water arriving at the water table, and aquifer recharge is water reaching and renewing the groundwater aquifer.

The purpose of a recharge study should be carefully considered when selecting an appropriate method for recharge calculation as there are many ways in which it can be determined. Some of the general methods include: water-budgets; models; methods based on surface-water data (including base flow separation); physical methods; water table fluctuation methods, groundwater tracers and heat tracers (Healy, 2010).

Healy (2010) strongly encourages the use of more than one method to determine recharge. Scanlon et al. (2002) point out that the use of integrated surface and groundwater models can provide a more reliable recharge estimate than using one model in isolation. This is due to the fact that the multiple model framework for the total system can be used to check continuity at different points and serve to better constrain model parameters. Parameter calibration can be completed against multiple targets such as groundwater levels and stream flows.

Rivard et al. (2014) completed a comprehensive study in which regional recharge estimates were made using multiple methods across the Annapolis Valley, Nova Scotia, Canada. Their study is relevant to this study in it was situated in Nova Scotia and made use of publically available data. Where applicable the methods and results of the Rivard et al. (2014) study are included in the subsections below.

2.6.1 Water Budgets

A water budget is a mass balance of how much water is moving into, out of, or stored within a control volume and is the basis from which conceptual models of hydrologic systems are made. A simple water budget equation used to represent the mass balance of water in a one dimensional column of soil is presented in Equation 1 (Healy, 2010).

Equation 1

$$\Delta S = P - ET + R_{off} + D$$

Where:

ΔS = change in storage

P = precipitation

ET = evapotranspiration

R_{off} = direct runoff from precipitation

D = drainage or recharge out of the bottom of the column

The most common way estimates of recharge are made using a water budget, is indirectly, meaning that all variables in the water budget equation are known or estimated and Equation 1 is solved for recharge (Scanlon et al., 2002 and Healy 2010). While this approach is simple, it should be noted that the accuracy of the recharge estimate depends on the accuracy with which the other components in the water-budget are measured or estimated (Scanlon et al., 2002 and Healy 2010).

Rivard et al. (2014) used a soil moisture balance in ArcGIS to solve for aquifer recharge using the version of the water balance equation shown in Equation 2.

Equation 2

$$I = (P - R) - ETR - \Delta RAS \ \ and \ W = I - R_{sub}$$

Where:

I = Infiltration

P = Precipitation

R = Runoff

ETR = Real evapotranspiration

ΔRAS = Change in the readily available supply of water in soils

W = Aquifer recharge

R_{sub} = Interflow or base flow

Rivard et al. (2014) found aquifer recharge values to vary from 120 to 225 mm/year for the areas of Annapolis valley considered.

2.6.2 Modeling

Models are commonly used to simulate hydrologic processes and many can be used to estimate recharge. Most hydrologic and groundwater models incorporate the use of a water budget. Models can be extremely complex and based on physical processes or simple, such as empirical models, which at the simplest end of the spectrum equate recharge to a given fraction of precipitation.

Healy (2010) classifies models into the following categories: unsaturated zone water budget models, watershed models and groundwater flow models.

Unsaturated zone water budgets describe one dimensional water movement through the unsaturated soil zone to the underlying aquifer. Because of this, they are useful in estimating diffuse recharge (Healy, 2010). There are two major types, those based on a soil water budget and those based on Richards equation.

Soil water budget models can consider the surface and subsurface to be a series of buckets (or reservoirs) through which water is added or subtracted using transfer functions. Or they can be based on physical relationships such as the Richards equation. The Richards equation is derived from combining the continuity equation and Darcy's Law in the vertical direction, (Equation 3), which describes the movement of water within the unsaturated zone (Dingman, 2002).

Equation 3

$$q_z = -K(\theta) - K(\theta)\left(-\frac{\partial\psi_m}{\partial\theta}\right)\frac{\partial\theta}{\partial z}$$

Where:

q_z = the volumetric flow rate in the z direction per unit cross-sectional area of medium

$K(\theta)$ = the unsaturated hydraulic conductivity which varies as a function of θ, the water content

ψ_m = the matrix potential of the soil (also known as soil pressure or capillary potential or soil suction, which is the force required to remove water from the soil) and also varies as a function of water content.

From Equation 3 it can be seen that the use of the Richards equation requires data regarding how hydraulic conductivity and matrix potential vary with water content for a given soil. While these relationships can be measured from field and laboratory studies, empirical equations have also been derived to represent these relationships (Van Genuchten 1980). Because of the nonlinear nature of the hydraulic conductivity and matrix potential relationships with water content, numerical solutions to the Richards equation are computationally complex. In situations where field data is lacking, coupled with the difficulties of determining spatially representative soil parameters, large uncertainties can be introduced to recharge estimates made using water budgets which rely on the Richards equation (Healy 2010).

Watershed modeling can be used to estimate recharge rates, however the primary intent of most watershed models is to estimate runoff and streamflow. Watershed models are all based on the water budget equation but vary in terms of spatial scales, the processes considered, techniques used to represent the processes and the data required to run the model. Watershed models represent the surface and subsurface as a series of reservoirs (similar to the buckets described above). These models can be lumped or spatially disaggregated into hydrologic-response units (HRUs) (Scanlon et al., 2001). The models may include physical or empirical relationships to describe the movement of water and measured streamflow is used to calibrate model parameters.

Rivard et al. (2014) used the 1D infiltration model HELP to model infiltration. HELP was originally developed to evaluate landfill cover performance using equations which describe physical processes (Schroeder et al. 1994). Rivard et al. (2014) combined HELP with ArcGIS to obtain a distributed estimate of recharge. Net recharge was found to range from 81 to 181 mm/year across the Annapolis Valley, which overlaps but is less than the range determined using the water balance approach (120 to 225 mm/year).

Rivard et al. (2014) used the groundwater model FEFLOW to validate both aquifer recharge and hydraulic conductivity values for the region. They assumed each bedrock unit was homogeneous and that bedrock fractures could be modeled as a porous medium. Bedrock hydraulic conductivity values were generally found to be close to the average values obtained from pumping test results. The weighted aquifer recharge obtained for the entire study area was 115 mm/year.

2.6.3 Surface Water Data

Surface water data methods for estimating recharge are based on groundwater movement to or from streams but are also applicable to other surface water bodies. Flows from loosing streams, where the water table stage is below that of the stream, can be used to estimate focused recharge. Flows to gaining streams, where the water table stage is above that of the stream, can be used to estimate diffuse recharge from the tributary watershed (Healy, 2010).

Stream water-budgets, streambed seepage measurements, flow duration curves and streamflow hydrograph analysis are surface water data methods (Healy, 2010). A particularly common method to determine baseflow and recharge is through hydrograph analysis (Lim et al., 2005), which refers to both empirical hydrograph separation methods and recession-curve displacement analysis.

While these methods were traditionally analysed graphically, on an event basis, they are now automated. The use of computer programs has removed subjectivity and reduced the time required to analyse complex hydrographs (Lim et al., 2005). Computers employ an empirical formula or low-frequency filter for separating baseflow from the stream flow hydrograph to partition streamflow into direct runoff and baseflow (Eckhardt, 2005). Digital filtering, borrowing from the field of signal processing, is based on the observation that baseflows are more likely to be associated with long waves while direct runoff is associated with higher frequency waves (Eckhardt, 2005).

Rivard et al. (2014) used seven hydrograph separation methods to partition streamflow into direct runoff and baseflow, as part of their study to estimate regional recharge in the Annapolis Valley, Nova Scotia. The methods included one digital filter (Chapman, 1991) and six graphical methods (Neff et al. 2005). For six gauging stations across the Annapolis Valley, based on a mean total precipitation of 1,180 mm/year, the Chapman method produced a net infiltration depth of 364 mm/year and the graphical methods produced net infiltration rates in the order of 450 mm/year. Rivard et al. (2014) note that hydrograph separation methods tend to overestimate baseflows during the winter period. Rivard et al. (2014) found that only considering net infiltration from June through October for a given year, reduced aquifer recharge estimates to 161 mm/year.

Kennedy et al. (2010) used a digital recursive filter based on the work by Lim et al. (2005) to estimate recharge in gauged watersheds in Nova Scotia. Kennedy et al. (2010) expressed their results in the form of a recharge ratio. Recharge ratios, for areas corresponding to watersheds from which the stream flows were gauged, can be used to estimate aquifer recharge using Equation 4.

Equation 4

$$Aquifer\ Recharge = \alpha * Precipitation$$

Where:

Aquifer recharge and precipitation are in mm/year

α = recharge ratio.

Kennedy et al. (2010) report recharge ratios ranging from 0.25, in northern Cape Breton, to 0.14 along the southern shore of Nova Scotia.

2.6.4 Physical Methods

Lysimeters are used to measure the flux of water movement through the unsaturated soil zone. Lysimeters consist of a cylinder that is inserted into soil so that it is hydrologically isolated from the surrounding soil and make use of a balance to measure slight changes in weight in order to quantify water storage fluctuations. Lysimeters can be as small as 100 cm^2 or cover surface areas as large of 300 m^2 with depths ranging from centimeters to 20 m (Ward and Gee 1997). Lysimeters can be used to measure recharge rates at time scales from minutes to years but their use is limited because they are expensive and difficult to construct and maintain (Scanlon et al., 2002).

Xu and Chen (2005) made use of detailed measurement of evapotranspiration and groundwater recharge recorded using lysimeters in Germany to calibrate parameters within 7 different evapotranspiration models for their geographical region. The calibrated evapotranspiration models were then used to evaluate water balance models and allowed Xu and Chen (2005) to be able to rank model performance in terms of estimating groundwater recharge.

Another physical approach used to measure recharge is referred to as the water table fluctuation method. This method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table (Healy and Cook, 2002). Recharge is calculated using Equation 5.

Equation 5

$$R = S_y \frac{dh}{dt}$$

Where:

R = recharge

S_y = specific yield

h = water table height

t = time

The water table fluctuation method is best suited for short time periods of time, in regions having shallow water tables that display sharp rises and declines in water levels (Healy and Cook 2002) and cannot be used to estimate steady state recharge (Healy and Cook 2002). Scanlon et al. (2002) point out that difficulties in using this method can be attributed to identifying the cause of the water table fluctuation, as well as the need to estimate a value of specific yield for the aquifer.

Park and Parker (2008) developed a simple physically based model for quantifying groundwater fluctuations in response to precipitation as an extension of the Rasmussen and Andreasen model originally published in 1959. Using observed precipitation data and groundwater elevations, Park and Parker (2008) were able to calibrate their model and use it to produce groundwater elevations for periods when only precipitation was available.

Sophocleous (1991) presents a simple approach for calculating groundwater recharge in semiarid environments with shallow water tables. His approach termed a “hybrid water-fluctuation method”, involves the combination of water balance and groundwater fluctuation methods. Water table rises associated with specific precipitation events are combined with recharge estimates from soil water balance analysis for a given site, in order to estimate the effective storativity (specific yield, Equation 5). Once calibrated, storativity can be used to translate each water table rise related to a given precipitation event into groundwater recharge.

2.6.5 Tracers

Tracers provide both qualitative and quantitative information on the sources of recharge, flow velocities, preferential flow paths, hydrodynamic dispersion, diffusion (Healy, 2010 and Braud et al. 2009). The use of tracers can be simple and involve the comparison of isotopes in upstream to downstream waters to determine the relative contribution of stream water and precipitation to groundwater recharge, or more involved where chemical tracers are applied as a pulse at the soil surface (Scanlon et al., 2002). Infiltration transports the chemical tracer to depth, at which point the distribution of the tracer can be determined by digging a trench for visual inspection and sampling or by drilling test holes (Healy, 2010). Other tracers that have been used include heat and radioisotopes that have been emitted by anthropogenic activities such as nuclear bomb testing (Scanlon et al., 2002). Tracer techniques used to investigate water movement in the unsaturated zone are generally divided into three categories (Koeniger et al. 2016): artificial labelling with stable isotopes and tritium; seasonal variations of stable isotopes in precipitation; and evaluation of stable isotope evaporation signals. Elevated levels of radioactive tritium, emitted to the atmosphere in the 1950s and 1960s as a result of nuclear weapon testing, have been used to age groundwater (Koeniger et al. 2016). The stable version of tritium has been used as an applied tracer. Seasonal variations of stable isotopes are caused by temperature driven processes and can be used to track soil water displacement. The viability of this method greatly depends on meteorological conditions and requires a significant difference in seasonal temperatures (Koeniger et al. 2016). And lastly advances to groundwater recharge estimates have been made through the improvement of soil water balance estimations using the characteristic stable isotope pattern caused by the evaporation of soil water (Braud et al. 2009). Evaporation causes an enrichment of heavy isotopes in the remaining soil water which can be measured (Koeniger et al. 2016).

CHAPTER 3 METHODOLOGY

3.1 Research Strategy

A modeling approach was used to determine how development, and stormwater management practices, influence groundwater availability at the Seven Lakes study area. Data from the study area was collected and used to calibrate and validate hydrologic and hydrogeologic models. The models were then used to make predictions about how development scenarios influence groundwater supplies when using conventional and LID stormwater management techniques.

3.1.1 Model Framework

The framework consists of a land cover representation model, a water balance model and a groundwater flow model, Figure 3-1. The land cover representation model, constructed in ArcGIS version 10.2, represents the study area in two dimensions. It is where spatial information about the study area is stored and manipulated to suit the needs of the other models. Spatially weighted, or lumped, land use characteristics calculated in ArcGIS are input to PCSWMM, the hydrologic model. PCSWMM outputs are used to calculate net infiltration rates for different pre- and post-development scenarios. The net infiltration rates are passed to MODFLOW, the hydrogeologic model, to estimate aquifer recharge. MODFLOW is used to assess how post-development conditions impact hydraulic head throughout the aquifer for a proposed water withdrawal scenario.

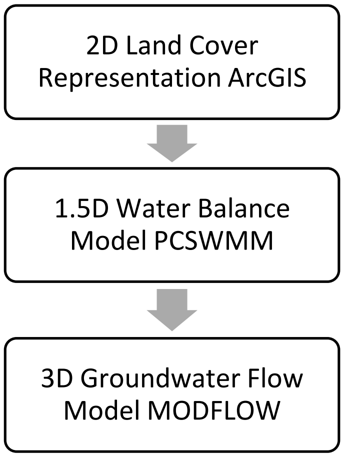


Figure 3-1 Model Framework

In order to fulfill the objectives of this study, to determine the influence of LID on groundwater, a hydrologic model requires the ability to simulate hydrologic processes, partition infiltration into evapotranspiration, lateral groundwater flow and groundwater recharge, and the capability to represent LID features on a continuous timescale.

While the L-THIA-LID model is able to represent LID features, it does not consider infiltration partitioning to be able to assess effects to groundwater recharge and does not consider frozen conditions. Therefore, it was deemed unsuitable to use in this study. Recalling that the purpose of this study does not extend to optimizing the selection and placement of LID features and the fact that SUSTAIN employs algorithms from SWMM5 to simulate infiltration partitioning suggests that SWMM5 may be more suitable than SUSTAIN for this study. It was also noted that the USEPA is no longer developing or supporting SUSTAIN and they have no plans to support newer versions of SUSTAIN for later versions of Windows or ArcGIS, make SUSTAIN unsuitable for fulfilling the objectives of this study. Based on the objectives to the study and the fact that SWMM5 is largely a process based model capable of simulating LID features and infiltration partitioning on a continuous basis, SWMM5 was selected as the most appropriate model.

In order to simulate the effects of LID on groundwater supplies, a model was required for which various recharge values could be input, with or without pumping from the aquifer. Based on the wide use, the fact that it is commonly included within other models (GSFLOW and GMS) and availability, MODFLOW was selected.

3.1.2 Scenarios

The calibrated models were used to simulate two scenarios: pre- and post-development under both mean and drought precipitation conditions. Pre-development refers to the study area prior to any activities related to the development of Seven Lakes (2013). Post-development refers to the time period after construction activities have been completed at the study area (Phase 1, not completed as 2017).

In order to determine representative mean and drought hydrologic conditions for the scenario analysis, precipitation depths for the period of May through October from 1990 through 2015 were analyzed based on total depths for each year, with a sufficient data record, Table 1.

Two stormwater management scenarios were simulated: conventional and LID, Table 2.

Table 1 May through October Precipitation Depths in ascending order.

Year	Total Precipitation May through October (mm)	Classification
1997	457.2	Drought
1994	482.5	--
2014	511.8	--
2004	524.1	--
2010	535.1	--
2006	538.7	--
2002	571.5	--
2008	572.7	--
2001	578.0	--
1999	592.4	--
1993	602.4	--
2000	602.6	--
2003	613.5	Mean
1990	621.4	--
2015	654.6	--
2012	658.2	--
1991	696.7	--
2007	702.7	--
1995	704.5	--
2009	716.8	--
2005	734.2	--
2013	780.8	--
1998	784.9	--
2011	876.8	--
1996	1014.0	--

Post-development scenarios are based on the first phase of the Seven Lakes development. This consists of 100, rural residential units, each serviced by individual drilled wells. The development is serviced by a centralized wastewater treatment system. For the purpose of the model, the Seven Lakes Phase 1 plan was modified so that the entire extent of Phase 1 is tributary to the stream gauging station. Under the post-development conventional scenario, stormwater from each lot is directed to ditches and conveyed to a receiving watercourse. The post-development scenario with LID includes rain gardens (bio-retention areas) on each lot sized to accommodate a specific depth of precipitation falling on the impervious area.

Table 2 Modeled Scenarios

Scenario	Hydrologic Condition	Precipitation (May – October) (mm)	Details
1A	Drought (1997)	457	Pre-development
1B	Drought (1997)	457	Post-Development with Conventional Stormwater
1C	Drought (1997)	457	Post-Development with LID Stormwater
2A	Mean (2003)	613	Pre-development
2B	Mean (2003)	613	Post-Development with Conventional Stormwater
2C	Mean (2003)	613	Post-Development with LID Stormwater

3.2 Seven Lakes Site Description and Field Monitoring Program

The entire Seven Lakes development will include 634 residential units over 7 phases of development, of mixed styles. The first phase is the only phase considered by this study and was described above (Section 3.1.2). The study area is located in an area known as Porter's Lake, approximately 30 km east of Halifax, Nova Scotia, Canada, and the first phase is situated west of Bell Lake, Figure 3-2.

Prior to development, the study area was partially forested with some cleared areas, and was partially occupied by an old quarry. As of November 2013, the study area was in initial stages of development with no clearing or construction, except for access roads to allow for groundwater well drilling. As of December 2016, roughly a dozen homes have been built, many lots have been cleared, the wastewater treatment system is functional, wells have been drilled and the roads paved. One raingarden was installed by the Ecology Action Centre and Dalhousie University, June 14, 2015, in the side yard of a model home on Founders Court.

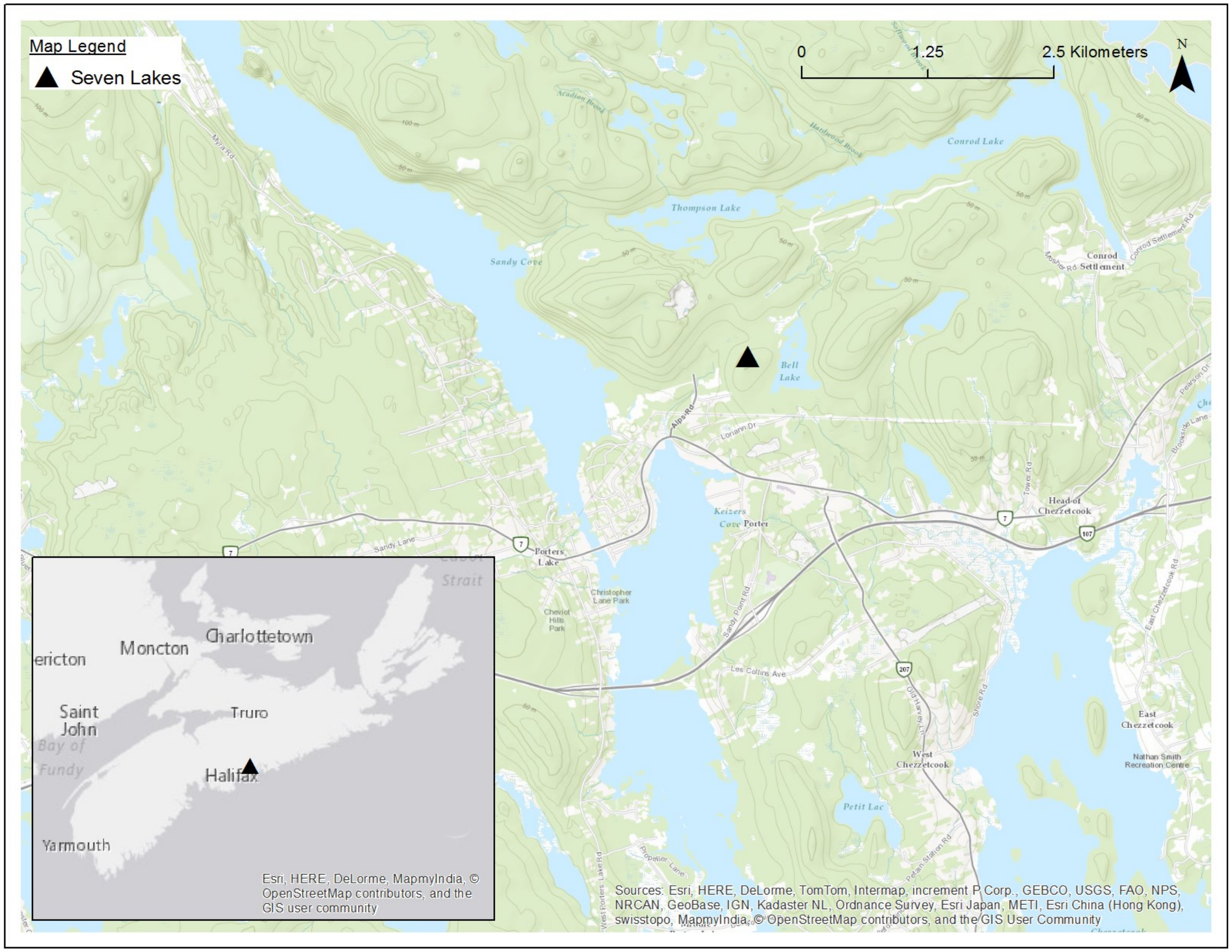


Figure 3-2 Study Area, Seven Lakes, location map.

3.2.1 Surficial Geology

Provincial soil mapping shows that the study area is overlain by soils from the Halifax soil series. The Halifax soil series is described as a brown sandy loam over yellowish sandy loam with good to excessive drainage. The parent material is olive to yellowish-brown sandy loam to gravelly sandy loam glacial till derived mainly from quartzite (MacDougall et al. 1963).

3.2.2 Bedrock Geology

The bedrock which underlies the site is of the Goldenville Formation of the Meguma group. The Halifax formation, also of the Meguma group, is also present within the extent of the groundwater modeling domain. The Goldenville formation is comprised of metasandstone, metasiltstone and slate while the Halifax formation is comprised of slate, siltstone and minor sandstone (Keppie 2002). Both are metamorphic rock formations, which mainly yield water from fractures.

3.2.3 Topographic and Land Use Data

As previously mentioned, ArcGIS was used to organize data related to the study. Many digital data sets were processed in ArcGIS prior to information being used in PCSWMM and/or MODFLOW, Table 3. A 20 m by 20 m DEM of the study area was used to delineate the subcatchment of the study area. This was completed using Arc Hydro within ArcGIS.

3.2.4 Monitoring Methods

A field sampling program was initiated in October 2013. The monitoring methods are presented in the following subsections.

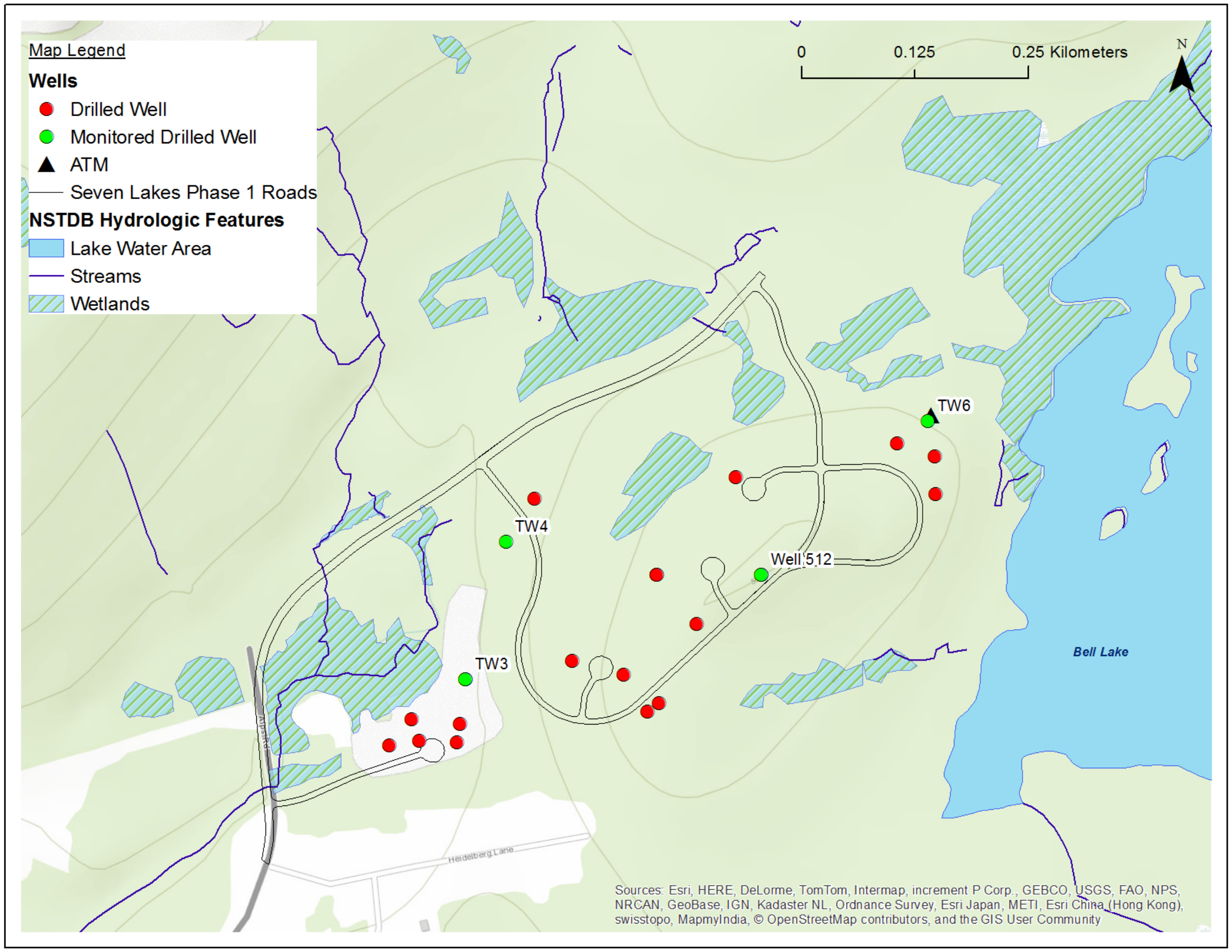
3.2.4.1 Continuous Groundwater Level Monitoring

Three groundwater monitoring wells, Test Well (TW) 3, TW4, and TW6, were designated as continuous water level measurement points, with monitoring initiated in October 2013. Continuous monitoring in an additional well, Well 512, began September 16, 2014, refer Appendix A for groundwater levels for wells. The location of the monitoring wells, and with other wells which have been drilled in the study area to date are shown in Figure 3-3. Borehole logs describing the monitored wells, and those used in the groundwater model calibration (Figure 3-10, Section 3.4.5), can be found in Appendix B.

Table 3 Summary of Digital Datasets

Data	Description	Source:
DEM	20 m by 20 m digital elevation raster	Dalhousie GIS Centre
NSTDB 10000	Nova Scotia Topographic Data 2012 (includes topographic data, water features, roads, trails and rails and utilities)	Province of Nova Scotia
Soils	Soil Survey of Halifax County, Nova Scotia	National Soil DataBase, Agriculture and Agri-Food Canada (2002)
Bedrock	Geological Map of the Province of Nova Scotia.	Nova Scotia Department of Natural Resources (NSDNR), Mineral Resources Branch
Land use	Forest Inventory	NSDNR
NS Well Database	Nova Scotia Well Logs Data Base	NSDNR and NSE
Wetland and Streams	Detailed delineation of watercourses and wetlands at the site	WSP
Study Area Survey	Detailed survey of the study area topography	WSP

HOBO U20 Water Level Loggers (Onset® Computer Corporation, Bourne, Massachusetts, United States) were installed in wells and programmed to record pressure and temperature on an hourly time step. Data from the loggers was regularly downloaded and manual readings of the water level elevations were recorded. Manual water level readings were collected upon transducer deployment and each time data was downloaded.



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 3-3 Seven Lakes study area drilled groundwater wells. Continuously monitored wells (green) and drilled to date (red), ATM means atmospheric pressure logger.

A Heron Instruments dipper-T Water Level Meter (Heron Instrument Inc., Dundas, Ontario, Canada) was used to determine depth to water from the top of the well casing. Pressure readings from the wells were corrected using barometric pressure recorded at the Environment Canada Shearwater RCS Station (Climate ID 8205092), located 20 km south west of the study area, for data prior to February 2, 2015. After February 2, 2015, a HOBO U20 Water Level Logger (Onset® Computer Corporation, Bourne, Massachusetts, United States) was placed in the study area to measure barometric pressure and used to correct pressure recorded in the wells. The logger was located at surface within 5 m of TW6, Figure 3-3. Corrected pressures were converted to a height of water above the sensor using Equation 6.

Equation 6

$$P = \rho g h$$

Where:

P = pressure (kPa)

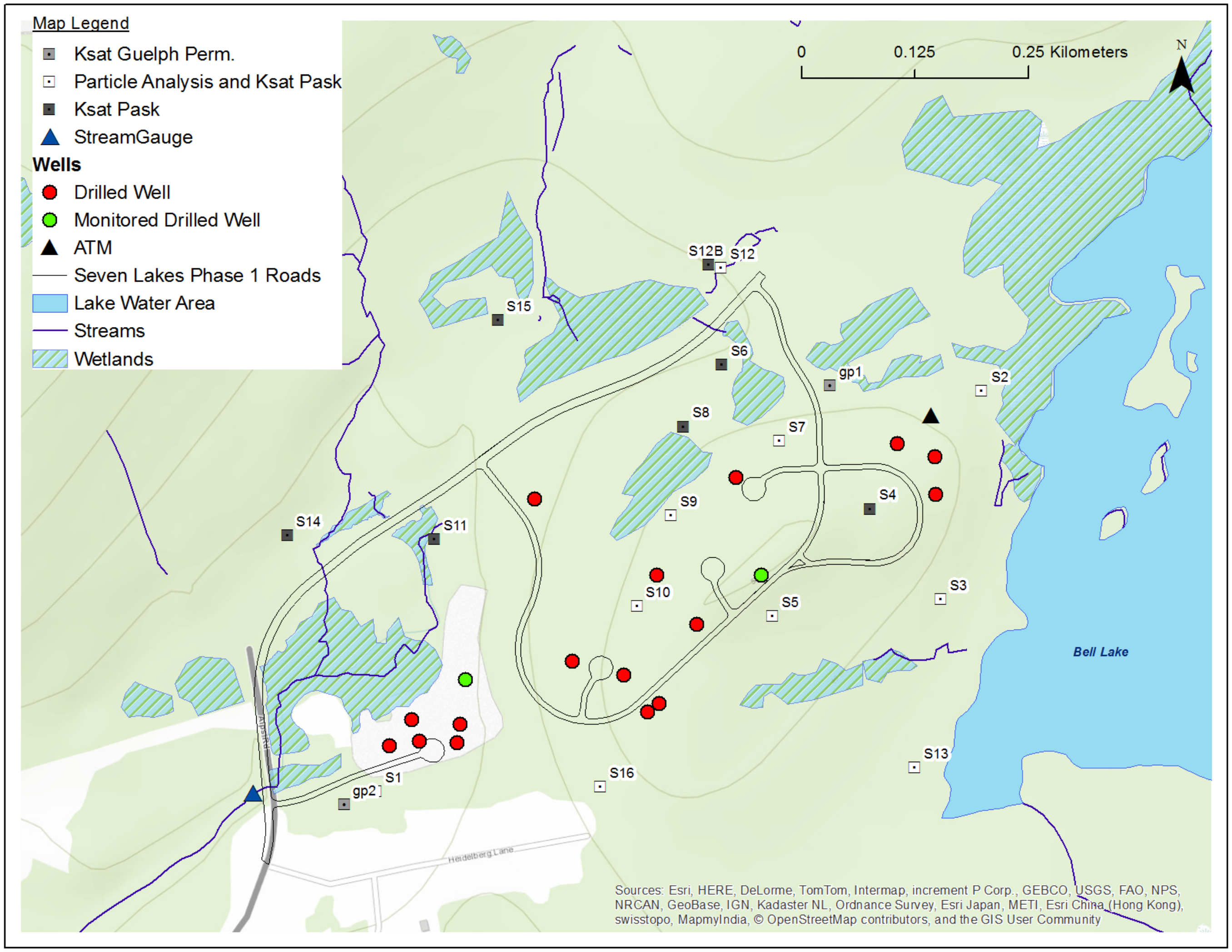
ρ = density of water, assumed to be 1000 kg/m^3

g = gravity, assumed to be 9.81 m/s^2

h = head of water above the sensor (m)

3.2.4.2 Soil Texture Analysis

A total of 10 surficial soil samples were collected from the study area (Figure 3-4), from below the organic soil horizon using a drive cylinder. Sieve analysis was completed on the samples to determine grain size distributions for particles greater than 0.08 mm in size, and hydrometer testing was done to determine the distribution of fine particles less than 0.08 mm in size. Sieve and hydrometer analysis was completed in accordance with a laboratory method based upon ASTM (2007) standard D422 -63. Using grain size distribution data obtained from sieve and hydrometer analyses, soil texture was classified based on percent sand, silt and clay using a standard soil texture diagram as given by Dingman (2002).



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 3-4 Seven Lakes study area soil sample locations.

3.2.4.3 Hydraulic Conductivity

Hydraulic conductivity was measured *in-situ* soils for the study area using either a Pask or Guelph permeameter (Soilmoisture Equipment Corp., Goleta, California, United States). Both permeameters allow the user to estimate the steady state rate of water recharge into unsaturated soil from a cylindrical well hole, in which a constant depth of water is maintained (Reynolds and Elrick 1985; Elrick and Reynolds 1986).

The Pask permeameter was used following the methodology described in the Nova Scotia Onsite Sewage Disposal Technical Guidelines Appendix C, which has been adapted based on the work of Reynolds (1993) and Elrick and Reynolds (1986). Measurements were taken at 16 locations from May 15, 2015 to July 9, 2015 (Figure 3-4).

The Guelph permeameter (Soilmoisture Equipement Copr., Goleta, California, United States) model 09.07 was used following the methodology described in the operating instructions published by Eijkelkamp (2011). The two head method using the combined reservoir option was used. Measurements were taken at 2 locations on September 18, 2015, (Figure 3-4) The Guelph Permeameter Ksat Calculator version 3 published by Soil Moisture was used to calculate soil parameters.

3.2.4.4 Continuous Surface Water Level Monitoring

A streamflow monitoring station was installed in the primary watercourse downstream of the development, Figure 3-4. A HOBO U20 Water Level Logger (Onset® Computer Corporation, Bourne, Massachusetts, United States) pressure transducer programmed to log water level readings on a 15-minute time step was installed within a section of 50 mm (2 “), perforated, PVC pipe anchored to rebar secured into the stream bed. The pressure transducer was installed November 2014 and the final reading for this study was taken August 26, 2016. The pressure readings from the transducer were corrected using barometric pressure measured in the study area.

3.2.4.5 Surface Water Velocity and Discharge

Stream gauging was carried out at the surface water monitoring location during baseflow and storm flow conditions. Velocity and depth measurements were taken using either a USGS Model 6205 Pygmy current meter (Gurley Precision Instruments, Troy, New York, United States) or a FlowTracker Acoustic Doppler Velocimeter (ConTek/YSI, San Diego, California, United States). The velocity-area method (Dingman, 2002) was used to calculate flow across the stream section. A manual elevation survey of the cross section of the stream and flood banks at the monitoring location was also completed in order to estimate an extreme high flow using Manning's equation to complete the stage discharge curve. A stage discharge relationship was then constructed, Appendix C.

3.2.4.6 Climate Data

Climate data from Environment Canada was used to run PCSWMM and to calculate potential daily evapotranspiration. The nearest Environment Canada Weather station to the study area is the Shearwater Station, for which there are 4 different stations recording data over the past 30 years. Where necessary, data from these stations has been combined, Table 4.

3.3 Hydrologic Model: PCSWMM

Computational Hydraulics International's (CHI) PCSWMM modeling software, a proprietary version of SWMM5, was used to model net infiltration in the study area. Subcatchments are represented as a single spatial unit, with lumped model parameters and the surface layer of the subcatchment is treated as a reservoir overlying a two-zone groundwater submodel. The primary input parameters for the model are summarized in Table 5 surface parameters, Table 6 snow parameters and groundwater parameters, Table 7, which are detailed in the following sections and describe how the various hydrological process are computed.

Table 4 Environment Canada Climate Data Summary

Station Name	**Shearwater A**	**Shearwater AUTO**	**Shearwater Jetty**	**Shearwater RCS**	**Halifax Int'L A CWEEDS**[a]
Climate ID	8205090	9205091	9205093	8205092	8202250
			Rain Data hourly		
Hourly Precipitation	Jan. 1, 1990 to Apr. 2, 2007	Apr. 2, 2007 to June 26, 2008	--	June 26, 2008 to Sept. 23, 2016	--
			Evapotranspiration daily		
Max temperature	Jan. 1, 1990 to Dec. 31, 2005	Jan. 1, 2006 to Aug. 20, 2008	--	Aug. 20, 2008 to Sept. 27, 2016	--
Min temperature	Jan. 1, 1990 to Dec. 31, 2005	Jan. 1, 2006 to Aug.t 20, 2008	--	Aug. 20, 2008 to Sept. 27, 2016	--
Average temperature	Jan. 1, 1990 to Dec. 31, 2005	Jan. 1, 2006 to Aug. 20, 2008	--	Aug. 20, 2008 to Sep. 27, 2016	--
Average wind speed	Jan. 1, 1990 to Dec. 31, 2005	--	Jan. 1, 2006 to Aug. 20, 2008	Aug. 20, 2008 to Sept. 27, 2016	--
Dew point temperature	Jan. 1, 1990 to Dec. 31, 2005	Jan. 1, 2006 to Aug. 20, 2008	--	Aug. 20, 2008 to Sept. 27, 2016	--
Atmospheric Pressure	Jan. 1, 1990 to Dec. 31, 2005	Jan. 1, 2006 to Aug. 20, 2008	--	Aug. 20, 2008 to Sept. 27, 2016	--
Extra-terrestrial Irradiance	--	--	--	--	Jan. 1, 1990 to Dec. 31, 2005
Global horizontal irradiance or solar radiation	--	--	--	--	Jan. 1, 1990 to Dec. 31, 2005

[a] CWEEDS Canadian Weather Energy and Engineering Datasets

Table 5 PCSWMM Surface Model Parameters

Parameters	Description	Units
Surface Parameters		
N Imperv	Manning's n valued for impervious surfaces	--
N Perv	Manning's n valued for pervious surfaces	--
D store Imperv	Depression storage for impervious surfaces	mm
D store Perv	Depression storage for pervious surfaces	mm
Curve Number	SCS Curve Number describing the subcatchment	--
Drying Time	Number of days it takes a fully saturated soil to dry	days

3.3.1 Surface Water Model

PCSWMM treats each subcatchment surface as a non-linear reservoir. Inflows to the surface reservoir include precipitation and snow melt, while include/ evaporation, infiltration and runoff, once the depression storage for the surface has been exceeded, Figure 3-5.

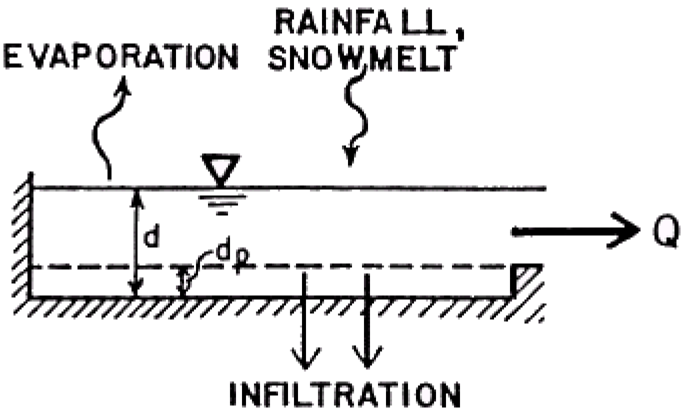


Figure 3-5 PCSWMM Surface Model (James et al. 2010), where d is the depth of water over the subcatchment and d_p is the depth of depression storage.

Table 6 PCSWMM Snow Model Parameters

Parameters	Description	Units
Min. Melt Coeff	The degree-day snow melt coefficient that occurs on December 21	mm/hr/°C
Max Melt Coeff	The degree-day snow melt coefficient that occurs on June 21	mm/hr/°C
TBASE	Base Melt Temperature, temperature at which snow begins to melt	°C
FWFRAC	Fraction Free Water Holding Capacity, volume of a snow pack's pore space which must fill with melted snow before liquid runoff from the pack begins	--
Depth at 100% Cover	Depth of snow beyond which the entire area remains completely covered and is not subject to any areal depletion effect	mm
Dividing Temp Snow and Rain	Temperature below which precipitation falls as snow instead of rain	
ATI weight	Antecedent temperature index weight, reflects the degree to which heat transfer within a snow pack during non-melt periods is affected by prior air temperature	--
Negative Melt Ratio	Ratio of the heat transfer coefficient of a snow pack during non-melt conditions to the coefficient during melt conditions	--

3.3.1.1 Infiltration

PCSWMM includes three options to calculate surface infiltration: Horton's equation, the Green-Ampt method and the Curve Number method. The Curve Number method for estimating runoff, adopted from the Natural Resources Conservation Service, formerly the Soil Conservation Service (SCS) Curve Number, was selected for use within this study.

Table 7 PCSWMM Groundwater Model Parameters

Parameters	Description	Units
Porosity	Volume of voids divided by total soil volume	--
Wilting Point	Soil moisture content at which plants cannot survive	--
Field Capacity	Soil moisture content after all free water has drained	--
Conductivity	Soils saturated hydraulic conductivity	mm/hr
Conductivity Slope	Average slope of log (conductivity) versus soil moisture deficit curve	--
Tension Slope	Average slope of soil tension versus soil moisture content curve	mm
Upper Evap. Fraction	Fraction of total evaporation available for evapotranspiration in the upper unsaturated zone	--
Lower Evap. Depth	Maximum depth into the lower saturated zone over which evapotranspiration can occur	m
Lower GW Loss Rate	Rate of percolation from saturated zone to deep groundwater	mm/hr
A1	Groundwater flow coefficient	--
B1	Groundwater flow exponent	--
A2	Surface water flow coefficient	--
B2	Surface water flow exponent	--
A3	Surface-groundwater interaction coefficient	--

3.3.1.2 Snow

PCSWMM has largely adopted the work of the National Weather Service (Anderson, 1973) to model snow using a modified degree-day model. A snow-cover depletion curve accounts for varying snow-cover area with depth, and explicit accounting for snowpack surface temperature, cold content, and liquid water routing are also included (DeWalle and Rango, 2008).

3.3.1.3 Evapotranspiration

There are 5 choices for specifying evapotranspiration (ET) demand in PCSWMM: a constant specified value, data from a time series, directly from climate file, specified monthly averages, and computed from temperatures in a climate file using the Hargraves method. The option of using data from a time series was chosen and the Priestly Taylor (PT) method was selected to calculate daily potential evapotranspiration based on available climate data.

The PT method was originally developed as a substitute for the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith method. The PT method (Equation 7) is semi-empirical and generally based on an energy balance which relies on solar radiation observations (Xu and Singh, 2002). According to Allen et al. (1990) the PT method was developed for calculating ET in wet and humid conditions.

Equation 7

$$ET = \alpha \cdot \frac{\Delta}{\Delta + \gamma} \cdot \frac{Rn}{\lambda}$$

Where

ET = reference evapotranspiration (mm/day)

Rn = net radiation at the crop surface (cal/cm2/day)

Δ = slope of the vapour pressure curve (mb/°C)

λ = latent heat (calories/gram)

α = empirical constant equal to 1.26

Net solar radiation was calculated from observations made as part of Environment Canada’s Canadian Weather Energy and Engineering Dataset (CWEEDS). This dataset ends December 31, 2005, after which net solar radiation was estimated using methods described by Allen et al. (1998). Code for calculating ET was developed in MATLAB R2014a following the equations presented by Xu and Singh (2002) and Chapter 3 of FAO paper 56 (Allen at al., 1998). The MATLAB code is provided in Appendix D.

3.3.2 Groundwater

PCSWMM uses a two-zone water budget model to represent water movement in the soil. The upper zone is unsaturated with variable moisture content. The lower zone is fully saturated. For each time step, water fluxes are calculated and a mass balance for each zone is computed in order to update the water table depth and the moisture content of the unsaturated zone (James et al. 2010), Figure 3-6 and Table 8.

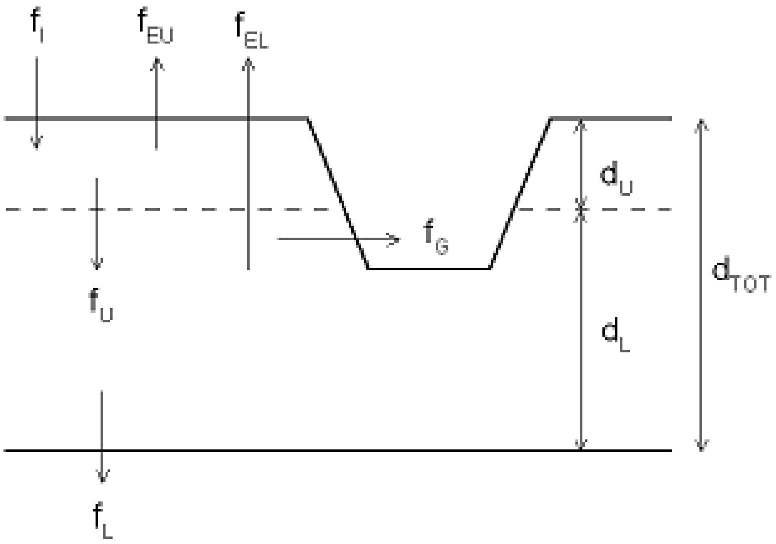


Figure 3-6 PCSWMM Conceptual Two-Zone Groundwater Model (James et al. 2010)

Table 8 PCSWMM Groundwater Model Fluxes (James et al, 2010).

Flux	**Interpretation**
f_I	Infiltration from the surface
f_{EU}	Evapotranspiration from the upper zone which is a fixed fraction of the unused surface evaporation
f_U	Percolation from the upper to lower zone which depends on the upper zone moisture content and depth (d_U) and is refer to as net infiltration.
f_{EL}	Evapotranspiration from the lower zone, which is a function of the depth of the upper zone (d_U)
f_L	Percolation from the lower zone to deep groundwater which depends on the lower zone depth (d_L)
f_G	Lateral groundwater interflow to the drainage system, which depends on the lower zone depth (d_L) as well as the depth in the receiving channel or node.

Lateral groundwater flow is represented by a general equation (Equation 8), Figure 3-7.

Equation 8

$$Q_{gw} = A1(H_{gw} - H^{*})^{B1} - A2(H_{SW} - H^{*})^{B2} + A3(H_{gw})(H_{SW})$$

Where:

Q_{gw} = groundwater flow

H_{gw} = height of saturated zone above bottom of aquifer

H_{SW} = height of surface water at receiving node above aquifer bottom

H^{*} = the threshold groundwater height

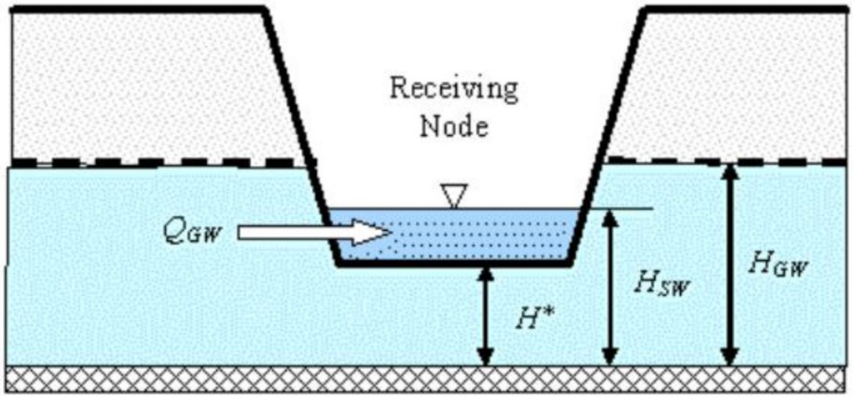


Figure 3-7 PCSWMM Groundwater Flow Conceptual Model (James et al. 2010).

Equation 8 can be modified to approximate the Dupuit-Forchheimer equation (Equation 9) representing lateral groundwater flow to a channel driven by the difference in groundwater and surface water heads, by setting B1 and B2 equal to 1, A1 equal to the proportionality factor, A2 equal to -A1, and A3 equal to 0:

Equation 9

$$Q_{gw} = \frac{4k}{L^{2}}\left[(H_{gw} - H^{*})^{2} - (H_{gw})(H_{SW})\right]$$

Where:

k = soil lateral saturated hydraulic conductivity

L = ½ the subcatchment flow length

3.3.2.1 Net Infiltration: PCSWMM

Percolation from the upper soil zone to the lower saturated soil zone has been interpreted to be net infiltration (f_U, Figure 3-6). PCWMM does not explicitly calculate percolation as a time series but it can be calculated from model outputs for a given time step using the water budget equation for the unsaturated soil zone:

Equation 10

$$TH2 = \left\{ \begin{matrix} [(ENFIL - ETU)PAREA - PERC]DELT \\ +(D1 - D2)TH2 + TH * DWT1 \end{matrix} \right\} / (DTOT - D2)$$

Where:

TH2 = end of time step upper zone moisture content (fraction)

ENFIL = infiltration rate

ETU = upper zone evapotranspiration rate

PAREA = pervious area divided by total area

PERC = percolation rate (f_U)

DELT = time step value

D1 = beginning of time step lower zone depth

D2 = end of time step lower zone depth

TH = beginning of time step upper zone moisture content (fraction)

DWT1 = beginning of time step upper zone depth

DTOT = total depth of upper and lower zone = D1 + DWT1

Solving Equation 10 for PERC provides a means of calculating the net infiltration rate for each time step:

Equation 11

$$PERC = (ENFIL - ETU)PAREA - \left\{ \begin{bmatrix} TH2(DTOT - D2) - \\ TH2(D1 - D2) - TH * DWT1 \end{bmatrix} / DELT \right\}$$

Net infiltration values were calculated and used as inputs to the groundwater model, MODFLOW.

3.3.3 Model Calibration

3.3.3.1 Sensitivity Analysis

A local differential sensitivity analysis was used to quantify the effect of varying the calibration parameters in PCSWMM for this study's objective functions: mean streamflow and net infiltration depths. The calibration parameters were varied one at a time, and the objective functions recorded. Using the range of input parameters, and the corresponding model outputs, a relative measure of sensitivity was calculated. The measure of sensitivity was normalized to provide a valid means for comparing the sensitivity of multiple model parameters (McCuen, 1973). Equation 12 is the general formula used to calculate relative sensitivity (R_s). The non-linear terms of the model were assumed to be negligible and the partial differentials were approximated used a finite difference method.

Equation 12

$$R_s = \frac{\partial F_0 / F_0}{\partial F_i / F_i} = \frac{\partial F_0}{\partial F_i} * \frac{F_i}{F_0}$$

Where:

F_0 = model output also referred to as an objective function

F_i = the parameter input to the model

d = change in the variable

The relative sensitivity was ranked into classes ranging from negligible to very high following the scheme presented by Lenhart et al. (2002), Table 9.

Table 9 Relative Sensitivity Classification Scheme

Class	**Rs**	**Sensitivity Class**
1	0.00 <=│Rs│< 0.05	Small to negligible
2	0.05 <=│Rs│< 0.2	medium
3	0.2 <=│Rs│< 1.00	high
4	│Rs│>= 1.00	Very high

3.3.3.2 Calibration and Validation

Calibration refers to adjusting the values of parameters nested within mathematical relationships to achieve the best match between the model predictions and the actual measured response. In order to evaluate the success or “goodness of fit”, statistical assessments of the degree to which the model predictions match the actual response are used (Legates and McCabe, 1999). Once a pre-defined goodness of fit has been achieved, the parameters are said to be calibrated. The model, with calibrated parameters, can then used to simulate study area responses for additional hydrological events for which actual responses have not been observed. A model is said to be validated if the calibrated model is able to adequately match observed for a time period outside of that used for model calibration (Woessner and Anderson, 1992).

The Nash-Sutcliffe Coefficient (NSE), a goodness of fit metric, also known as the coefficient of efficiency, is widely used in the field of hydrology for evaluating model fit (Equation 13) (Legates and McCabe, 1999). The values of NSE range from minus infinity to 1.0 with high values indicating better agreement. Values between 0 and 1.0 indicates that the model produces a better estimate than simply using the mean of the observed data. Whereas values less than 0 indicate unacceptable performance. Moriasi et al. (2007) note that the time step considered has an influence on the value of NSE that is deemed acceptable, and that NSE values greater than 0.5, calculated on a monthly time step, are generally reported to be acceptable.

Equation 13

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{P})^2}$$

Where:

O = observed values

P = predicted or calculated values, where the overbar denotes the average value over the considered time series

While the NSE is typically used to evaluate hydrologic models, Legates and McCabe (1999) note that the largest disadvantage of the NSE is the fact that differences between the observed and predicted values are calculated as squared values. In terms of the response of hydrological models, this metric tends to put more weight on matching peak flow values, as opposed to matching lower flow values typical of baseflow conditions. Karuse et al. (2005) present a metric to dampen this effect by reducing the sensitivity of NSE to extreme values. Karuse et al. (2005) propose that the NSE is calculated with logarithmic values of calculated and observed data, Equation 14. By instead using the logarithmic transformation of the values, the influence of the low flow values is increased in comparison to the flood peaks resulting in an increase in sensitivity of lnNSE to systematic over or under prediction.

Equation 14

$$LnNSE = 1 - \frac{\sum_{i=1}^{N}(lnO_i - lnP_i)^2}{\sum_{i=1}^{N}(lnO_i - ln\bar{P})^2}$$

In addition to comparing observed and simulated model responses on a continuous time basis, the total stream flow volumes over the simulation period were considered in model calibration, and were assessed based on percent difference.

PCSWMM was calibrated using the automated calibration tool built into the model called the Sensitivity-based Radio Tuning Calibration (SRTC) tool.

3.3.4 Development Scenarios

Post-development scenarios were constructed using the Seven Lakes Phase 1 development plan. The plan was modified so that the entire extent of Phase 1 is situated within the catchment area tributary to the stream flow monitoring gauge (Figure 3-8). Using dimensions from seven lots constructed at the study area to date (August 2016), estimates of lot sizes and impervious areas were made. These measurements served as the basis for estimating the impervious area of the study area post-development. In order to estimate post-development Manning's n and depression storage values, the percent difference between the initially estimated pre-development parameters and the calibrated model parameters was calculated. This difference was then applied to the estimated post-development lumped parameters in order to determine the final post-development parameters.

3.3.4.1 Conventional Stormwater Management

Under post-development conditions with conventional stormwater management, precipitation falling on the post-development impervious area was routed directly to the subcatchment outlet. This is based on the assumption that stormwater from each lot would be directed to ditches that flow to the watercourse leaving the study area.

3.3.4.2 LID Stormwater Management

Under post-development conditions with LID stormwater management, precipitation falling on the post-development impervious area is directed to rain gardens. Rain gardens were modeled in PCSWMM as bio-retention cells. Bio-retention cells include surface depressions with vegetation grown in an engineered soil mixture placed above a gravel drainage bed. They provide storage, infiltration and evaporation of both direct rainfall and runoff captured from surrounding areas (James et al. 2010). Once full, flow is directed to the ditched stormwater system and the subcatchment outlet.

Bio-retention areas were sized to capture 7 mm of precipitation falling on the impervious area of each lot using Equation 15 and Equation 16.

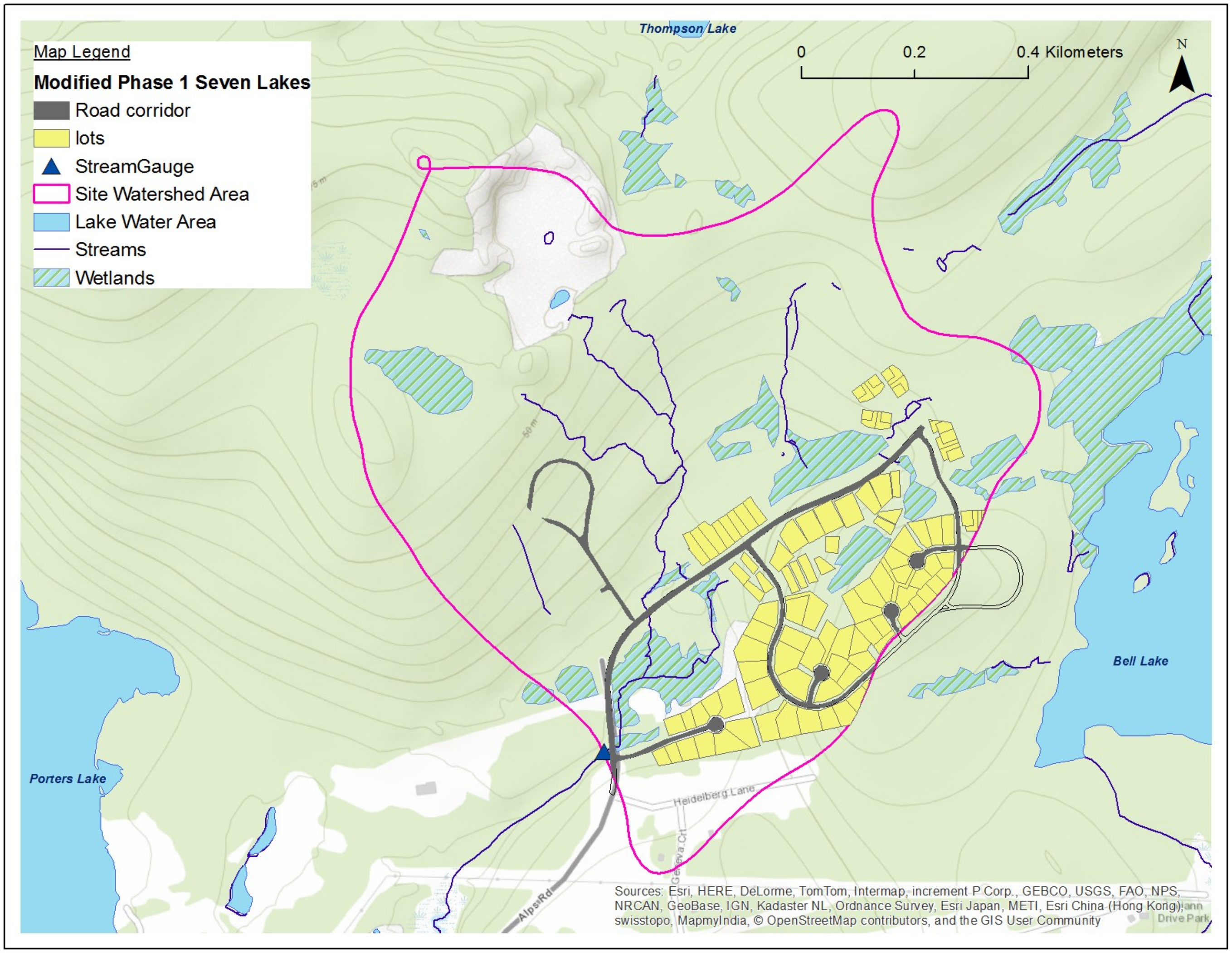


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Figure 3-8 Post-development modified lot and road layout.

7 mm was determined as the capture depth based on the dimensions of an existing bio-retention cell at the study area.

Equation 15

$$V_F = \frac{D_R * A_{lot}}{V_r}$$

Where:

V_F = cell volume for required capture depth of rainfall (m^3)

D_R = depth of rainfall (m)

A_{lot} = impervious area of the lot (m^2)

V_r = void ratio (fraction)

The surface area of the bio-retention cell was then calculated based on a known cell depth, Equation 16.

Equation 16

$$A_F = \frac{V_F}{d_c}$$

Where:

A_F = cell surface area (m^2), and

d_c = depth of cell (m).

One bio-retention cell was added to each proposed lot. Additional details regarding bio-retention cells required by PCSWMM are summarized in Table 10 and where applicable were based on the design and construction of an existing rain garden in the study area.

3.4 Hydrogeologic Model: MODFLOW

The purpose of the groundwater model was to simulate the effect of net infiltration depths from different development scenarios on both the amount of aquifer recharge and the depth of available head in water supply wells. Results were used to assess the sensitivity of the aquifer to both conventional and LID stormwater management designs.

Table 10 PCSWMM LID Parameter Descriptions

Parameter Name	Description	Value
Berm Height (mm)	Maximum depth to which water can pond.	100
Vegetation volume (fraction)	Fraction of volume within the storage depth filled with vegetation.	0
Soil thickness (mm)	Thickness of the soil of the layer.	175
Soil porosity	The volume of pore space relative to total volume of soil.	0.5
Soil field capacity	Volume of pore water relative to total volume after the soil has been allowed to drain fully.	0.2
Soil wilting point	Volume of pore water relative to total volume for a well dried soil where only bound water remains.	0.1
Soil conductivity (mm/hr)	The saturated hydraulic conductivity for the type of soils used.	50
Soil conductivity slope	Slope of the curve of log(conductivity) versus soil moisture content.	5
Soil suction head (mm)	The average value of capillary suction along the wetting front.	60
Storage thickness	The thickness of a gravel layer under the soil layer.	50
Storage void ratio	The volume of void space relative to the volume of solids in the layer.	0.75
Storage seepage rate (mm/hr)	The maximum allowable rate at which water infiltrates into the native soil below the layer.	5
Area of each unit (m^2)	Surface area of each unit.	50
Number of replicate units	The number of units within the subcatchment.	103
% of impervious area treated	Percent of the impervious area treated by LID feature.	18.4

3.4.1 Conceptual Model

As previously mentioned the geology of the study area consists primarily of bedrock of the Goldenville Formation, part of the Meguma group, and is overlain by a Quartzite till. Typical values of hydrogeologic parameters of fractured metamorphic rock from literature and a hydrogeological investigation of the study area completed by Strum (2011) were review, Table 11.

A continuum approach to modeling flow in fractured rocks has been used to model the study area. This means that the fractured mass has been assumed to be the hydraulic equivalent to a porous medium. The aquifer was also assumed to be isotropic in the horizontal direction and anisotropic in the vertical direction.

Table 11 Typical Values of Hydrogeologic Parameters of Fractured Metamorphic Rock

Hydrogeologic Parameter	Typical Values	Observed Data	Reference
Hydraulic Conductivity (m/s)	8E-9 to 3E-4[a]	1.9E-7[b]	[a]Domenico and Schwartz, 1990 [b]NSE and NSDNR, 2011
Transmissivity (m^2/day)	--	0.39 [a] 0.2 – 5[b]	[a]NSE and NSDNR, 2011 [b]Strum, 2011
Specific yield	0.27[a]	--	[a] Domenico and Schwartz, 1990
Specific storage (1/m)	3E-6 to 7E-5	--	Anderson and Woessner, 1992
Storativity	1.83E-4	2.3E-6 to 1.6E-4 [b]	[a]NSE and NSDNR, 2011 [b]Strum, 2011

3.4.2 Numerical Model

Visual Modflow Flex (MODFLOW) version 2015.1 (32 Bit) (Waterloo Hydrogeoloic, 2015) was used to model groundwater flow. This version of the model is a based on the three-dimensional finite-difference groundwater model USGS MODFLOW published by the United States Geological Survey (USGS) and includes a graphical user interface.

MODFLOW solves the non-linear water balance equation (Equation 17) allowing for 3D flow in an unconfined aquifer (Harbaugh, 2005).

Equation 17

$$\frac{d}{dx}\left(K_x \frac{dh}{dx}\right) + \frac{d}{dy}\left(K_y \frac{dh}{dy}\right) + \frac{d}{dz}\left(K_z \frac{dh}{dz}\right) = S_s \frac{dh}{dt} - W$$

Where:

K_x, K_y, K_z = hydraulic conductivity in the x, y and z directions

h = potentiometric head

S_s = specific storage for the porous material

t = time

W = sink/source term

MODFLOW was run in steady state mode using pre- and post-development net infiltration values for mean and drought conditions generated from PCSWMM. When Equation 17 is solved in steady state, the parameters associated with aquifer storativity, S_s, does not have an effect on model results. The time dependent term in Equation 17, is reduced to 0, therefore the storage parameters do not influence the model output (Harbaugh, 2005). Other model parameters which are not relevant to the solution of Equation 17, in the context of this study, include total and effective porosity. These parameters are employed when modeling contaminant advective-transport and particle tracking (Harbaugh, 2005).

The gauged watercourse leaving the study area was modeled as a drain boundary condition. The lateral flow to the drain was subtracted from net infiltration to calculate actual aquifer recharge for each scenario.

For the pre-development scenario, observations wells were added at each hypothetical proposed lot location. Typical pumping conditions required to service a household were applied in post development scenarios. The change in head in wells under each scenario served as the means for measuring the influence of different stormwater management techniques on the aquifer.

3.4.2.1 Model Properties

The spatial extent considered for the groundwater model was much greater than that considered by PCSWMM. This was done to be able to designate hydrologically correct boundary conditions, such as constant head (sea level) and no flow (watershed divide) boundaries. Figure 3-9 illustrates the extent of the groundwater model and the topography of the surface layer.

The surface of the model was built using a combination of a 20 m digital elevation model (DEM) published by NSDNR and surveyed topography of the study area completed by a local consulting company (WSP). Where the datasets overlapped, the survey data was used. A 40 m by 40 m rectangular gird was assigned to the model domain. Six layers were used to describe the groundwater system.

Layer 1, used to describe the till layer, has a variable thickness that was constructed in ArcGIS using the kriging interpolation tool across the site and layer depths taken from well logs. In areas where well logs did not exist, a thickness of 2 m was assumed. Layers 2 through 6 were each assigned a constant thickness.

The bottom of layer 1 was modeled as the transition from the overburden to the bedrock surface. Layer 2 was modeled as weathered bedrock and the remaining layers represent bedrock of decreasing hydraulic conductivity with depth. Pre-calibration aquifer hydraulic conductivity and storage properties were assigned to each layer, Table 12.

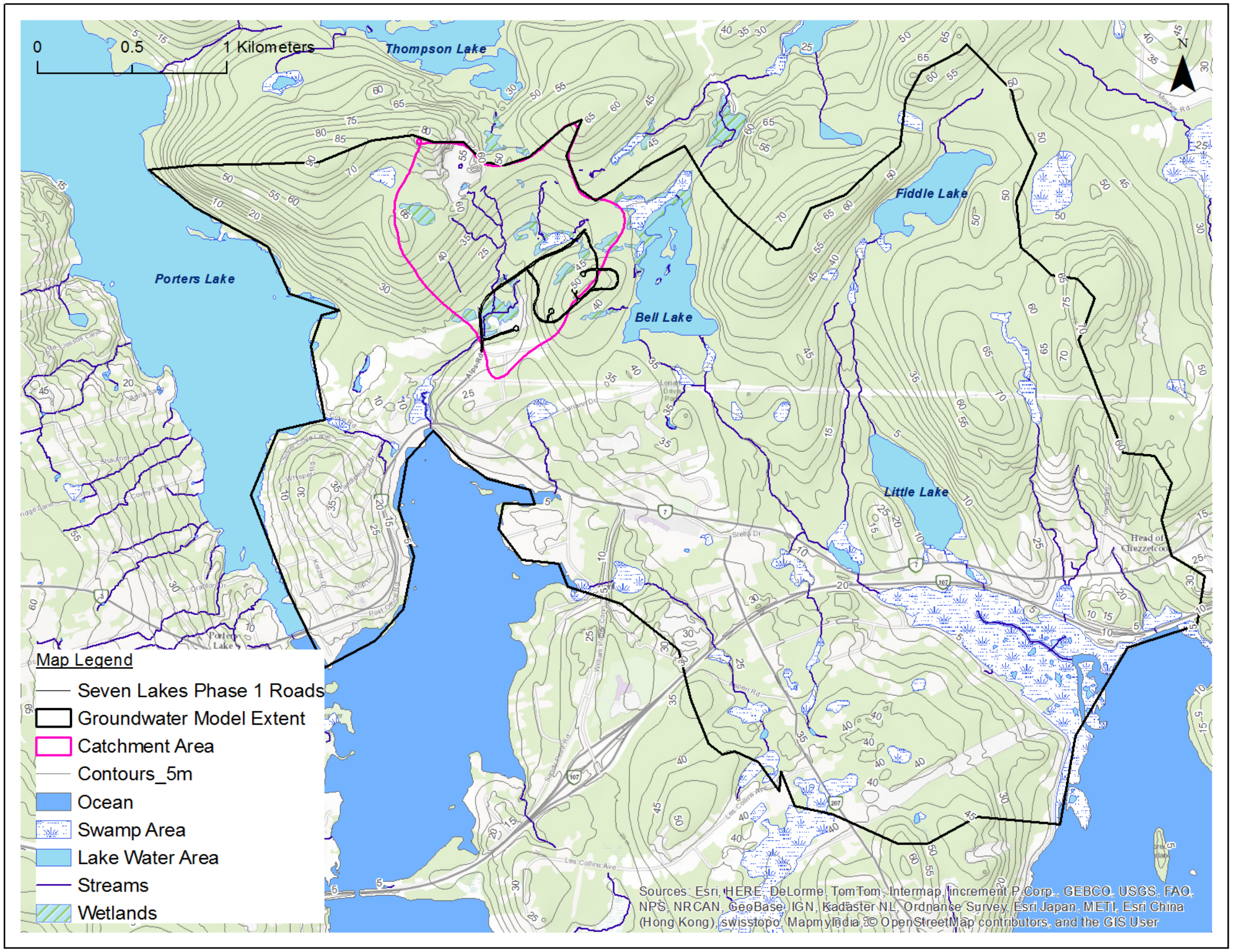

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Figure 3-9 MODFLOW boundary conditions

Table 12 Pre-Calibration Model Layer Properties

Layer No.	Thickness (m)	Kx and Ky (m/s)	Kz (m/s)
1	Variable	2E-5	2E-6
2	10	8E-6	8E-7
3	20	2E-6	2E-7
4	20	4E-7	4E-8
5	22.5	8E-8	8E-9
6	22.5	8E-8	8E-9

3.4.3 Boundary Conditions

There are many different boundary conditions which a user can specify in MODFLOW. A brief description of each type selected for use within this study is provided below.

The constant head boundary condition, used to assign a head value to a given cell in the model, was applied to cells along the edge of the model domain where the domain abuts the ocean. These cells were given head values of 0 m to represent sea level.

No flow boundary conditions were assigned to the edge of the model domain which coincides with major watershed divides inferred from the topography of the land surface. Water cannot flow through the edge of a cell specified as no flow boundary.

A drain boundary was used to represent the watercourse leaving the study area. Drains are used to simulate features which remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head or elevation. Cells assigned as drains require the following input information:

- Elevation (m): the drain elevation, and
- Conductance (m^2/day): a lumped coefficient describing the head loss between the drain and the groundwater system.

The location of the drain was assigned using the surveyed length of the stream. Elevations were assigned to the head and end of the stream using values from the DEM, and elevations for each cell in between were interpolated. The drain conductance parameter was used to calibrate the flow to the stream against the average lateral groundwater flows calculated from PCSWMM.

Lake boundary conditions were assigned to the three major lakes within the model domain using the Lake (LAK3) package developed by Merritt and Konikow (2000). The Lake package represents lakes as a volume of inactive cells within the model domain where cells bordering the inactive volume exchange water with the lake at a rate determined by relative heads and by a leakance parameter. The leakance parameter represents the resistance of flow through the lakebed. Cells assigned as lakes require the following input information:

- Stage (m): The initial stage of the lake at the beginning of the run, considered to be constant under steady state conditions.
- Bottom (m): The elevation of the bottom of the seepage layer of the lake.
- Leakance (1/day): A measure of the resistance of flow between the boundary head and the model domain. Leakance can be input directly or calculated as a lakebed hydraulic conductivity divided by the lakebed thickness.
- Precipitation Rate (mm/year): The rate of precipitation per unit area at the surface of the lake.
- Evaporation Rate (mm/year): The rate of evaporation from the surface of the lake.
- Overland Runoff (m^3/day): Overland runoff from an adjacent watershed entering the lake.
- Artificial Withdrawal (m^3/day): The flux of water removal from a lake by artificial means for human use.

The location and area of the three lakes considered in the model, Bell, Fiddle and Little, were determined by the NSTDB 1:10000 mapping, Figure 3-9. Lake stage, or depth, of Bell Lake is 4 m, as determined from bathymetric mapping of the lake (CWRS, 2013), Fiddle and Little were assumed to be 6 m and 3.3 m respectively based on the surface areas of the lakes and assumption that they are of similar type due to proximity to Bell Lake. The precipitation rate was estimated to be 1643 mm/year for the calibration year of 2014, 925 mm/year for drought conditions (1997), and 1200 mm/year for mean hydrologic conditions (2003). An evaporation rate of 400 mm/year was used based on the mean potential evaporation rate determined using the PT method (Section 3.3.1.3). Overland runoff was assumed to be 10% of the precipitation falling on the land area tributary the lakes based on the assumption that overland flow would be small due predominately forested nature of the lake catchments. No artificial withdrawals were considered. The leakance value was used as a calibration parameter.

The recharge boundary condition was used to apply a uniform net infiltration depth across the entire model domain. Variable net infiltration depths calculated from the PCSWMM model for different scenarios were used.

3.4.4 Wells

Wells were added to the model domain applying the constructions specifications recorded in well logs where available. All wells drilled in the study area are open hole with variable lengths of casing ranging from 6 to 12 m long. Wells that have yet to be drilled at the study area (future wells) were also added to each lot according to the Phase 1 development plan. The well depths of future wells were calculated in ArcGIS using kriging interpolation based on the depths of existing wells. A casing length of 10 m was assigned to each future well.

A pumping schedule was added to the wells post-development. Wells were pumped at a rate of 1.35 m^3/day, the minimum target volume recommended for Atlantic Canada (CBCL, 2004) for a single household.

3.4.5 Model Calibration

Model parameters, Table 12, were varied manually to achieve an acceptable goodness of fit between observed and simulated heads. The goodness of fit was evaluated using two metrics: the root mean squared error (RMS) and the normalized root mean squared error (NRMS) as shown in Equation 18 and Equation 19.

Equation 18

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}$$

Equation 19

$$NRMS = RMS/\bar{O}$$

Where:

n = number of data points in the set

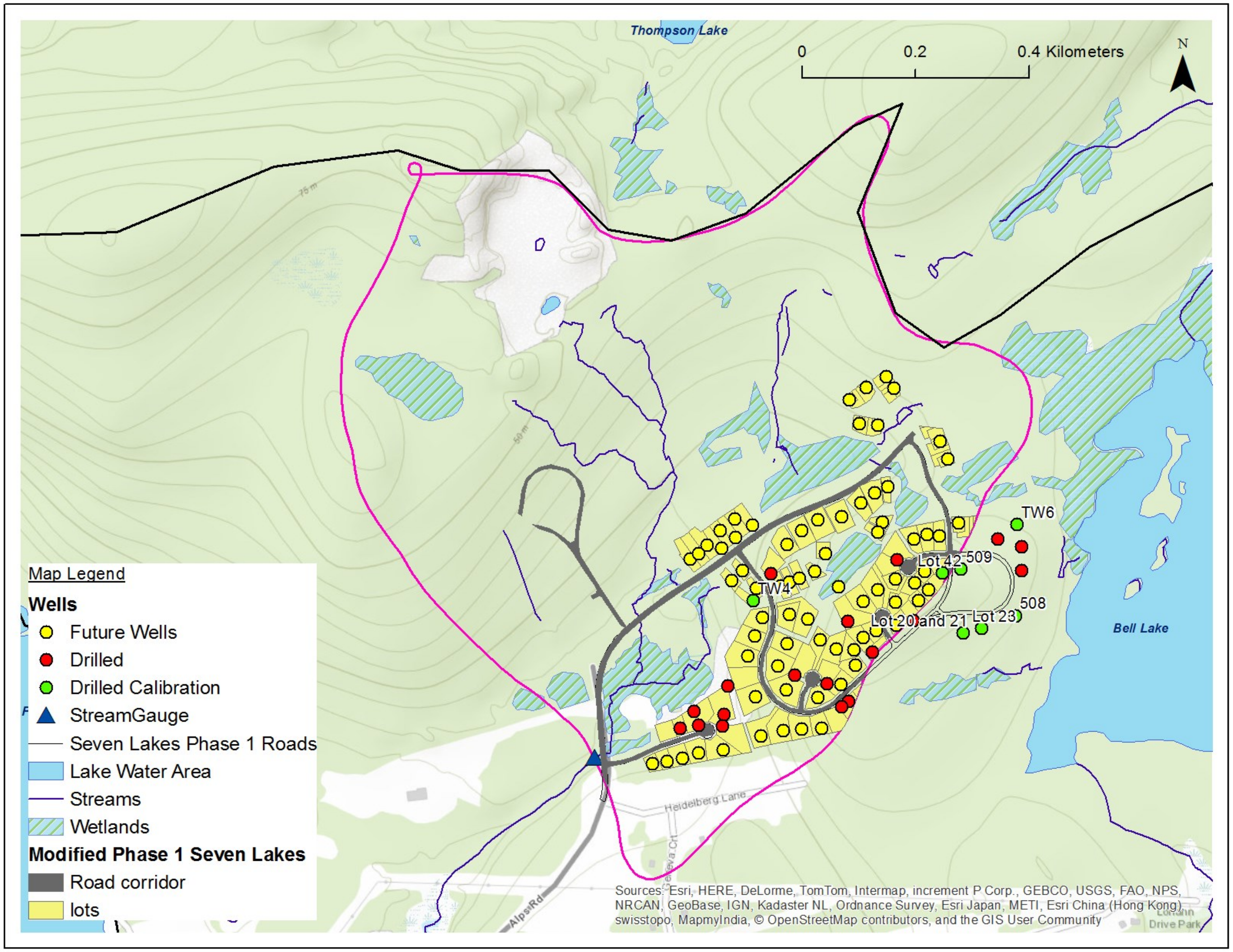
O = observed data

P = predicted or modeled data

Groundwater models are typically considered calibrated if the RMS is less than 5 m and the NRMS is less than 10% (Wels et al. 2012). Average measured groundwater elevation in wells TW4 and TW6 from 2014, as well as the static water levels recorded in wells 508, 509, Lot 42, Lot 20 and Lot 23 served as the observed data, Figure 3-10.

Wells 508, 509, Lot 42, Lot 20 and Lot 23 were selected based on the depths to which they were drilled (< 50 m). Open hole wells are not ideal for determining aquifer head at variable depths because they are entirely open beneath the casing.

The wells selected for calibration have a total depth less than 50 m and it was assumed that these wells were measuring heads in layer 3 or 4 of the model. The mean groundwater outflow from PCSWMM was used to calibrate the flow to the drain using the leakance parameter and assessed based on the percent difference between modeled and calibrated flows.



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 3-10 Wells used for MODFLOW calibration (green), drilled (red) and future wells (yellow).

3.4.6 Sensitivity Analysis

After the model was calibrated, a sensitivity analysis was conducted in place of model verification due to the lack of an additional set of field data. Calibrated values of hydraulic conductivity, net infiltration and boundary conditions were systematically varied over plausible ranges. The effect of the parameter changes on the steady state heads in existing and future wells were classified using the relative sensitivity index (Table 9, Section 3.3.3.1).

3.5 Groundwater Assessment for Subdivision Developments Toolkit

The Groundwater Assessment for Subdivision Developments Toolkit (GW Toolkit), version 1, developed by Nova Scotia Environment and Nova Scotia Department and Natural Resources was used to calculate drawdown in wells at the study area as a result of development. The GW Toolkit was designed as a screening tool to determine if there is sufficient groundwater to service a proposed development at a planning level. A comparison of the GW Toolkit results and the modeled results under different development scenarios was made in order to assess the predictive ability of the GW Toolkit. Details regarding the GW Toolkit can be found within the Guide to Groundwater Assessments for Subdivisions Serviced by Private Wells (NSE, 2011) and in the GW Toolkit, an excel spreadsheet model, which is available for download (https://novascotia.ca/nse/groundwater/).

The GW Toolkit well interference calculator was used to compare the predicted drawdown from the study area post development to that using MODFLOW. The well interference calculator uses the Theis equation (Equation 20 and Equation 21) to estimate the cumulative drawdown of proposed pumping rates on a well placed in the centre of the subdivision.

Equation 20

$$h_0 - h = \frac{Q}{4\pi T} W(u)$$

Where:

Equation 21

$$u = \frac{r^2 S}{4Tt}$$

h_0 = the initial hydraulic head (m)

h = the hydraulic head (m)

Q = the constant pumping rate (m^3/day)

T = aquifer transmissivity (m^2/day)

$W(u)$ = well function of Theis

r = radial distance from the pumping well (m)

S = aquifer storativity (dimensionless)

The parameters used to describe the aquifer in the Theis equation are transmissivity and storativity. Calibrated and measured values of transmissivity and storativity were both used in the well interference calculator to be able to compare results.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Site Characterization

4.1.1 Soil Analysis

Soil samples were taken at various locations throughout of the study area (Figure 3-4). For each sample the particle size analysis and soil class are presented in Table 13 and in Appendix E.

Table 13 Soil Texture Results

Sample ID	% Sand	% Silt	% Clay	Soil Class
S1	47	52	0	Silt loam
S2	43	52	4	Sandy loam
S3	70	30	0	Sandy loam
S5	91	8	1	Sand
S7	51	47	2	Sandy loam
S9	68	27	5	Sandy loam
S10	62	36	2	Sandy loam
S12	51	49	0	Sandy loam
S13	86	13	2	Loamy sand
S13	80	20	0	Loamy sand

The soil in the study area was found to be a sandy loam. This finding agrees with the soil mapping reported by MacDougall et al. (1963). Pre-calibration soil parameters were estimated based on the soil texture class according to Rawls et al., (1983), Table 19 (Section 4.3.2). Saturated *in-situ* hydraulic conductivity of the soil was measured at various locations throughout the study area (Figure 3-4), Table 14.

Rawls et al. (1983) report hydraulic conductivity values for sandy loam textured soils to be 2.8E-06 m/s or 10 mm/hr. This agrees reasonably well with values of hydraulic conductivity measured across the study area.

Table 14 Saturated in-situ Hydraulic Conductivities (m/s)

Location ID	Hydraulic Conductivity (m/s)	Location ID	Hydraulic Conductivity (m/s)
S1	1.7E-05	**S10**	1.62E-05
S2	9.9E-06	**S11**	2.2E-06
S3	2.0E-06	**S12B**	3.3E-05
S4	5.6E-06	**S13**	1.2E-05
S5	1.2E-05	**S14**	6.3E-06
S6	7.3E-06	**S15**	1.91E-05
S7	5.4E-06	**S16**	4.9E-06
S8	4.6E-06	**GP1**	1.06E-07
S9	1.7E-05	**GP2**	4.43E-07
Mean		5.6E-06	

4.2 Watershed Characterization

The study area subcatchment was found to be 94.2 ha, Figure 4-1. ArcGIS spatial analyst tools were used to calculate the average slope of the subcatchment and was found to be 8%.

The NSDNR Forest Inventory was used to calculate the % impervious and Manning's n values for both pervious and impervious areas of the subcatchment. The Forest Inventory is a digital data set of forest stand delineations digitized from air photos, digital satellite images, field silvicultural activities, other field data and data from the wetland interpretation project (Nova Scotia Natural Resources, 2006). Of specific importance to this study, is an attribute called FORNON which describes land uses other than forested. An estimate of percent pervious and Manning's n values for impervious and pervious areas has been associated with applicable FORNON classifications, Table 15 and Figure 4-1.

Post-development land use was derived from mapping provided by the Seven Lakes Developers. The average lot size was found to be 1200 m^2 with 30% of the lots covered with impervious surface (drive way and roof area).

Table 15 Forest Inventory Land Use Categories and estimates of % impervious and Manning's values for pervious and impervious areas.

Description (FORNON Code)	% Impervious	Manning's n Pervious[a]	Manning's n Impervious[a]	Depression Storage Pervious[a] (mm)	Depression Storage Impervious[a] (mm)
Natural Stand (0)	0	0.8	--	8	--
Cut Forest Stand (61)	0	0.8	--	8	--
Inland Water (77)	100	--	0.03	--	0.1
Urban (87)	75	0.41	0.01	2.5	1
Gravel Pit (95)	75	0.41	0.01	8	1.5
Powerline Corridor (97)	0	0.8	--	8	1.5

[a] James et al. 2010

A portion of Phase 1 is not situated within the delineated subcatchment of the study area. In order to estimate the influence of the entire development the portion outside of the study area was moved within the subcatchment, Figure 4-2. Manning's n and depression storage values were assumed for the lots and roads, post development, Table 16. The distribution of pervious and impervious area pre- and post-development and the percent change was calculated, Table 17.

Table 16 Post-Development Land Use Manning's n and Depression Storage Values

Land Use	% Impervious	Manning's n Pervious[a]	Manning's n Impervious[a]	Depression Storage Pervious[a] (mm)	Depression Storage Impervious[a] (mm)
Lots	30	0.41	0.01	4	1.5
Roads	100	--	0.01	--	1.5

[a] James et al. 2010

Table 17 Pervious and Impervious Areas Pre- and Post-Development

Area	Pre-Development (ha)	Post-Development (ha)	Change (ha)
Impervious	11.7	15.4	+3.7
Pervious	82.7	79	-3.7

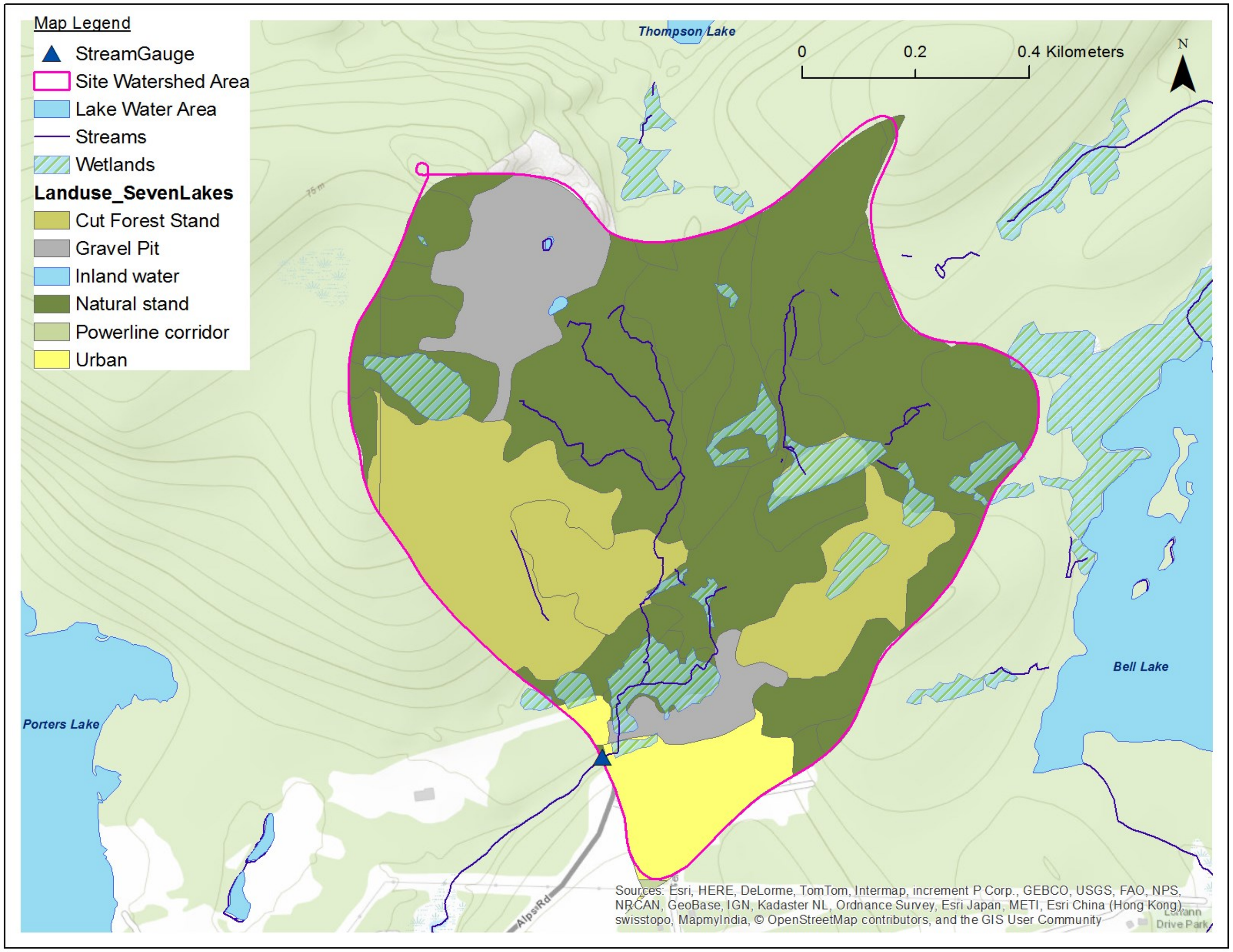


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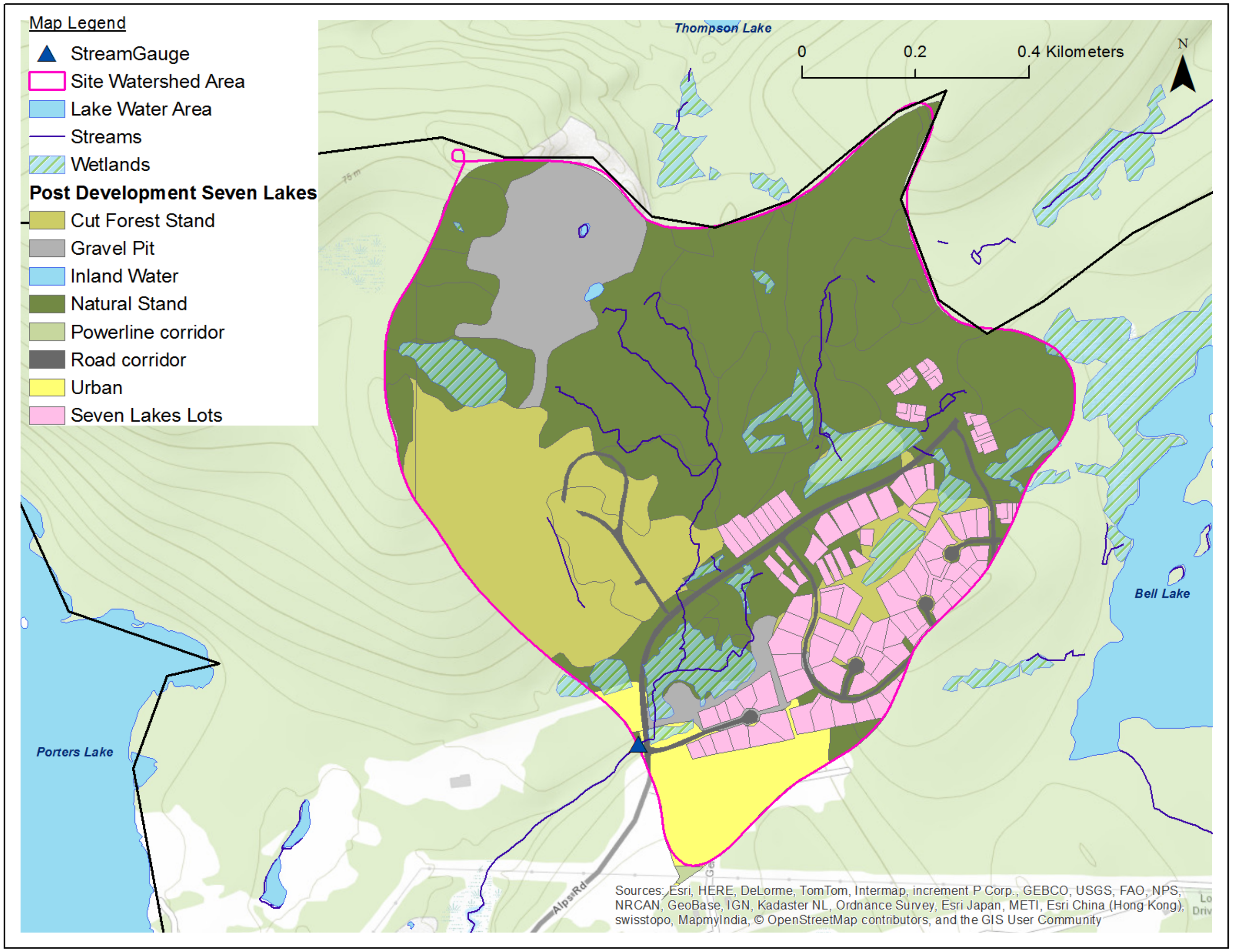
Figure 4-1 Study area pre-development land use.



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 4-2 Study area post-development land use

4.3 Hydrologic Model

4.3.1 Sensitivity Analysis

A sensitivity analysis was completed on the PCSWMM parameters, Table 18. The range of each parameter used in the analysis was selected based on a combination of the ranges suggested by James et al. (2010) and measured values from the study area. A sensitivity class was assigned to each parameter based on values of R_s as presented in Table 9 (Section 3.3.3.1).

Table 18 PCSWMM Sensitivity Analysis Results

Parameter	**Calibrated Value**	**Low Input**	**High Input**	**Sensitivity Ranking**	
				Mean Total Streamflow	**Net Infiltration**
Curve Number	64	60	85	neg	very high
Drying Time	7	2	14	neg	neg
Width (m)	75	50	500	neg	neg
N Imperv	0.017	0.011	0.024	neg	neg
N Perv	0.772	0.02	0.9	neg	neg
Dstore Imperv (mm)	1.3	0.3	2.3	neg	neg
Dstore Perv (mm)	20	2.5	25	neg	medium
Porosity	0.5	0.398	0.5	neg	neg
Wilting Point	0.15	0.024	0.265	neg	neg
Field Capacity	0.3	0.16	0.378	neg	neg
Conductivity (mm/hr)	5	0.25	125	neg	neg
Upper Evap. Fraction	0.5	0.35	0.6	medium	neg
Lower Evap. Depth	5	0	10	neg	neg
Lower GW Loss rate	0.04	0.002	0.4	neg	neg
A1 and (A3)	(-)1E-06	--	(-)1E-04	neg	neg
Pervious Area (%)	87	77	97	high	very high

Where neg = negligible

Mean total streamflow was most sensitive to the Upper Evaporation Fraction, a parameter used to describe the fraction of total evaporation available for evapotranspiration in the upper unsaturated zone of the aquifer. Decreasing this fraction caused an increase in the stream flow as less infiltrated water would be available for evapotranspiration, ultimately generating more lateral flow to a channel.

Net infiltration was very sensitive to the curve number and had a medium sensitivity to the depth of depression storage on pervious area. The curve number is the main parameter used in PCSWMM to determine how much precipitation is infiltrated into the ground. As the depression storage depth of pervious area increases, net infiltration decreases because more water is held within the surface reservoir and is available for evaporation.

Net infiltration was insensitive to the other model parameters. Revisiting Equation 11 (Section 3.3.2.1) reveals that net infiltration (PERC) is a function of infiltration, upper soil zone evaporation, the physical configuration of the groundwater aquifer and the fraction of the catchment area that is pervious. While not used as a calibration parameter, pervious area was included in the sensitivity analysis to demonstrate how sensitive both mean stream flow and net infiltration are to this model parameter (Table 18). The fact that most model parameters were not found to be sensitive can be attributed to the fact that the applicable objective functions for this study are net infiltration and mean stream flow. If alternative objectives functions were of interest, such as peak stream flows or time to peak streams, it would be expected that many other parameters would be sensitive such as flow width and Manning's roughness coefficients.

4.3.2 Model Calibration

PCSWMM was calibrated on an hourly time step using the SRTC tool for the period of November 21, 2014 to October 19, 2015, Figure 4-3, and validated for the period of Oct 25, 2015 to August 22, 2016, Figure 4-4. The pre-calibration, and final calibrated parameters values are presented in Table 19. Calibration and validation goodness of fit metrics, as well as the percent difference in stream flow volumes for each period were determine, Table 20.

The model calibration was deemed satisfactory based on the mean monthly lnNSE value (0.63) which was greater than 0.5. The model performed slightly poorer during the validation period, with a mean monthly lnNSE of 0.42.

Table 19 PCSWMM Pre- and Post-Calibration Parameters

Parameter	Pre Calibration Values	Calibrated Values
	Surface Parameters	
Subcatchment width (m)	1000	75
N Imperv	0.01	0.017
N Perv	0.78	0.772
D store Imperv (mm)	1.3	1.3
Dstore Perv (mm)	7.9	20
Curve Number	70	64
	Groundwater Parameters	
Wilting Point	0.09	0.15
FC	0.2	0.4

Table 20 PCSWMM Calibration and Validation Results

Stream Flow	Calibration	Validation
Ln(NSE) hourly	0.34	0.41
Ln(NSE) mean monthly	0.63	0.42
% difference total flow	22%	54%

During both the calibration and validation periods, the model is over predicting stream flow values, as demonstrated by the % difference in total flow of 22% and 54% respectively. From observations at the study area, it is believed that discharge from the subcatchment is influenced by a wetland fringing the watercourse. The wetland is likely accepting a portion of runoff from the subcatchment and dampening the discharge response, which is not represented in the PCSWMM model. Future research activities at the study area could involve an examination of the role the wetland plays in the hydrologic response of the watershed.

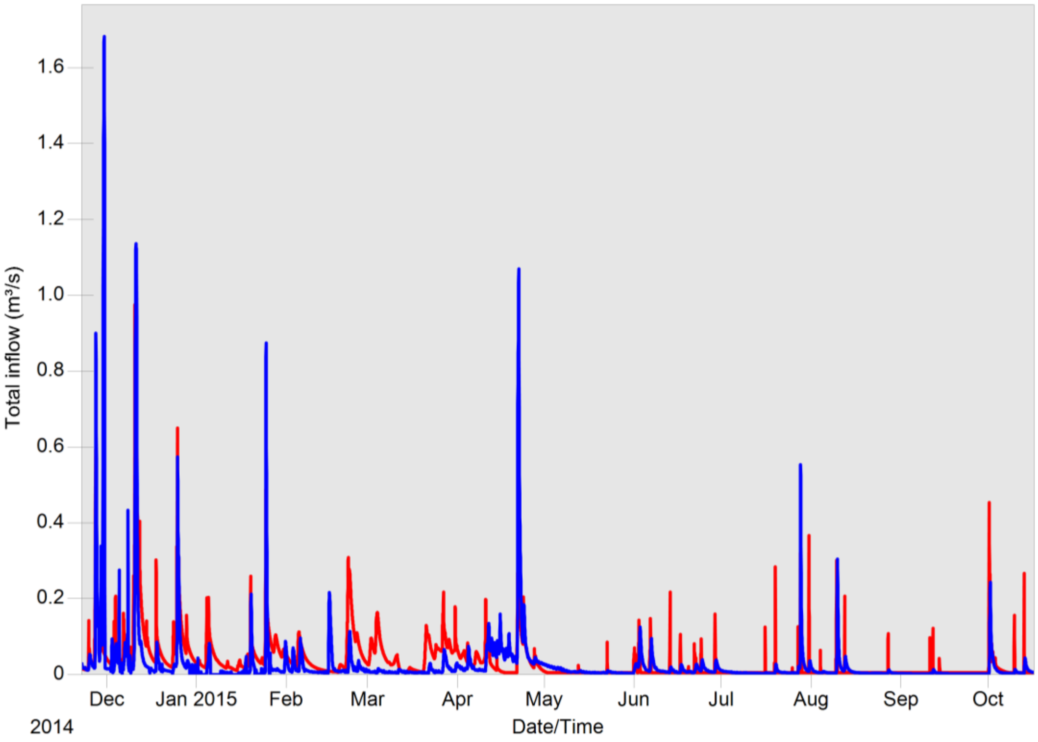


Figure 4-3 PCSWMM streamflow (Total inflow) calibration period, where observed data shown in blue and modeled in red.

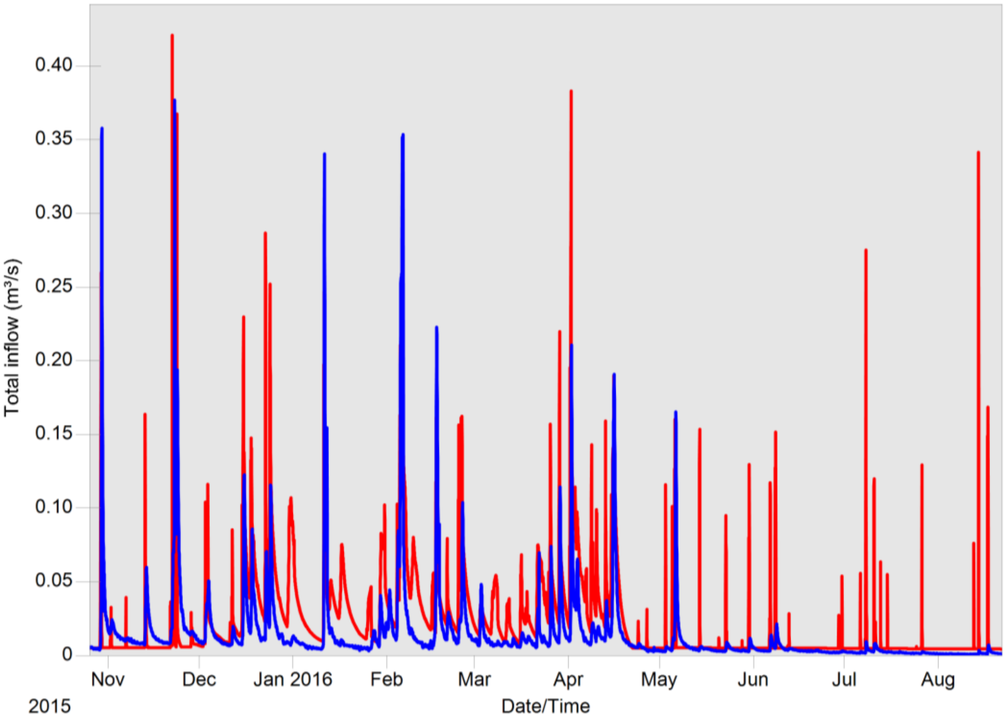


Figure 4-4 PCSWMM streamflow (Total inflow) validation period, where observed data shown in blue and modeled in red.

4.3.3 Net Infiltration

Net infiltration, also known as percolation or water arriving to the saturated soil zone, was calculated for pre- and post-development scenarios for mean and drought conditions using outputs from PCSWMM (Equation 11, Section 3.3.2.1). A net infiltration year was considered to be the period of October through September in order to account for any time delay in the arrival of water to the aquifer associated with snowmelt. Net infiltration was calculated for all scenarios, Table 21.

Table 21 Net Infiltration for Each Scenario

Hydrologic Conditions	**Net Infiltration (mm)**				
	Pre-Development	**Post-Conventional**	**% difference**	**Post-LID**	**% difference**
Drought (1997)	184	168	-8.7	189	2.7
Mean (2003)	479	438	-8.6	466	-2.7

For pre-development scenarios net infiltration ranged from 184 mm, in the drought year, to 479 mm in a mean year. The difference can be attributed to the difference in precipitation for each year.

Post-development with conventional stormwater management caused net infiltration to decrease by 8.7% and 8.6% in the mean and drought years, respectively. Incorporating LID stormwater management features post-development caused a 2.7% decrease in net infiltration in the mean year and an increase of 2.7% in the drought year. From these results it can be seen that the impervious area added to the catchment decreases net infiltration and that LID can be used to offset the decrease by providing opportunities to enhance infiltration.

4.3.4 Comparison of Pre- and Post-Development Water Balances

The results from PCSWMM have been expressed as a water balance to illustrate the effects of each scenario on the fate of water in the system, for the period of January through December, Table 22, Figure 4-5 and Figure 4-6.

Table 22 PCSWMM Water Balance Results (1997 represents a drought year, 2003 represents a mean precipitation year)

Depth (mm)	Pre 1997	Post-Con 1997	Post-LID 1997	Pre 2003	Post-Con 2003	Post-LID 2003
			PCSWMM Surface			
Precipitation	926	926	926	1203	1203	1202
Evaporation	277	274	275	284	280	281
Infiltration	411	393	415	602	575	605
Surface Runoff	259	279	256	337	366	335
			PCSWMM Groundwater Aquifer			
Infiltration	411	393	415	602	575	605
Evapotranspiration	271	257	263	294	278	283
Deep Percolation	118	115	125	134	130	140
Lateral groundwater flow to stream	151	147	162	174	169	184

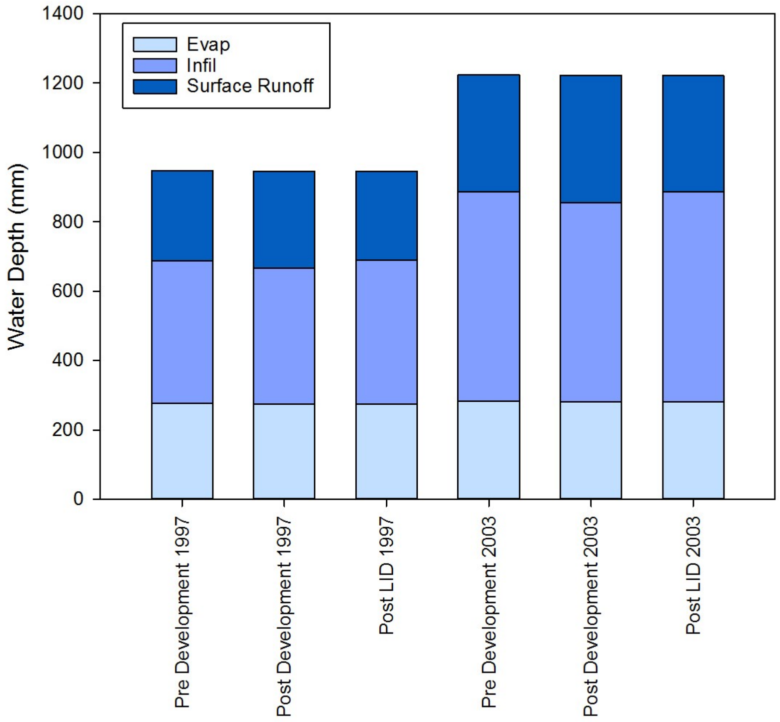


Figure 4-5 PCSWMM surface water balance results.

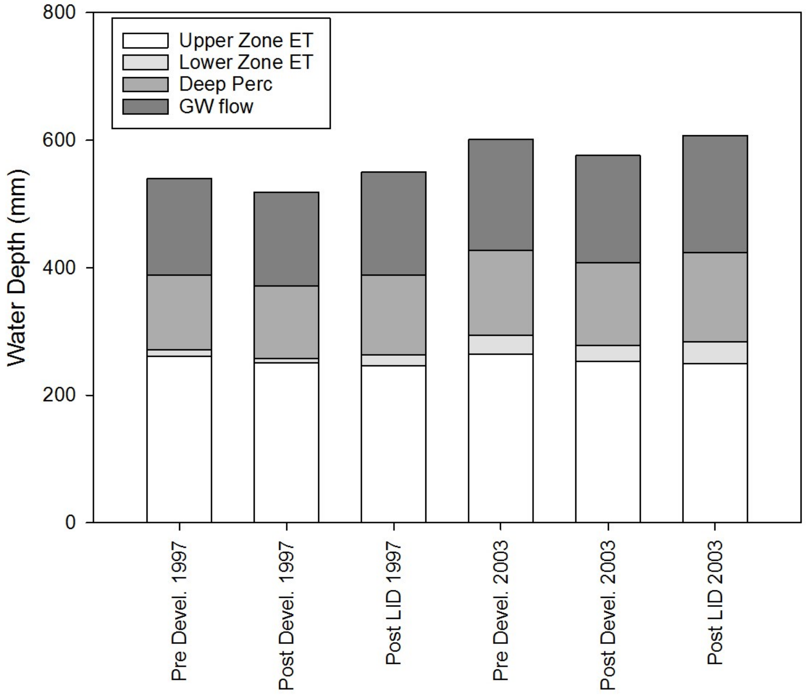


Figure 4-6 PCSWMM soil zones water balance results.

The changes in the water balance from pre- and post-development are not large. For each year, evaporation from the surface was consistent. Runoff increased post-development with conventional stormwater and was the same post-development with LID, when compared to pre-development. Infiltration decreased post-development with conventional stormwater and was the same post-development with LID, when compared to pre-development. Evapotranspiration from the soil zones decreased post-development, for both the conventional and LID stormwater scenario, although the LID scenario decreased less.

Deep percolation to the lower groundwater aquifer was consistent for each year. Lateral groundwater flow to the stream was greatest under the post-development scenario with LID. This can be attributed to the increase of infiltration due to LID and the fact that PCSWMM is not distributed. This means that infiltration due to LID features contributes to raising the groundwater table and therefore increasing lateral groundwater flow to the stream. While physically this may be the case in a limited area in proximity to the watercourse, generally it is not. Hence the decision to use the distributed groundwater model (MODFLOW) to determine lateral stream flow in order to calculate aquifer recharge for each scenario.

4.4 Groundwater Model

4.4.1 Model Calibration

MODFLOW was calibrated in steady state mode for the period of 2014 using a net infiltration depth of 468 mm and drain flow of 446 m3/day (0.0052 m3/s) (calculated in PCSWMM as lateral groundwater flow), Table 23 and Figure 4-7. The goodness of fit parameters for the calibrated model were a RMS of 4.36 m and NRMS of 20.23% and a percent difference in groundwater flow of 9%.

Calibrated hydraulic conductivity values in the horizontal direction (x and y) of layers 1 through 6 ranged from 3.56E-04 m/s to 1.74 E-06 m/s respectively. The hydraulic conductivity in the vertical direction (z) of layers 1 through 6 ranged from 4.10E-05 m/s to 1.25E-07 m/s, respectively. These values fall within the range of values reported for fractured metamorphic aquifers (Domenico and Schwartz, 1990; NSE and NSDNR 2011). The ratio of hydraulic conductivity in the vertical to horizontal directions was 12%, with the exception of layer 6 which was 7%.

Bell Lake leakance was calibrated to be 0.00036/d. Leakance represents the resistance of flow through the lakebed. Recalling that leakance can be calculated as the lakebed hydraulic conductivity divided by lakebed thickness, a value of 0.00036/d means that if the lakebed thickness were 1 m, the lakebed hydraulic conductivity would be 0.00036 m/d or 4.2E-09 m/s, much smaller than the hydraulic conductivity of the layers in which the lakes are situated.

While the calibrated leakance value allows the model to produce representative estimates of groundwater head within the study area, confidence in the resulting physical representation of the lakes is questionable. Measured values of the hydraulic conductivity of the lakebed material in addition to estimates of stream flows into and of the lakes would help improve the water balance of the lakes and increase the confidence in the model results, especially in the vicinity of the lakes.

Table 23 MODFLOW Calibrated Model Parameters

Layer No.	Thickness (m)	Kx and Ky (m/s)	Kz (m/s)
1	Variable	3.56E-4	4.10E-5
2	10	2.60E-5	3.00E-6
3	20	1.91E-5	2.20E-6
4	20	7.81E-6	9.00E-7
5	22.5	1.74E-6	2.00E-7
6	22.5	1.74E-6	1.25E-7
Boundary Conditions	**Leakance (1/day)**		
Fiddle Lake	**3.6E-4**		
Little Lake	**3.6E-4**		
Bell Lake	**3.6E-4**		
Drain	**1.5**		

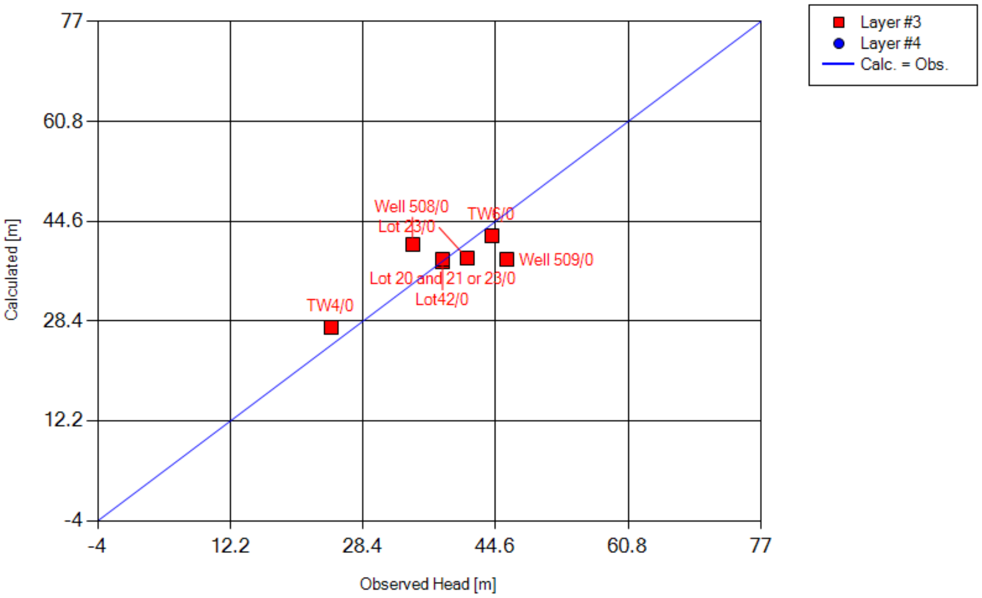


Figure 4-7 MODFLOW Calibration Results: Observed vs. Simulated Heads

The mean groundwater outflow from PCSWMM was used to calibrate the leakance value for the drain boundary within MODFLOW. The mean groundwater outflow from PCSWMM was found to be 0.0052 m^3/s. The calibrated drain flow was found to be 0.0056 m^3/s, or 9% greater than the observed flow. A leakance value of 1.5/d, assuming a stream bed thickness of 0.5 m, results in a stream bed hydraulic conductivity of 8.6E-06 m/s, which is an order of magnitude greater than the hydraulic conductivity of the surrounding model layers. While the thickness of the streambed material is unknown, it is reasonable that streambed material is coarser than the surrounding materials due to scouring of fine sediments.

4.4.2 Sensitivity Analysis

A sensitivity analysis was conducted on MODFLOW calibration parameters, Table 24 and Figure 4-8. Calibrated values of hydraulic conductivity, storage, net infiltration and the leakance values for the drain and lakes were systematically varied over plausible ranges to assess sensitivity on the steady state head in existing and future wells.

The model was found to be most sensitive to the values of hydraulic conductivity and net infiltration; both were classified as highly sensitive. All other parameters were classified as having negligible influence on the model results. Varying the hydraulic conductivity across all layers of the model, in both the vertical and horizontal directions, by -70 and 150% caused the mean hydraulic head in wells to increase by 120% and decrease by 46%, respectively. Varying the net infiltration by -75 to 75% caused the mean hydraulic head in wells to decrease by 43 % and increase by 38%, respectively.

Conversely, varying the drain leakance parameter by -99 and 99% caused the mean hydraulic head in wells to increase by only 4.3% and decrease by only 3%, respectively and the results were even less significant for the leakance value for all lakes. While the leakance value was not found to be a sensitive parameter on the head in the wells considered in the study, it could have a significant effect on the area immediately surrounding these features and should be refined if these areas are of interest in future studies.

Table 24 MODFLOW Sensitivity Analysis Results

	Range of % Change	Mean Head (m)		% Change		Sensitivity Class
Calibrated Head	--	33.1		--		--
Kxyz	-70 to +150	73.1	17.9	120.4	-46.0	high
Net Infiltration	-75 to +75	18.9	45.6	-43.0	37.5	high
Drain Leakance	-99 to +99	34.6	32.2	4.3	-3.0	neg
Lake Leakance	-99 to +99	32.6	33.4	-1.5	0.6	neg

Where neg = negligible

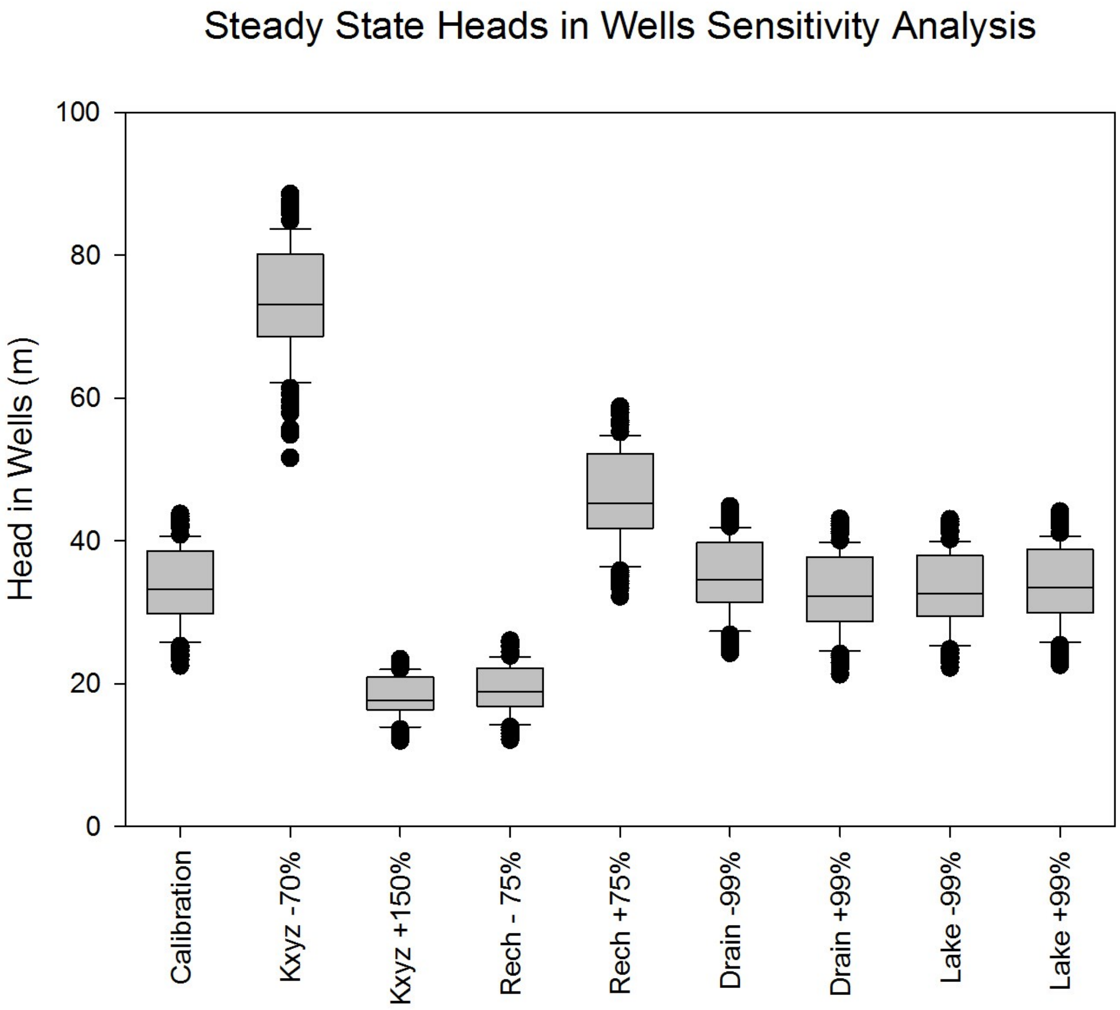


Figure 4-8 MODFLOW Sensitivity Analysis: Range of Steady State Head in Wells

4.4.3 Scenario Results

The calibrated model was run using the various net infiltration depths associated with pre- and post-development scenarios, under both mean and drought hydrologic conditions, Table 25 and Figure 4-9. For each scenario, the metric used to describe the availability of groundwater is the mean, and range, of hydraulic head across all of the study area water supply wells. Also provided in Table 23 is the percent change from the pre-development conditions.

Table 25 Scenario Analysis Results, % Change in Mean Well Heads

Scenario	Net infiltration (mm/year)	Aquifer recharge (mm/year)	Pumping rate per well (m^3/day)	Mean head (m)	Change (m)
Pre-development (1997)	185	182	--	18.4	--
Post-conventional (1997)	168	167	1.35	16.7	-1.7
Post-LID (1997)	189	187	1.35	17.9	-0.5
Pre-development (2003)	479	304	--	31.7	--
Post-conventional (2003)	438	288	1.35	29.9	-1.8
Post-LID (2003)	466	301	1.35	30.8	-0.9

Under drought conditions net infiltration and aquifer recharge were found to be approximately equal. In this scenario the elevation of the water table was simulated to below that of the stream for most of the year, and therefore minimal lateral groundwater flow was occurring. Under such conditions, one would expect to see the small stream dry up. Under mean hydrologic conditions, aquifer recharge is less than net infiltration, due to the elevated water table conditions which leads to lateral groundwater flow to the stream.

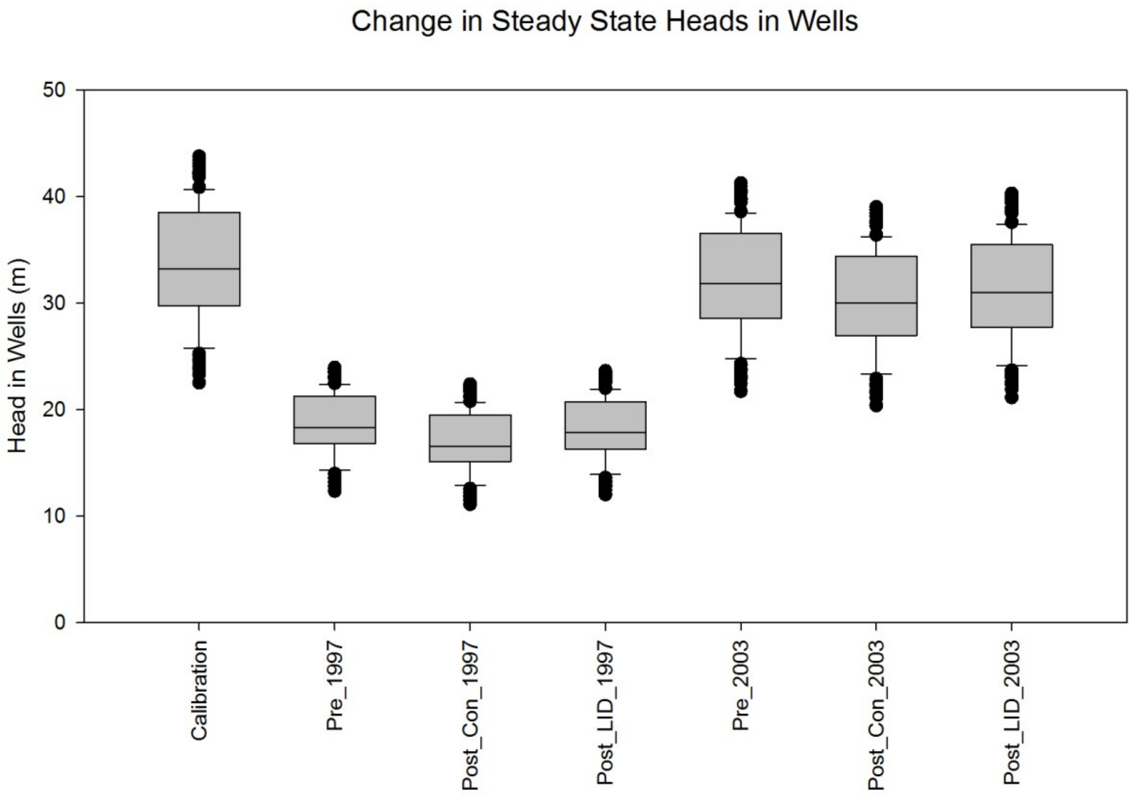


Figure 4-9 Scenario Analysis Results: Change in Steady State Heads in Wells

Pre-development aquifer recharge values were found to range from 182 to 304 mm/year. To put this range in context, the aquifer recharge values produced by Rivard et al. (2014) for the Annapolis valley ranged from 80 to 175 mm/year. The aquifer recharge estimated for the study area using the recharge ratio published by Kennedy et al. (2010), 0.17, for 1997 and 2003, produces a range of 157 to 204 mm/year, respectively.

However, the comparison of the estimates produced using the recharge ratios presented by Kennedy et al. (2010), in which stream base flow was equated to groundwater recharge, to the aquifer recharge values modeled in this study, may not be valid.

Under drought conditions, development with conventional and LID stormwater management caused the mean head in wells to decrease by 1.7 and 0.5 m, respectively.

Under mean hydrologic conditions, development with conventional and LID stormwater management caused the mean head in wells to decrease by 1.8 and 0.9 m, respectively.

The same trend was seen for both hydrologic conditions in pre- and post-development scenarios: mean heads decreased post-development but the decrease was less when LID stormwater management practices were applied. LID was shown to mitigate the effect of the increase in impervious area on the groundwater elevation. However, the effects were not large under this specific development scenario. If the catchment area were smaller and the impervious area greater, the influence of LID on the groundwater would play a more significant role.

Under mean hydrologic conditions, the difference between post-development scenarios with LID stormwater and conventional stormwater aquifer recharge rates is 13 mm/year. This depth applied over the catchment area of the study area modeled in PCSWMM (92 ha), results in a volume of 12,000 m^3/year. Considering the daily household demand of 1.35 m^3/day, this means that 24 households could be serviced by the additional aquifer recharge as a result of LID when considered on an annual basis.

Findings in this study support previous research of LID stormwater management techniques. Marchildon and Kassenaar (2013) modeled the impact of LID on groundwater recharge using a continuous fully distributed coupled groundwater and surface water model (GSFLOW) from a sub set of the Greater Toronto region of Ontario, Canada, called Oak Ridges. They predicted that conventional development caused groundwater drawdown greater than 4.5 m due to a reduction in groundwater recharge created by the increased imperviousness and the routing of stormwater to conventional stormwater facilities. While, distributed LID features, such as routing impervious areas to bioswales, and the use of an infiltration gallery, reduced the groundwater drawdown to 1 m and increased baseflow to streams.

Stephens et al. (2012), modeled the ability of LID to enhance groundwater recharge in New Mexico, through the observation that an existing stormwater bio-retention cell was causing groundwater mounding, 3 to 10 m thick, in an area that receives approximately 330 mm/year.

Hood et al. (2007) compared stream flow characteristics in two watersheds with residential development, one with centralized and the other with distributed LID stormwater management, in Southeastern Connecticut, USA. Hood et al. (2007) found that the watershed with LID had a significantly greater time to peak than conventional development for small storms, < 25.4 mm, but not for large storms > 25.4 mm and that the greater precipitation threshold to runoff for the watershed with LID was attributed to infiltration enhancement.

Loperfido et al. (2014) in a study of gauged urban catchments in Chesapeake Bay, Washington, D.C., found that catchments with distributed stormwater BMPs led to slightly less stormflow and significantly greater baseflow when compared to those with centralized BMPs due to the presence of infiltration BMPs.

The number of studies which assess the influence of LID on groundwater recharge using actual monitoring data was found to be limited (Hood et al. 2007 and Loperfido et al. 2014). The continued collection of stream flow data and groundwater levels from the study area, would provide the opportunity to present the actual effects of the built LID features on the groundwater aquifer.

4.4.4 Assumptions and Model Uncertainty

Limitations of the model are introduced when assumptions are made in order to represent the aquifer mathematically. For the study area, the assumption of isotropy in the horizontal plane of the aquifer in terms hydraulic conductivity is most likely not representative of actual geological conditions due to the fact that fractures are likely the main pathways in which water moves. It was also assumed that the aquifer can be modeled as a porous medium. While both assumptions are likely valid over larger areas, they may not represent the aquifer as well at smaller scales.

The model was found to be highly sensitive to the values of hydraulic conductivity and net infiltration. In this particular case, if net infiltration values were incorrect, the calibrated hydraulic conductivity values would be different. Equifinality is a term used to describe this situation. It means that there may be many representations, i.e. sets of parameters, which are equally able to produce simulated model results that match observed data (Beven, 2002). While the calibrated model parameters show good agreement with observed groundwater elevation, equifinality could influence the confidence in predicting how land use change could affect water resources.

The collection of data specific to LID features could be used to refine the estimates of net infiltration made using PCSWMM. This could include the LID parameters related to the bio-retention areas soil characteristics, as well as the seepage rate from the bottom of the LID feature to the surrounding soil. Other means of refining the estimate of net infiltration could include the collection of more detailed soil infiltration at various depths throughout the subcatchment. This soil profile information could be noted during excavation for lot development and as additional wells are drilled.

Uncertainty associated with the streamflow data used for hydrologic model calibration was introduced to the observed data through multiple means. Firstly, it is introduced through the use of a stage discharge relationship ($R^2 = 0.88$) which was developed using directly measured stream flows and one estimate of flood flow using Manning's equation. While necessary due to the lack of gauged flood events, Harmel et al. (2006) recommend that flows estimated using Manning's equation be avoided if possible due to the added uncertainty. As previously mentioned, an additional source of uncertainty is likely the wetland fringing the watercourse, and dampening the catchment response. Hamel et al. (2006) in a review of published information on uncertainty in measured data for small watersheds, found cumulative probable uncertainty in measured stream flows range from 6 to 19%.

Uncertainty associated with the hydraulic heads used for groundwater model calibration may have been introduced to the data through the use of barometric pressure data from Environment Canada's Shearwater station, located 20 km south of the study area to determine the head of water above the pressure transducers in wells. Another source of uncertainty relates to the fact that wells were drilled for use as production wells and are open hole below the casing installed at ground surface. This results in measurement of an average head across all layers intersected by the open hole.

The continued collection of groundwater and stream flow data from the study area would provide the opportunity to calibrate post-development scenarios and reduce uncertainty in the model predictions. Although when doing so, the modified lot layout used within this study to represent post-development should be considered.

4.5 Comparison of GW Toolkit with MODFLOW

The GW Toolkit, produced for Nova Scotia to assess groundwater supplies for subdivisions, includes a well interference calculator to estimate drawdown using measured and calibrated aquifer parameters. The outputs from the GW Toolkit were compared to the predicted drawdown generated using MODFLOW in order to assess the differences in results and the predictive nature of the GW Toolkit.

4.5.1 GW Toolkit Input Parameters

In order to use the GW Toolkit well interference calculator, the user must input values of transmissivity and storativity, as well as the available head in a well placed at the centre of the site.

MODFLOW does not explicitly require transmissivity as a model parameter. It does however use hydraulic conductivity. Transmissivity was calculated using the depth and calibrated hydraulic conductivity of each model layer. A weighted harmonic mean was used to produce a representative transmissivity value for the aquifer for layers 2 through 5, those likely contributing flow to the well. As stated within the results of the MODFLOW sensitivity analysis (Section 4.4.2), the storage parameters had no effect on model results due to the model being solved in steady state mode. With no confidence in the value of storativity in the calibrated model, the median value reported from metamorphic groundwater regions in Nova Scotia as part of the NS Pumping Test Database and published by NSE and NSDNR (2011) was used in the well interference calculator.

Measured values of transmissivity and storativity at the study area were sourced from the hydrogeological investigation completed by Strum (2011). An average value was used when multiple estimates were made from multiple wells. All input parameters are presented in Table 26.

For each scenario the drawdown in the well located at the middle of the study area was calculated and used to determine the % of available head drawdown the development would cause (Table 26). A value of available head in this well of 34.1 m, as calculated in MODFLOW in pre-development mean hydrologic conditions, was used as a reference for all scenarios. NSE (2011) recommends that the total predicted drawdown for the subdivision not exceed 50% of the available drawdown.

Table 26 GW Toolkit Drawdown Results vs. MODFLOW Results

	Inputs		**Results**		
	Transmissivity (m^2/day)	**Storativity**	**Drawdown (m)**	**Available Head (m)**	**% of Available Head**
		GW Tool Kit Well Interference Calculator			
Calibrated MODFLOW	8	1.83E-04[a]	15	34.1	44%
Measured	2.6	8.12E-05	32	34.1	94%
		MODFLOW Results			
Post-Con 2003	--	--	3.4	34.1	10%
Post-LID 2003	--	--	2.4	34.1	7%
Post-Con 1997	--	--	17.1	34.1	50%
Post-LID 1997	--	--	15.8	34.1	46%

[a] NSE and NSDNR (2011).

From Table 26, it can be seen that the calibrated MODFLOW results used in the GW Toolkit well interference calculator, caused 44% of available head to be drawdown, but that using the measured values from Strum (2011) caused a drawdown of 94%. Post-conventional and -LID stormwater management under mean hydrologic conditions, drew down 10% and 7% of available head, respectively. Post-conventional and -LID stormwater management under drought conditions, drew down 50% and 46% of available head, respectively. All scenarios, as simulated by MODFLOW, passed the 50% drawdown threshold. However, the post-development with conventional stormwater scenario, under drought conditions, was exactly 50%.

The % of available head drawdown using the measured values from the study area were much greater than those from the calibrated values from MODFLOW. While this suggests that the GW Toolkit produced conservative results, it may also be attributed to the value of transmissivity reported by Strum (2011). Strum (2011) calculated transmissivity using drawdown values from within the same well that was being pumped during their pump tests. Driscoll (1986) report that drawdown data from observation wells are usually more reliable than drawdown data from pumped wells when determining aquifer properties. Driscoll (1986) attributes this to the fact that observation wells are less susceptible to minor changes in well discharge cause by variations in pump speed, as well as lack of uncertainty in the measurements of the true water level because of turbulence in the well bore.

Strum (2011) also computed transmissivity values using data collected from observation wells. When the mean of these values were used, the % of available head drawdown was reduced to 70% (from 94%), but still falls below the 50% threshold recommended by NSE (2011). This analysis indicates that the GW Toolkit is producing conservative results when compared to the calculated drawdowns using MODFLOW. In this situation additional studies would be required to demonstrate that there is sufficient groundwater to supply the subdivision as proposed (NSE 2011).

Another parameter within the GW Toolkit which has an influence on the calculation of the % of head drawdown, is the selection of available head assigned to the well placed in the centre of the subdivision. This well could be either real or hypothetical. As observed in most wells, the head varies from season to season and from year to year. For given values of transmissivity and storativity, the available head assigned to the well can cause the % of available head to increase or decrease, thus changing the result of the screening test.

CHAPTER 5 CONCLUSION

The first objective of this study was to develop, calibrate and validate a modeling framework which can be used to assess how stormwater management practices influence recharge rates and groundwater availability. The second objective of the study was to assess the influence of stormwater management practices on groundwater recharge rates and availability in a proposed subdivision in HRM called the Seven Lakes Development.

The modeling framework was comprised of a hydrologic model, PCSWMM, which was used to generate estimates of net infiltration for conventional and LID stormwater management practices under both mean and drought hydrologic conditions. Net infiltration rates were coupled with a groundwater model, MODFLOW, which was used to determine aquifer recharge rates and test the availability of groundwater for the proposed Seven Lakes Development. Both models were calibrated using data collected from the Seven Lakes Development. Key conclusions from the study were:

- The measured values soil parameters, soil class and hydraulic conductivity from the study area, agree with available soil mapping and estimates published by Rawls et al. (1983).
- Net infiltration rates calculated in PCSWMM are most sensitive to the curve number and the depth of depression storage on pervious areas.
- The increase of impervious area in the study area catchment due to development decreases net infiltration, but LID practices can be used to offset the decrease by providing opportunities to enhance infiltration. This was achieved by designing LID bio-retention areas to capture a depth of 7 mm of precipitation from impervious areas.
- MODFLOW was found to be most sensitive to the values of hydraulic conductivity and net infiltration; both were found be in the high sensitivity class. All other parameters were classified as having negligible influence on the model results. The parameters associated with aquifer storativity (specific storage,

specific yield and porosity) did not have an effect on model results. This can be attributed to the fact that the model was run in steady state conditions.

- Pre-development aquifer recharge values were found to range from 182 to 304 mm/year. Post-development aquifer recharge values were found range from 167 to 288 mm/year with conventional stormwater management and 187 to 301 with LID.
- Under drought conditions, development with conventional and LID stormwater management caused the mean head in wells to decrease by 1.7 and 0.5 m, respectively. Under mean hydrologic conditions, development with conventional and LID stormwater management caused the mean head in wells to decrease by 1.8 and 0.9 m, respectively. In general, the same trend was seen under both hydrologic conditions for pre- and post-development scenarios; mean heads decreased post-development but the decrease was less with LID than conventional stormwater management practices.
- Under mean hydrologic conditions, the difference in the aquifer recharge rates for development with LID stormwater and conventional stormwater produced sufficient water to service 24 households when considered on an annual basis.
- The GW Toolkit was shown to provide conservative drawdown estimates as compared to MODFLOW simulations. All MODFLOW scenarios produce less than 50% drawdown in a well location at the centre of the Seven Lakes site, while the GW Toolkit caused 44% drawdown with calibrated MODFLOW parameters and 94% drawdown with the measured aquifer parameters (Strum, 2011). Post-conventional and -LID under mean hydrologic conditions, drew down 10% and 7% of available head, respectively. Post-conventional and -LID under drought conditions, drew down 50% and 46% of available

5.1 Recommendations for Future Research

The results of this study have highlighted areas where future research is warranted. They are summarized as follows:

- The completion of a sensitivity analysis to determine the density of development that would hinder the use of groundwater as a drinking water source. This analysis would provide the opportunity to determine the design for LID features, within this bedrock region, to offset the reduction in infiltration, thus making groundwater a viable source.
- Monitoring seepage rates beneath built LID features and soil depths as lots are developed could help to refine net infiltration estimates from PCSWMM.
- Seepage meters could be employed to measure seepage rates from the stream and lakes included within the groundwater model extent. This data could be used to calibrate the leakance parameter associated with these features and reduce model uncertainty in immediate vicinity of these features.
- A post audit of PCSWMM and MODFLOW models could be completed in order to calibrate and validate future predictions. This effort would benefit from continued data collection from the study area including stream flow and groundwater monitoring, as well as infiltration data from any bio-retention areas built within the study area. Although the modified Phase 1 plan for post-development scenarios should be modified to reflect as built conditions.
- Running transient simulations in MODFLOW would allow for the calibration of the aquifer storage parameters and provide a better insight to temporal variations of aquifer recharge and the influence of LID features.
- Additional groundwater quality data could be collected from the study area pre-development and could be used to calibrate models and make predictions related to the influence of LID stormwater management features on water quality. This could include the potential for LID features to contaminate groundwater especially in fractured bedrock.

- While the use of LID features produced positive results using a lumped hydrological model, specific details regarding the type and placement of LID features could be studied if a distributed hydrologic model was used. This type of model would require additional details regarding the surficial geology and topography of the study area.

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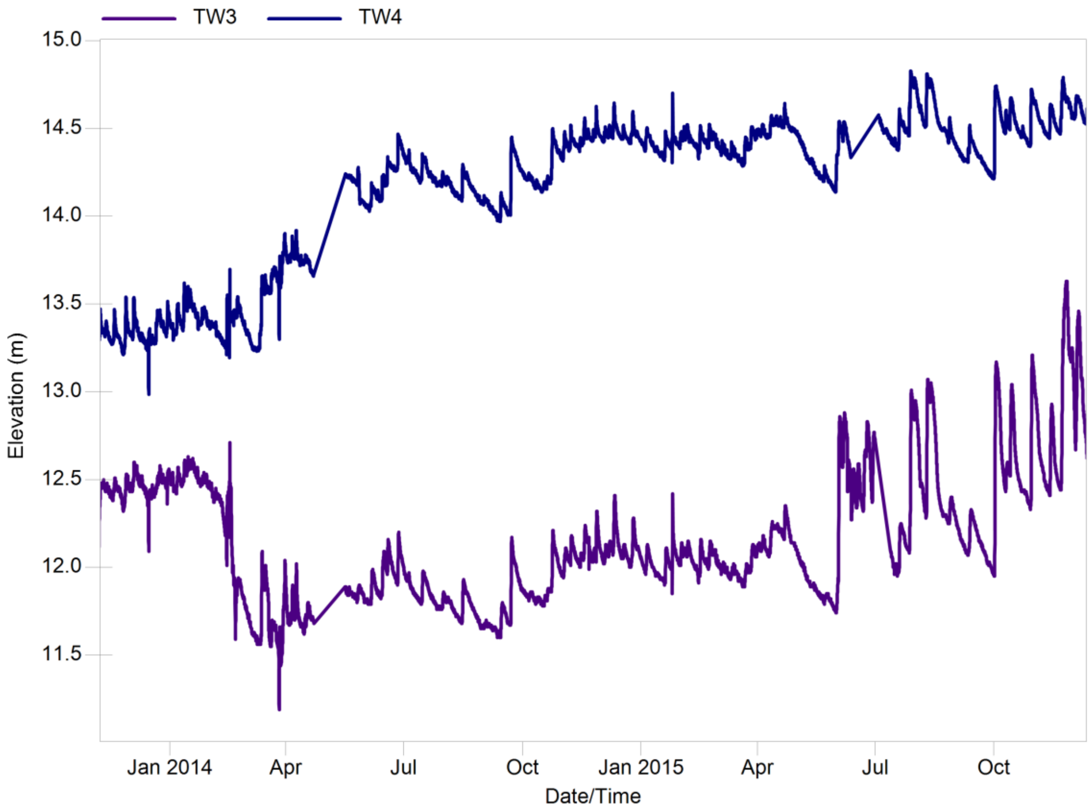
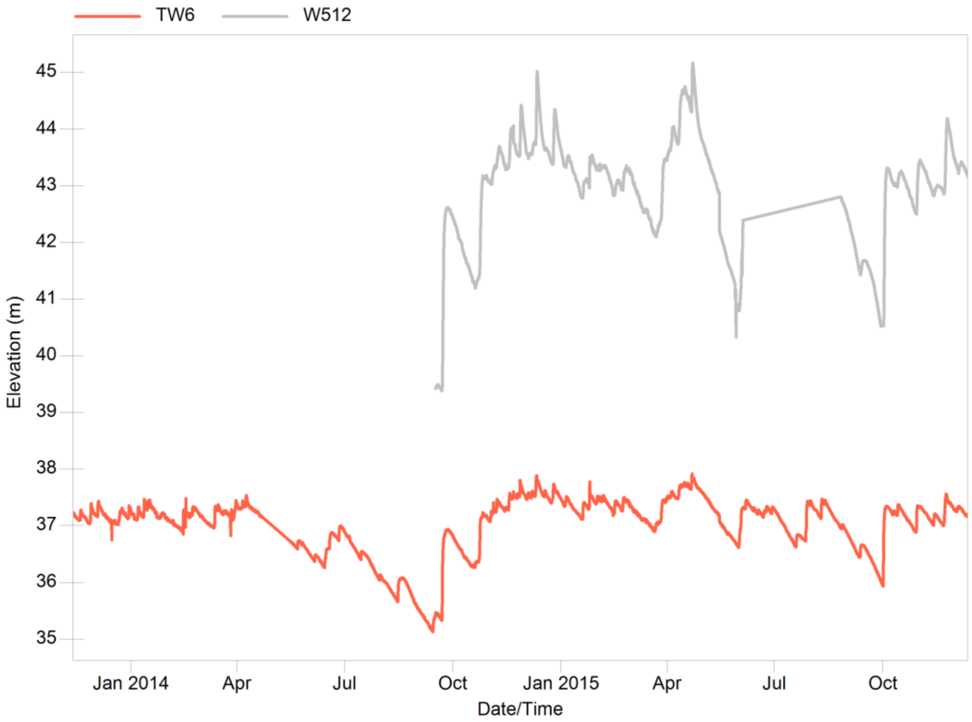
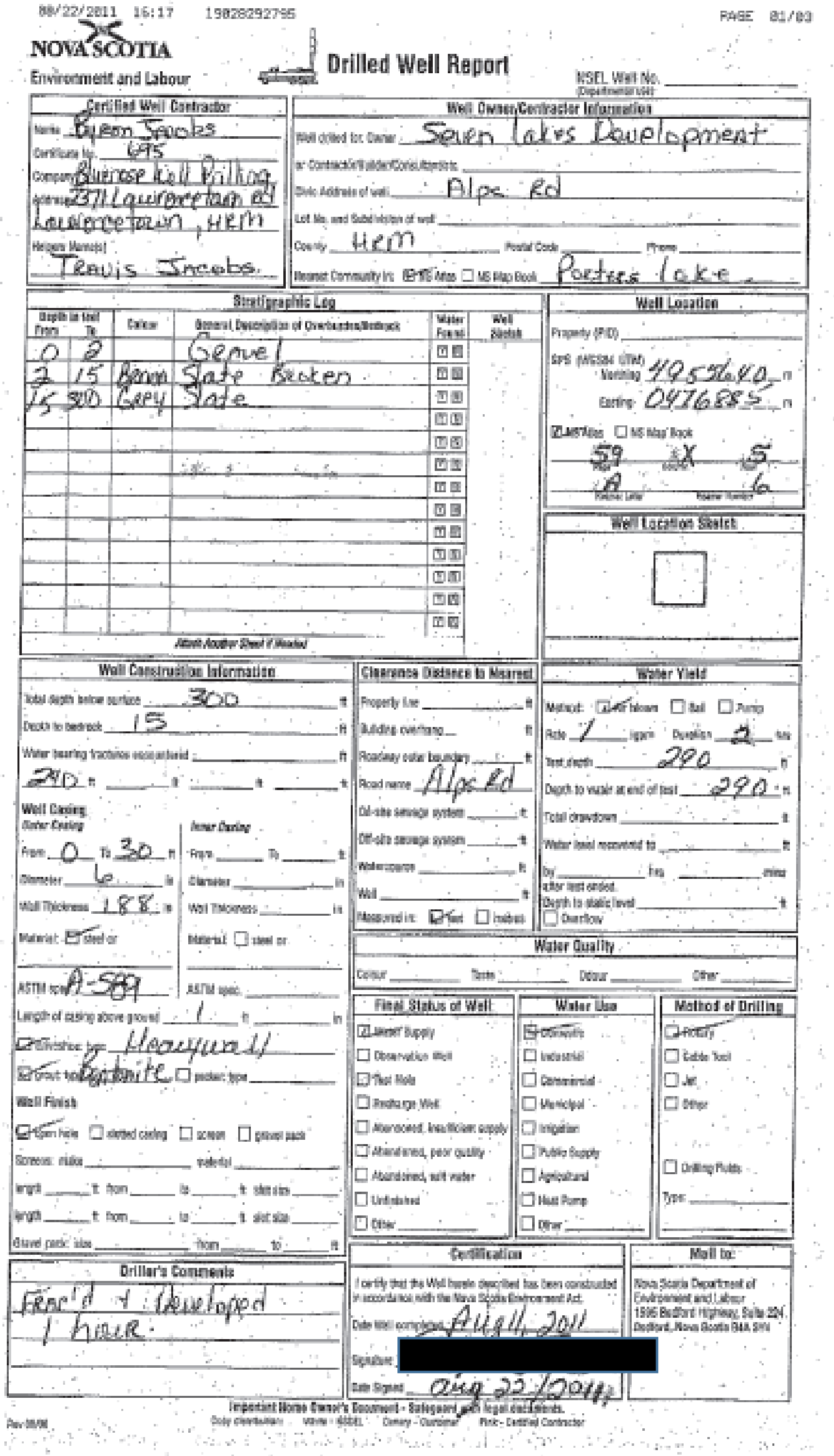
APPENDIX A GROUNDWATER ELEVATIONS





APPENDIX B BOREHOLE LOGS



TW3

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NOVA SCOTIA
Environment and Labour

Drilled Well Report

NSEL Well No. ____________ (Departmental use)

Certified Well Contractor

Name: Byron Sparks
Certificate No.: 695
Company: Bluerose Well Drilling
Address: 2371 Lawrencetown Rd Lawrencetown, HRM
Helpers Name(s): Travis Jacobs.

Well Owner/Contractor Information

Well drilled for: Owner: Seven lakes Development
or Contractor/Builder/Consultant etc.: ____________
Civic Address of well: Alps Rd
Lot No. and Subdivision of well: ____________
County: HRM Postal Code ______ Phone ______
Nearest Community in: ☑ NS Atlas ☐ NS Map Book Porters lake.

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found	Well Sketch
0	2		Gravel	Y N	
2	15	Brown	Slate Broken	Y N	
15	300	Grey	Slate	Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	

Attach Another Sheet if Needed

Well Location

Property (PID) ____________
GPS (NAD83 UTM) Northing 4956640 m
Easting 0476885 m
☑ NS Atlas ☐ NS Map Book
Map 59 Grid X Row 5
Reference Letter A Reference Number 6

Well Location Sketch

Well Construction Information

Total depth below surface 300 ft
Depth to bedrock 15 ft
Water bearing fractures encountered: ______ ft
290 ft ______ ft ______ ft ______ ft

Well Casing

Outer Casing
From 0 To 30 ft
Diameter 6 in
Wall Thickness .188 in
Material: ☑ steel or ______
ASTM spec A-589

Inner Casing
From ______ To ______ ft
Diameter ______ in
Wall Thickness ______ in
Material: ☐ steel or ______
ASTM spec. ______

Length of casing above ground 1 ft ______ in
☑ Driveshoe type Heavywall
☑ Grout type Bentonite ☐ packer type ______

Well Finish

☑ Open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screens: make ______ material ______
length ______ ft from ______ to ______ ft slot size ______
length ______ ft from ______ to ______ ft slot size ______
Gravel pack: size ______ from ______ to ______ ft

Clearance Distance to Nearest

Property line ______ ft
Building overhang ______ ft
Roadway outer boundary ______ ft
Road name Alps Rd
On-site sewage system ______ ft
Off-site sewage system ______ ft
Watercourse ______ ft
Well ______ ft
Measured in: ☑ feet ☐ inches

Water Yield

Method: ☑ Air blown ☐ Bail ☐ Pump
Rate 1 igpm Duration 2 hrs
Test depth 290 ft
Depth to water at end of test 290 ft
Total drawdown ______ ft
Water level recovered to ______ ft
by ______ hrs ______ mins after test ended.
Depth to static level ______ ft
☐ Overflow

Water Quality

Colour ______ Taste ______ Odour ______ Other ______

Final Status of Well

- ☑ Water Supply
- ☐ Observation Well
- ☑ Test Hole
- ☐ Recharge Well
- ☐ Abandoned, insufficient supply
- ☐ Abandoned, poor quality
- ☐ Abandoned, salt water
- ☐ Unfinished
- ☐ Other ______

Water Use

- ☑ Domestic
- ☐ Industrial
- ☐ Commercial
- ☐ Municipal
- ☐ Irrigation
- ☐ Public Supply
- ☐ Agricultural
- ☐ Heat Pump
- ☐ Other ______

Method of Drilling

- ☑ Rotary
- ☐ Cable Tool
- ☐ Jet
- ☐ Other
- ☐ Drilling Fluids
- Type: ______

Driller's Comments

Frac'd + Developed
1 hour.

Certification

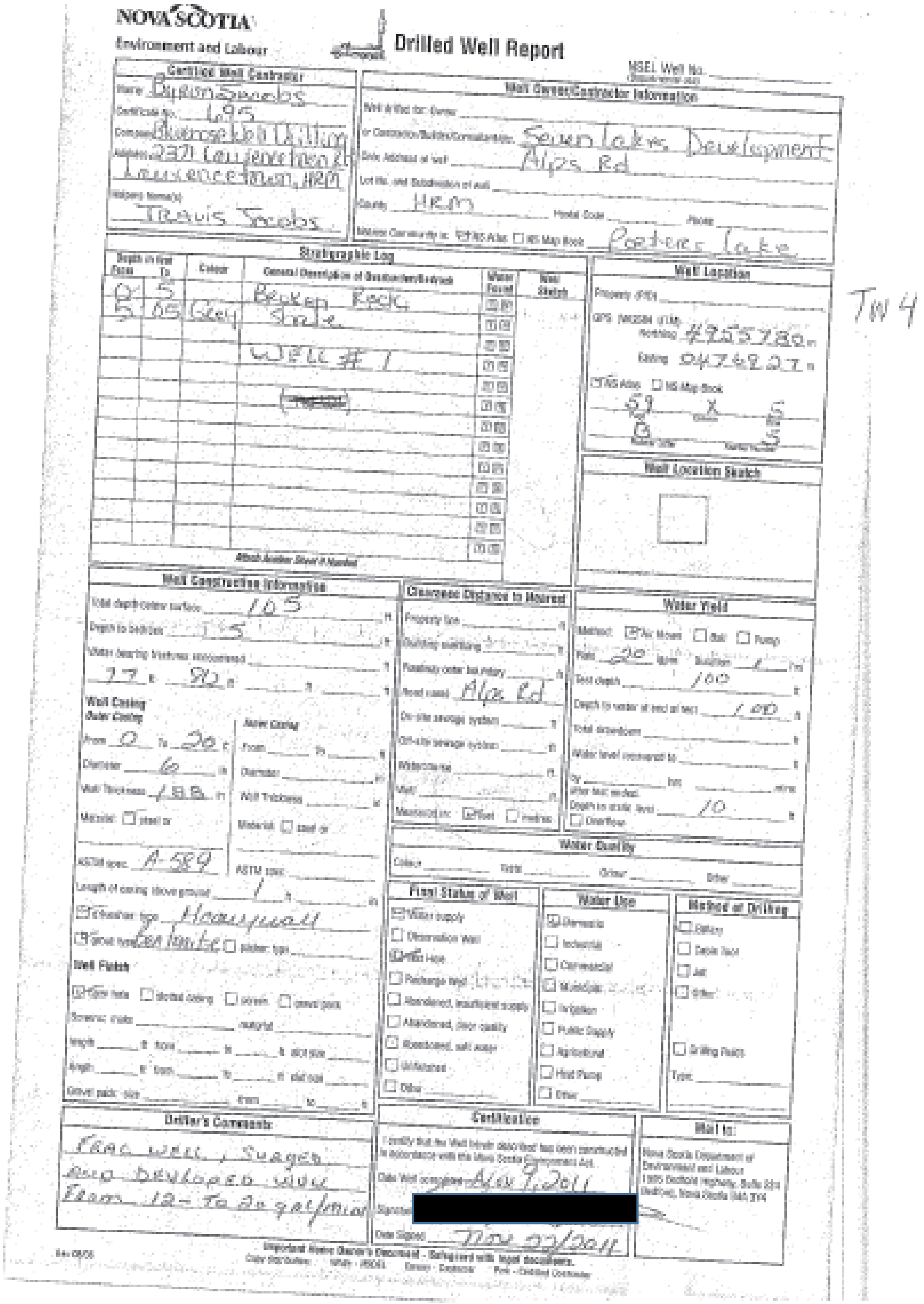
I certify that the Well herein described has been constructed in accordance with the Nova Scotia Environment Act.
Date Well completed Aug 4, 2011
Signature [redacted]
Date Signed Aug 22/2011

Mail to:

Nova Scotia Department of
Environment and Labour
1595 Bedford Highway, Suite 224
Bedford, Nova Scotia B4A 3Y4

Important Home Owner's Document - Safeguard with legal documents.
Copy distribution: White - NSEL Canary - Customer Pink - Certified Contractor

Rev 08/06



NOVA SCOTIA
Environment and Labour

Drilled Well Report

NSEL Well No. ______

Certified Well Contractor
Name: Byron Jacobs
Certificate No.: 695
Company: Bluerose Well Drilling
Address: 2371 Lawrencetown Rd
Lawrencetown, HRM
Helper(s) Name(s): Travis Jacobs

Well Owner/Contractor Information
Well drilled for: Owner ______
or Contractor/Builder/Consultant/etc.: Seven Lakes Development
Civic Address of well: Alps Rd
Lot No. and Subdivision of well: ______
County: HRM Postal Code ______ Phone ______
Nearest Community in: ☑ NS Atlas ☐ NS Map Book: Porters Lake

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found
0	5		Broken Rock	
5	105	Grey	Shale	
			WELL #1	

Attach Another Sheet if Needed

Well Location
Property (PID) ______
GPS (NAD83 UTM) Northing #955780 m
Easting 0476827 m
☑ NS Atlas ☐ NS Map Book
59 X 5
G 5

TW 4

Well Location Sketch

Well Construction Information
Total depth below surface: 105 ft
Depth to bedrock: 5 ft
Water bearing fractures encountered: ______ ft
77 ft 90 ft ______ ft ______ ft

Well Casing
Outer Casing: From 0 To 20 ft
Diameter: 6 in
Wall Thickness: .188 in
Material: ☐ steel or ______
ASTM spec: A-589
Inner Casing: From ______ To ______ ft
Diameter: ______ in
Wall Thickness: ______ in
Material: ☐ steel or ______
ASTM spec: ______
Length of casing above ground: 1 ft ______ in
☑ drive shoe type: Honeywell
☑ grout type: bentonite ☐ sealer type: ______

Well Finish
☑ open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screens: make ______ material ______
length ______ ft from ______ to ______ ft slot size ______
length ______ ft from ______ to ______ ft slot size ______
Gravel pack: size ______ from ______ to ______ ft

Clearance Distance to Nearest
Property line ______ ft
Building overhang ______ ft
Roadway outer boundary ______ ft
Road name: Alps Rd
On-site sewage system ______ ft
Off-site sewage system ______ ft
Watercourse ______ ft
Well ______ ft
Measured in: ☑ feet ☐ metres

Water Yield
Method: ☑ Air Mover ☐ Bail ☐ Pump
Rate: 20 gpm Duration: 1 hrs
Test depth: 100 ft
Depth to water at end of test: 100 ft
Total drawdown ______ ft
Water level recovered to ______ ft
by ______ hrs ______ mins after test ended
Depth to static level: 10 ft
☐ Overflow

Water Quality
Colour ______ Taste ______ Odour ______ Other ______

Final Status of Well
☑ Water supply
☐ Observation Well
☑ Test Hole
☐ Recharge Well
☐ Abandoned, insufficient supply
☐ Abandoned, poor quality
☐ Abandoned, salt water
☐ Unfinished
☐ Other

Water Use
☑ Domestic
☐ Industrial
☐ Commercial
☑ Municipal
☐ Irrigation
☐ Public Supply
☐ Agricultural
☐ Heat Pump
☐ Other

Method of Drilling
☑ Rotary
☐ Cable Tool
☐ Jet
☑ Other
☐ Drilling Fluids
Type: ______

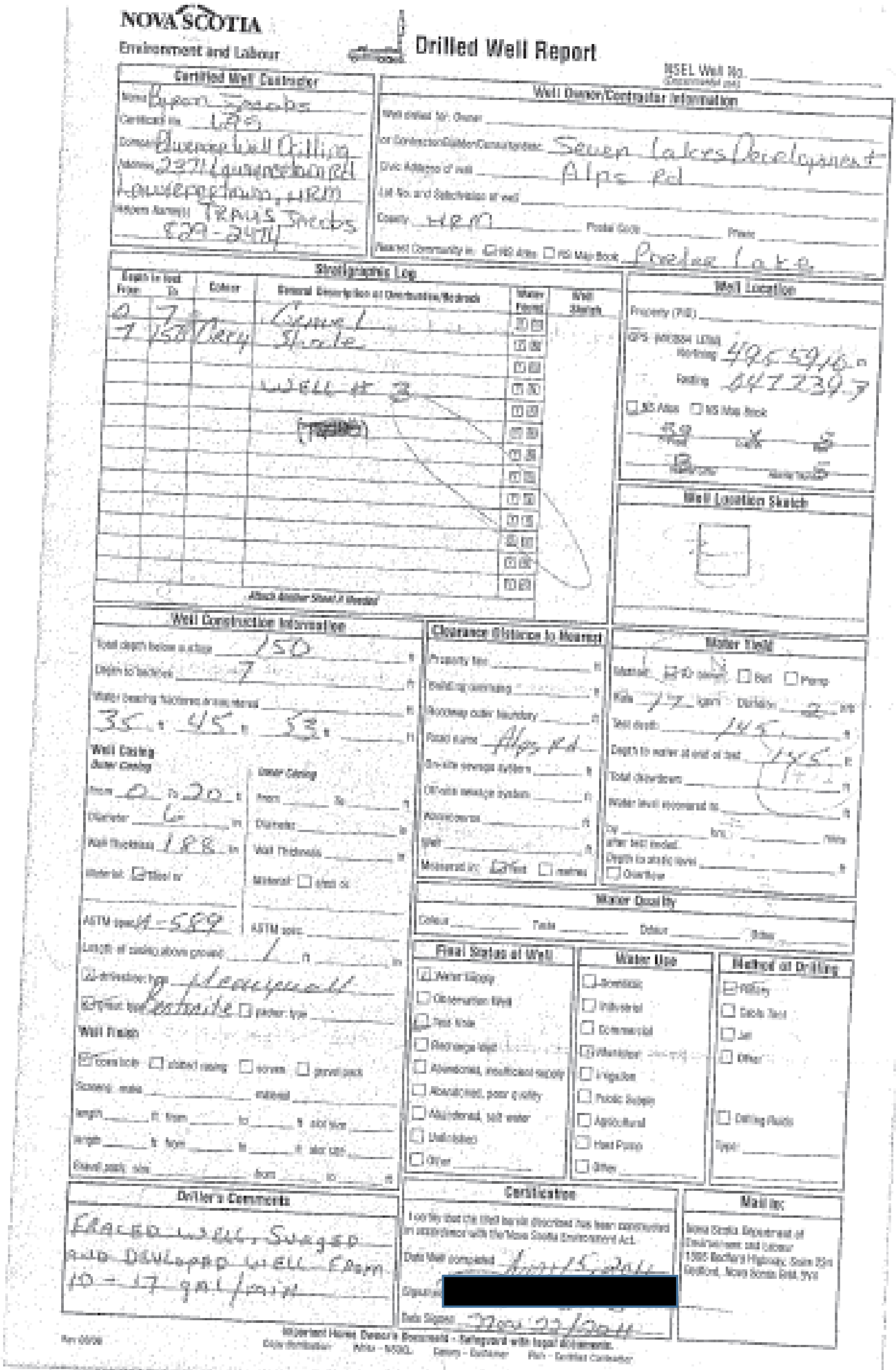
Driller's Comments
Frac well, Surged
and developed well
from 12 - to 20 gal/min

Certification
I certify that the Well herein described has been constructed in accordance with the Nova Scotia Environment Act.
Date Well completed: Nov 9, 2011
Signature: [redacted]
Date Signed: Nov 22/2011

Mail to:
Nova Scotia Department of
Environment and Labour
1995 Bedford Highway, Suite 224
Bedford, Nova Scotia B4A 3Y4

Rev 08/05

Important Home Owner's Document - Safeguard with legal documents.
Copy distribution: White - NSEL Canary - Customer Pink - Certified Contractor



NOVA SCOTIA
Environment and Labour

Drilled Well Report

NSEL Well No. ______

Certified Well Contractor

Name: Byron Jacobs
Certificate No.: 185
Company: Quenneville Well Drilling
Address: 2371 Lawrencetown Rd
Lawrencetown, HRM
Phone Number(s): TRAVIS Jacobs 829-2474

Well Owner/Contractor Information

Well drilled for: Owner ______
or Contractor/Builder/Consultant/etc.: Seven Lakes Development
Civic Address of well: Alps Rd
Lot No. and Subdivision of well: ______
County: HRM ______ Postal Code ______ Phone ______
Nearest Community in: ☑ NS Atlas ☐ NS Map Book: Porter Lake

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found	Well Sketch
0	7		Gravel	☐ ☐	
7	150	Grey	Shale	☐ ☐	
			WELL # 3	☐ ☐	

Attach Another Sheet if Needed

Well Location

Property (PID) ______
GPS (NAD83 UTM) Northing 4955916.0
Easting 447239.7
☐ NS Atlas ☐ NS Map Book
59 Page X Grid 5
8 Map Grid 5

Well Location Sketch

Well Construction Information

Total depth below surface: 150 ft
Depth to bedrock: 7 ft
Water bearing fractures encountered: ______ ft
35 ft, 45 ft, 53 ft, ______ ft

Well Casing
Outer Casing: From 0 To 20 ft; Diameter 6 in; Wall Thickness .188 in; Material: ☑ Steel or ______; ASTM spec. A-589
Inner Casing: From ______ To ______ ft; Diameter ______ in; Wall Thickness ______ in; Material: ☐ steel or ______; ASTM spec. ______
Length of casing above ground: 1 ft ______ in
☑ drive shoe type: Heavy wall
☑ grout: type Bentonite ☐ packer: type ______

Well Finish
☑ open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screen: make ______ material ______
length ______ ft from ______ to ______ ft slot size ______
length ______ ft from ______ to ______ ft slot size ______
Gravel pack: size ______ from ______ to ______ ft

Clearance Distance to Nearest

Property line ______ ft
Building or dwelling ______ ft
Roadway outer boundary ______ ft
Road name: Alps Rd
On-site sewage system ______ ft
Off-site sewage system ______ ft
Watercourse ______ ft
Well ______ ft
Measured in: ☑ feet ☐ metres

Water Yield

Method: ☑ Air ☐ Bail ☐ Pump
Rate 17 gpm Duration 2 hrs
Test depth 145 ft
Depth to water at end of test 145 ft
Total drawdown ______ ft
Water level recovered to ______ ft
in ______ hrs ______ mins after test ended.
Depth to static level ______ ft
☐ Overflow

Water Quality

Colour ______ Taste ______ Odour ______ Other ______

Final Status of Well

☑ Water Supply
☐ Observation Well
☐ Test Hole
☐ Recharge Well
☐ Abandoned, insufficient supply
☐ Abandoned, poor quality
☐ Abandoned, salt water
☐ Unfinished
☐ Other ______

Water Use

☐ Domestic
☐ Industrial
☐ Commercial
☑ Municipal
☐ Irrigation
☐ Public Supply
☐ Agricultural
☐ Heat Pump
☐ Other ______

Method of Drilling

☑ Rotary
☐ Cable Tool
☐ Jet
☐ Other
☐ Drilling Fluids
Type: ______

Driller's Comments

FRACED WELL, SURGED AND DEVELOPED WELL FROM 10 - 17 gal/min

Certification

I certify that the well herein described has been constructed in accordance with the Nova Scotia Environment Act.
Date Well completed: Aug 15, 2011
Signature [redacted]
Date Signed: Nov 22/2011

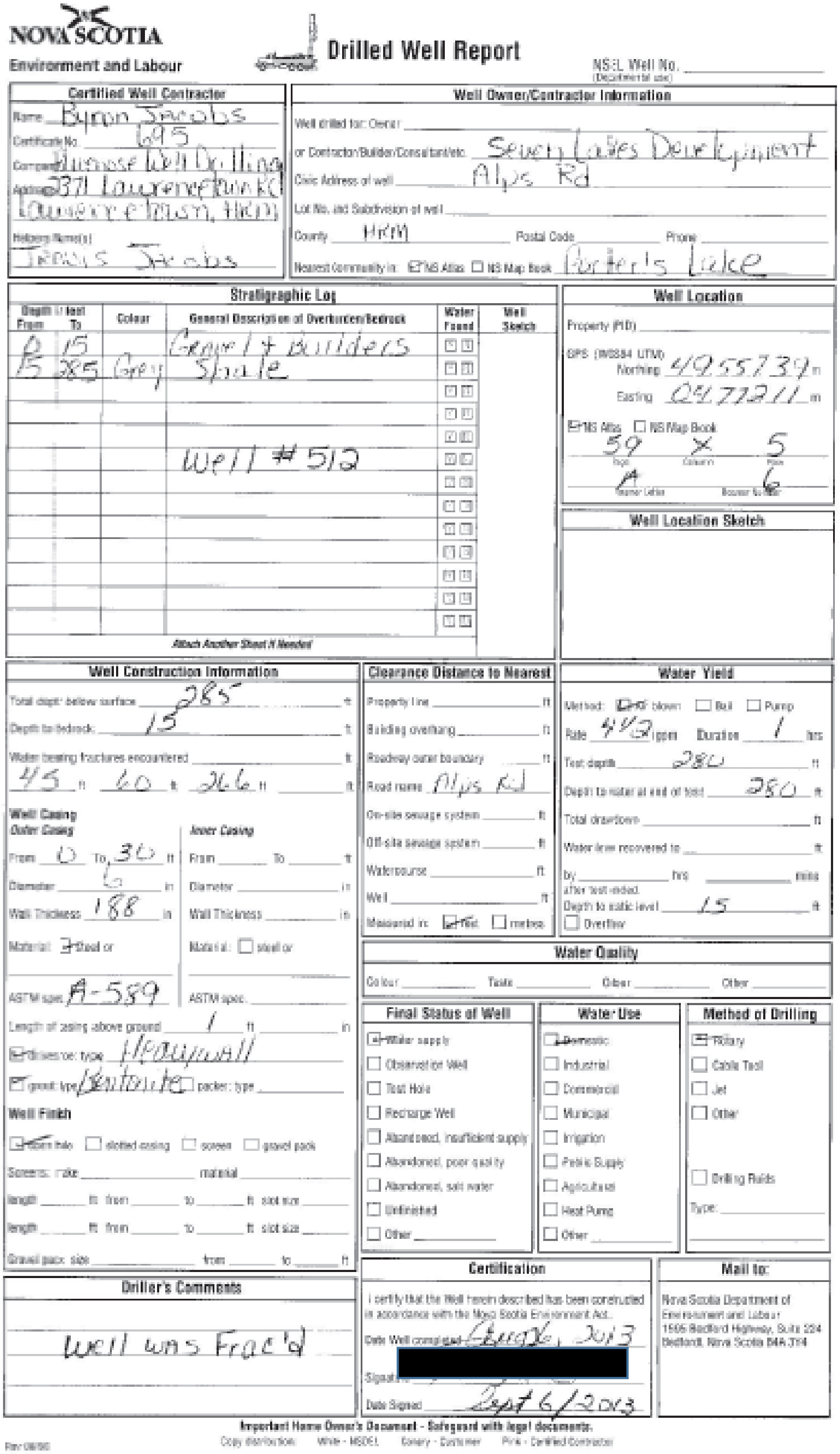
Mail to:

Nova Scotia Department of Environment and Labour
1505 Barrington Highway, Suite 201
Bedford, Nova Scotia B4A 5V9

Rev 05/06

Important Home Owner's Document - Safeguard with legal documents.
Copy distribution: White - NSEL Canary - Customer Pink - Certified Contractor

TW6



NOVA SCOTIA
Environment and Labour

Drilled Well Report

NSEL Well No. ____________ (Departmental use)

Certified Well Contractor

Name: Byron Jacobs
Certificate No. 695
Company: Bluenose Well Drilling
Address: 2371 Lawrencetown Rd
Lawrencetown, HRM
Helpers Name(s): Travis Jacobs

Well Owner/Contractor Information

Well drilled for: Owner: ____________
or Contractor/Builder/Consultant/etc. Seven Lakes Development
Civic Address of well: Alps Rd
Lot No. and Subdivision of well: ____________
County: HRM Postal Code: ______ Phone: ______
Nearest Community in: ☑ NS Atlas ☐ NS Map Book Porter's Lake

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found	Well Sketch
0	15		Gravel + boulders	☐ ☐	
15	285	Grey	Shale	☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
			Well #512	☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	

Attach Another Sheet If Needed

Well Location

Property (PID) ____________
GPS (WGS84 UTM) Northing 4955739 m
Easting 0477211 m
☑ NS Atlas ☐ NS Map Book
Page 59 Column X Row 5
Square Letter A Square Number 6

Well Location Sketch

Well Construction Information

Total depth below surface 285 ft
Depth to bedrock 15 ft
Water bearing fractures encountered ______ ft
45 ft 60 ft 266 ft ______ ft

Well Casing

Outer Casing
From 0 To 30 ft
Diameter 6 in
Wall Thickness 188 in
Material: ☑ Steel or ______
ASTM spec. A-589

Inner Casing
From ______ To ______ ft
Diameter ______ in
Wall Thickness ______ in
Material: ☐ steel or ______
ASTM spec. ______

Length of casing above ground 1 ft ______ in
☑ drive shoe: type Heavywall
☑ grout: type Bentonite ☐ packer: type ______

Well Finish

☑ open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screens: make ______ material ______
length ______ ft from ______ to ______ ft slot size ______
length ______ ft from ______ to ______ ft slot size ______
Gravel pack: size ______ from ______ to ______ ft

Clearance Distance to Nearest

Property line ______ ft
Building overhang ______ ft
Roadway outer boundary ______ ft
Road name Alps Rd
On-site sewage system ______ ft
Off-site sewage system ______ ft
Watercourse ______ ft
Well ______ ft
Measured in: ☑ feet ☐ metres

Water Yield

Method: ☑ Air blown ☐ Bail ☐ Pump
Rate 4 1/2 igpm Duration 1 hrs
Test depth 280 ft
Depth to water at end of test 280 ft
Total drawdown ______ ft
Water level recovered to ______ ft
by ______ hrs ______ mins after test ended.
Depth to static level 15 ft
☐ Overflow

Water Quality

Colour ______ Taste ______ Odour ______ Other ______

Final Status of Well

- ☑ Water supply
- ☐ Observation Well
- ☐ Test Hole
- ☐ Recharge Well
- ☐ Abandoned, insufficient supply
- ☐ Abandoned, poor quality
- ☐ Abandoned, salt water
- ☐ Unfinished
- ☐ Other ______

Water Use

- ☑ Domestic
- ☐ Industrial
- ☐ Commercial
- ☐ Municipal
- ☐ Irrigation
- ☐ Public Supply
- ☐ Agricultural
- ☐ Heat Pump
- ☐ Other ______

Method of Drilling

- ☑ Rotary
- ☐ Cable Tool
- ☐ Jet
- ☐ Other
- ☐ Drilling Fluids

Type: ______

Driller's Comments

Well was Frac'd

Certification

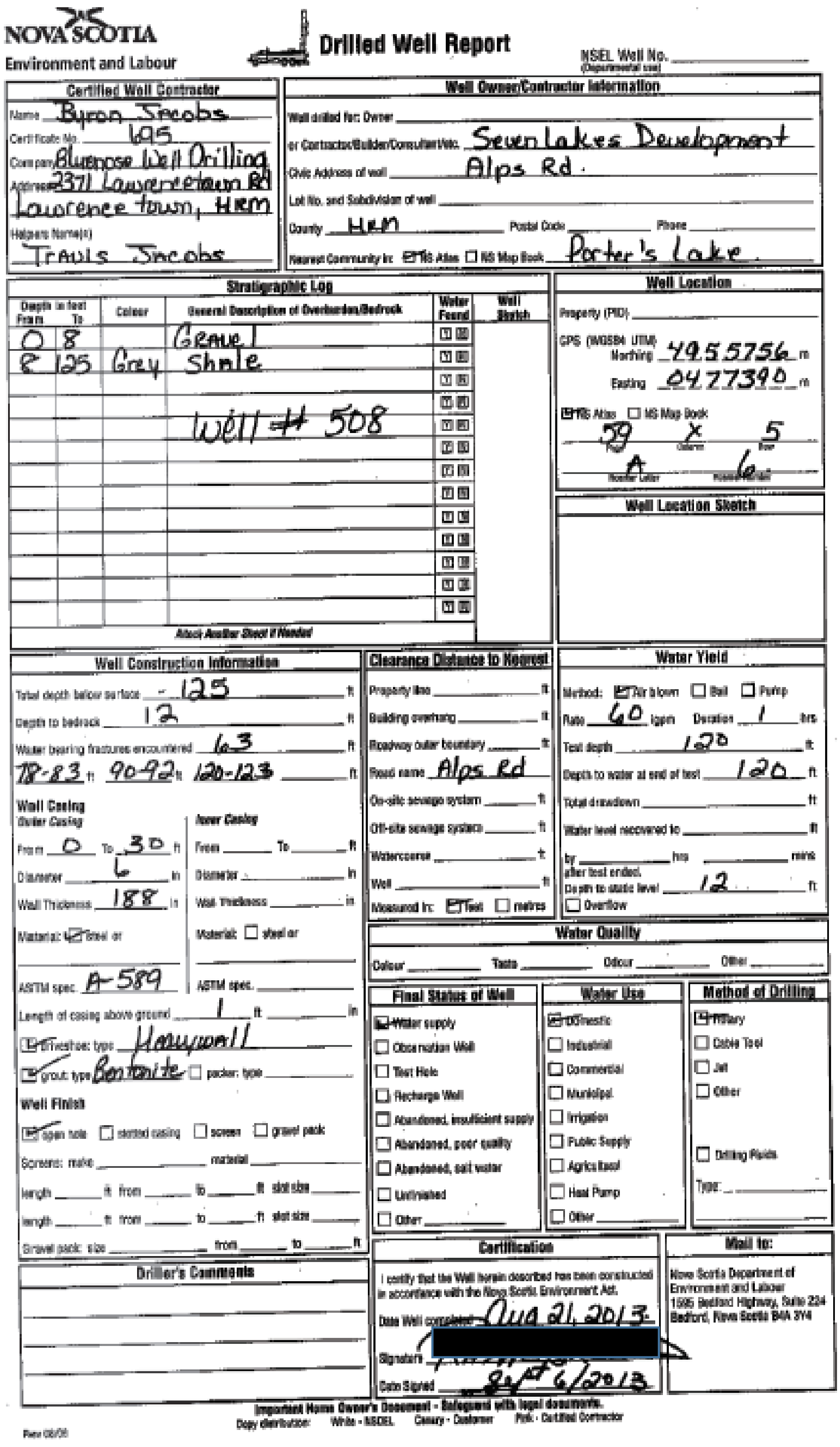
I certify that the Well herein described has been constructed in accordance with the Nova Scotia Environment Act.
Date Well completed Aug 26, 2013
[redacted]
Signature ______
Date Signed Sept 6/2013

Mail to:

Nova Scotia Department of
Environment and Labour
1505 Bedford Highway, Suite 224
Bedford, Nova Scotia B4A 3Y4

Important Home Owner's Document - Safeguard with legal documents.
Copy distribution: White - NSDEL Canary - Customer Pink - Certified Contractor

Rev 08/00



NOVA SCOTIA
Environment and Labour

Drilled Well Report

NSEL Well No. ____________
(Departmental use)

Certified Well Contractor

Name: Byron Jacobs
Certificate No. 105
Company: Bluenose Well Drilling
Address: 2371 Lawrencetown Rd
Lawrencetown, HRM
Helpers Name(s)
Travis Jacobs

Well Owner/Contractor Information

Well drilled for: Owner ____________
or Contractor/Builder/Consultant/etc. Sevenlakes Development
Civic Address of well: Alps Rd.
Lot No. and Subdivision of well ____________
County: HRM Postal Code ______ Phone ______
Nearest Community in: ☑ NS Atlas ☐ NS Map Book: Porter's Lake.

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found	Well Sketch
0	8		Gravel	☐ Y ☐ N	
8	125	Grey	Shale	☐ Y ☐ N	
				☐ Y ☐ N	
			Well # 508	☐ Y ☐ N	
				☐ Y ☐ N	
				☐ Y ☐ N	
				☐ Y ☐ N	
				☐ Y ☐ N	
				☐ Y ☐ N	
				☐ Y ☐ N	
				☐ Y ☐ N	
				☐ Y ☐ N	
				☐ Y ☐ N	

Attach Auxiliary Sheet if Needed

Well Location

Property (PID) ____________
GPS (WGS84 UTM) Northing 4955756 m
Easting 0477390 m
☑ NS Atlas ☐ NS Map Book
Page 59 Column X Row 5
Number Letter A Number 6

Well Location Sketch

Well Construction Information

Total depth below surface - 125 ft
Depth to bedrock 12 ft
Water bearing fractures encountered 63 ft
78-83 ft 90-92 ft 120-123 ft ______ ft

Well Casing

Outer Casing
From 0 To 30 ft
Diameter 6 in
Wall Thickness .188 in
Material: ☑ Steel or
ASTM spec. A-589

Inner Casing
From ______ To ______ ft
Diameter ______ in
Wall Thickness ______ in
Material: ☐ steel or
ASTM spec. ______

Length of casing above ground 1 ft ______ in
☑ Driveshoe: type Heavywall
☑ grout: type Bentonite ☐ packer: type ______

Well Finish

☑ open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screens: make ______ material ______
length ______ ft from ______ to ______ ft slot size ______
length ______ ft from ______ to ______ ft slot size ______
Gravel pack: size ______ from ______ to ______ ft

Clearance Distance to Nearest

Property line ______ ft
Building overhang ______ ft
Roadway outer boundary ______ ft
Road name Alps Rd
On-site sewage system ______ ft
Off-site sewage system ______ ft
Watercourse ______ ft
Well ______ ft
Measured in: ☑ feet ☐ metres

Water Yield

Method: ☑ Air blown ☐ Bail ☐ Pump
Rate 60 igpm Duration 1 hrs
Test depth 120 ft
Depth to water at end of test 120 ft
Total drawdown ______ ft
Water level recovered to ______ ft
by ______ hrs ______ mins
after test ended.
Depth to static level 12 ft
☐ Overflow

Water Quality

Colour ______ Taste ______ Odour ______ Other ______

Final Status of Well

☑ Water supply
☐ Observation Well
☐ Test Hole
☐ Recharge Well
☐ Abandoned, insufficient supply
☐ Abandoned, poor quality
☐ Abandoned, salt water
☐ Unfinished
☐ Other ______

Water Use

☑ Domestic
☐ Industrial
☐ Commercial
☐ Municipal
☐ Irrigation
☐ Public Supply
☐ Agricultural
☐ Heat Pump
☐ Other ______

Method of Drilling

☑ Rotary
☐ Cable Tool
☐ Jet
☐ Other
☐ Drilling Fluids
Type: ______

Driller's Comments

Certification

I certify that the Well herein described has been constructed in accordance with the Nova Scotia Environment Act.

Date Well completed Aug 21, 2013.
Signature [redacted]
Date Signed Sept 6/2013

Mail to:

Nova Scotia Department of
Environment and Labour
1595 Bedford Highway, Suite 224
Bedford, Nova Scotia B4A 3Y4

Important Home Owner's Document - Safeguard with legal documents.
Copy distribution: White - NSDEL Canary - Customer Pink - Certified Contractor

Rev 08/05

NOVA SCOTIA
Environment and Labour

Drilled Well Report

NSE. Well No. ____________ (Departmental use)

Certified Well Contractor

Name: Byron Jacobs
Certificate No.: 650
Company: [illegible]
Address: 3371 [illegible] Rd
[illegible], HRM
Helpers Name(s): Travis Jacobs

Well Owner/Contractor Information

Well drilled for: Owner ____________
or Contractor/Builder/Consultant etc. Seven lakes Development
Civic Address of well: Alps Rd
Lot No. and Subdivision of well ____________
County: HRM Postal Code ______ Phone ______
Nearest Community in: ☑ NS Atlas ☐ NS Map Book Porters lake.

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found	Well Sketch
0	10		Gravel & Boulders.	☐ ☐	
10	85	Grey	Shale	☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
			well # 509	☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	
				☐ ☐	

Attach Another Sheet if Needed

Well Location

Property (PID) ____________
GPS (WGS84 UTM) Northing 4955835 m
Easting 0477294 m
☑ NS Atlas ☐ NS Map Book
59 (Page) × (Column) 5 (Row)
A (Column Letter) 6 (Row Number)

Well Location Sketch

Well Construction Information

Total depth below surface 165 ft
Depth to bedrock: 10 ft
Water bearing fractures encountered ______ ft
42 ft 115 ft 125 ft 155 ft

Well Casing

Outer Casing
From 0 To 30 ft
Diameter 6 in
Wall Thickness .188 in
Material: ☑ Steel or ______
ASTM spec. A-589

Inner Casing
From ______ To ______ ft
Diameter ______ in
Wall Thickness ______ in
Material: ☐ steel or ______
ASTM spec. ______

Length of casing above ground 1 ft ______ in
☑ driveshoe: type Heavywall
☑ grout: type Bentonite ☐ packer: type ______

Well Finish

☑ open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screens: make ______ material ______
length ______ ft from ______ to ______ ft slot size ______
length ______ ft from ______ to ______ ft slot size ______
Gravel pack: size ______ from ______ to ______ ft

Clearance Distance to Nearest

Property line ______ ft
Building overhang ______ ft
Roadway outer boundary ______ ft
Road name Alps Rd.
On-site sewage system ______ ft
Off-site sewage system ______ ft
Watercourse ______ ft
Well ______ ft
Measured in: ☑ feet ☐ metres

Water Yield

Method: ☑ Air blown ☐ Bail ☐ Pump
Rate 56 igpm Duration 1 hrs
Test depth 160 ft
Depth to water at end of test 160 ft
Total drawdown ______ ft
Water level recovered to ______ ft
By ______ hrs ______ mins after test ended.
Depth to static level 14 ft
☐ Overflow

Water Quality

Colour ______ Taste ______ Odour ______ Other ______

Final Status of Well

☑ Water supply
☐ Observation Well
☐ Test Hole
☐ Recharge Well
☐ Abandoned, insufficient supply
☐ Abandoned, poor quality
☐ Abandoned, salt water
☐ Unfinished
☐ Other ______

Water Use

☑ Domestic
☐ Industrial
☐ Commercial
☐ Municipal
☐ Irrigation
☐ Public Supply
☐ Agricultural
☐ Heat Pump
☐ Other ______

Method of Drilling

☑ Rotary
☐ Cable Tool
☐ Jet
☐ Other
☐ Drilling Fluids
Type: ______

Driller's Comments

Certification

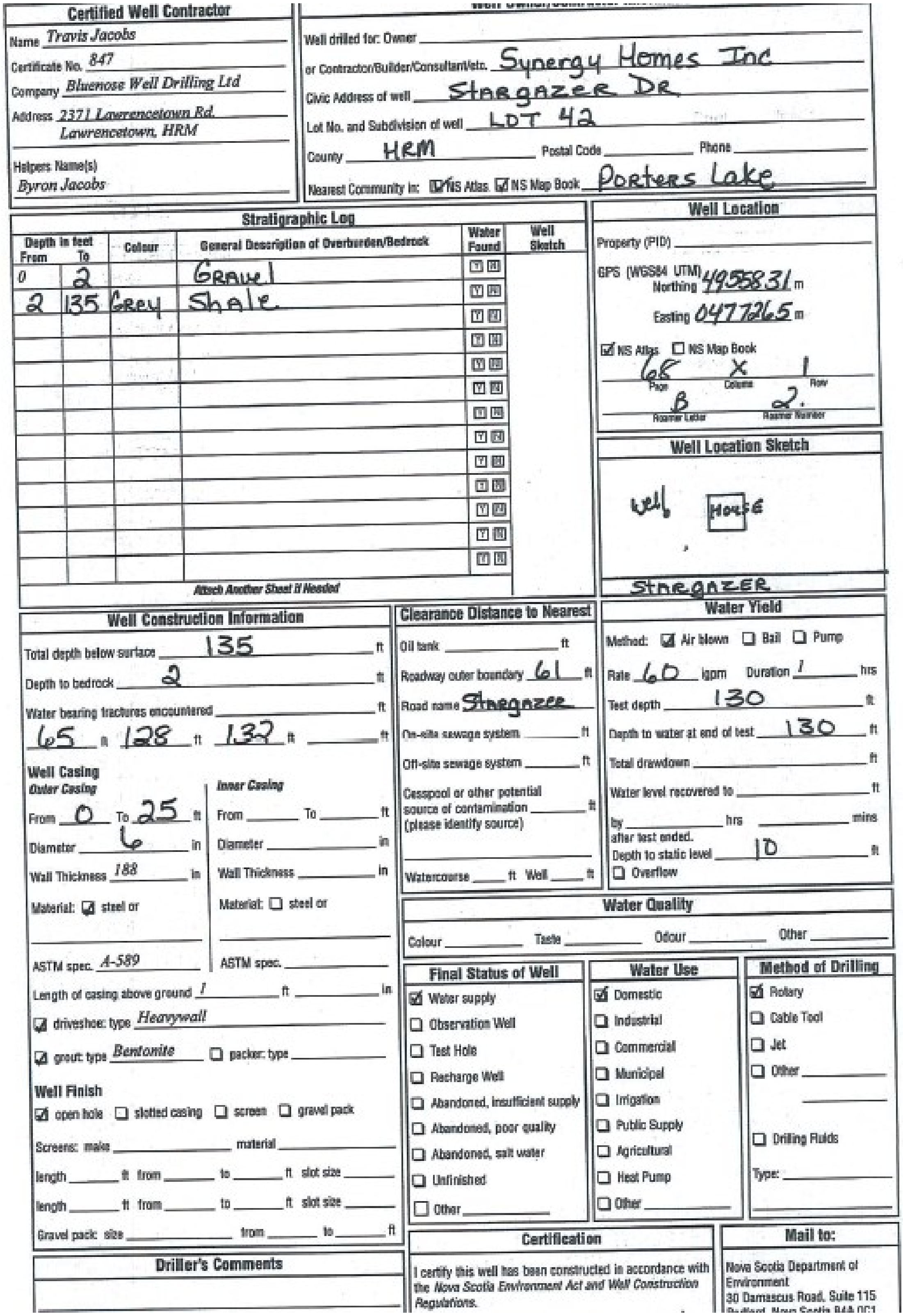
I certify that the Well herein described has been constructed in accordance with the Nova Scotia Environment Act.
Date Well completed Aug 23, 2013
Signature [redacted]
Date Signed Sept 6/2013

Mail to:

Nova Scotia Department of
Environment and Labour
1595 Bedford Highway, Suite 224
Bedford, Nova Scotia B4A 3Y4

Important Home Owner's Document - Safeguard with legal documents.
Copy distribution: White - NSEL Canary - Customer Pink - Certified Contractor

Rev 03/06



Certified Well Contractor

Name Travis Jacobs
Certificate No. 847
Company Bluenose Well Drilling Ltd
Address 2371 Lawrencetown Rd.
Lawrencetown, HRM

Helpers Name(s)
Byron Jacobs

Well drilled for: Owner
or Contractor/Builder/Consultant/etc. Synergy Homes Inc
Civic Address of well Stargazer Dr
Lot No. and Subdivision of well LOT 42
County HRM Postal Code Phone
Nearest Community in: ☑ NS Atlas ☑ NS Map Book Porters Lake

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found	Well Sketch
0	2		Gravel	Y N	
2	135	Grey	Shale	Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	

Attach Another Sheet If Needed

Well Location

Property (PID)
GPS (WGS84 UTM) Northing 4955831 m
Easting 0477265 m
☑ NS Atlas ☐ NS Map Book
Page 68 Column X Row 1
Reamer Letter B Reamer Number 2.

Well Location Sketch

Well
House
Stargazer

Well Construction Information

Total depth below surface 135 ft
Depth to bedrock 2 ft
Water bearing fractures encountered ft
65 ft 128 ft 132 ft ft

Well Casing

Outer Casing
From 0 To 25 ft
Diameter 6 in
Wall Thickness 188 in
Material: ☑ steel or
ASTM spec. A-589

Inner Casing
From To ft
Diameter in
Wall Thickness in
Material: ☐ steel or
ASTM spec.

Length of casing above ground 1 ft in
☑ driveshoe: type Heavywall
☑ grout: type Bentonite ☐ packer: type

Well Finish
☑ open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screens: make material
length ft from to ft slot size
length ft from to ft slot size
Gravel pack: size from to ft

Clearance Distance to Nearest

Oil tank ft
Roadway outer boundary 61 ft
Road name Stargazer
On-site sewage system ft
Off-site sewage system ft
Cesspool or other potential source of contamination ft
(please identify source)
Watercourse ft Well ft

Water Yield

Method: ☑ Air blown ☐ Bail ☐ Pump
Rate 60 igpm Duration 1 hrs
Test depth 130 ft
Depth to water at end of test 130 ft
Total drawdown ft
Water level recovered to ft
by hrs mins
after test ended.
Depth to static level 10 ft
☐ Overflow

Water Quality

Colour Taste Odour Other

Final Status of Well

- ☑ Water supply
- ☐ Observation Well
- ☐ Test Hole
- ☐ Recharge Well
- ☐ Abandoned, insufficient supply
- ☐ Abandoned, poor quality
- ☐ Abandoned, salt water
- ☐ Unfinished
- ☐ Other

Water Use

- ☑ Domestic
- ☐ Industrial
- ☐ Commercial
- ☐ Municipal
- ☐ Irrigation
- ☐ Public Supply
- ☐ Agricultural
- ☐ Heat Pump
- ☐ Other

Method of Drilling

- ☑ Rotary
- ☐ Cable Tool
- ☐ Jet
- ☐ Other
- ☐ Drilling Fluids

Type:

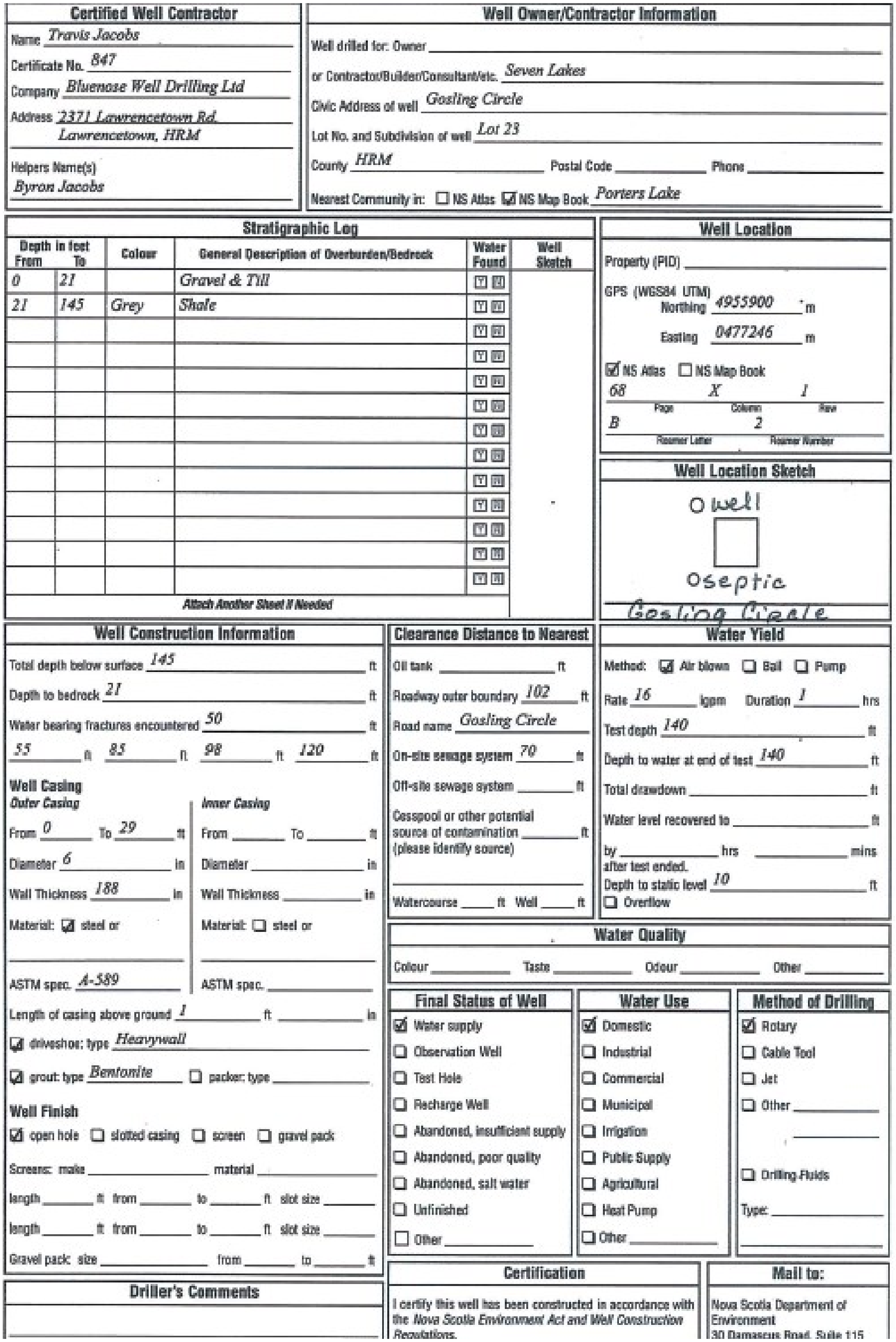
Driller's Comments

Certification

I certify this well has been constructed in accordance with the *Nova Scotia Environment Act and Well Construction Regulations.*

Mail to:

Nova Scotia Department of Environment
30 Damascus Road, Suite 115



Certified Well Contractor

Name Travis Jacobs
Certificate No. 847
Company Bluenose Well Drilling Ltd
Address 2371 Lawrencetown Rd.
Lawrencetown, HRM
Helpers Name(s)
Byron Jacobs

Well Owner/Contractor Information

Well drilled for: Owner
or Contractor/Builder/Consultant/etc. Seven Lakes
Civic Address of well Gosling Circle
Lot No. and Subdivision of well Lot 23
County HRM Postal Code Phone
Nearest Community in: ☐ NS Atlas ☑ NS Map Book Porters Lake

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found
0	21		Gravel & Till	Y N
21	145	Grey	Shale	Y N
				Y N
				Y N
				Y N
				Y N
				Y N
				Y N
				Y N
				Y N
				Y N
				Y N
				Y N

Well Sketch

Attach Another Sheet If Needed

Well Location

Property (PID)
GPS (WGS84 UTM) Northing 4955900 m
Easting 0477246 m
☑ NS Atlas ☐ NS Map Book

Page	Column	Row
68	X	1

Reamer Letter	Reamer Number
B	2

Well Location Sketch

O well
Oseptic
Gosling Circle

Well Construction Information

Total depth below surface 145 ft
Depth to bedrock 21 ft
Water bearing fractures encountered 50 ft
55 ft 85 ft 98 ft 120 ft

Well Casing

Outer Casing	*Inner Casing*
From 0 To 29 ft	From To ft
Diameter 6 in	Diameter in
Wall Thickness 188 in	Wall Thickness in
Material: ☑ steel or	Material: ☐ steel or
ASTM spec. A-589	ASTM spec.

Length of casing above ground 1 ft in
☑ driveshoe: type Heavywall
☑ grout: type Bentonite ☐ packer: type

Well Finish

☑ open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screens: make material
length ft from to ft slot size
length ft from to ft slot size
Gravel pack: size from to ft

Clearance Distance to Nearest

Oil tank ft
Roadway outer boundary 102 ft
Road name Gosling Circle
On-site sewage system 70 ft
Off-site sewage system ft
Cesspool or other potential source of contamination ft
(please identify source)
Watercourse ft Well ft

Water Yield

Method: ☑ Air blown ☐ Bail ☐ Pump
Rate 16 igpm Duration 1 hrs
Test depth 140 ft
Depth to water at end of test 140 ft
Total drawdown ft
Water level recovered to ft
by hrs mins
after test ended.
Depth to static level 10 ft
☐ Overflow

Water Quality

Colour Taste Odour Other

Final Status of Well

- ☑ Water supply
- ☐ Observation Well
- ☐ Test Hole
- ☐ Recharge Well
- ☐ Abandoned, insufficient supply
- ☐ Abandoned, poor quality
- ☐ Abandoned, salt water
- ☐ Unfinished
- ☐ Other

Water Use

- ☑ Domestic
- ☐ Industrial
- ☐ Commercial
- ☐ Municipal
- ☐ Irrigation
- ☐ Public Supply
- ☐ Agricultural
- ☐ Heat Pump
- ☐ Other

Method of Drilling

- ☑ Rotary
- ☐ Cable Tool
- ☐ Jet
- ☐ Other
- ☐ Drilling Fluids

Type:

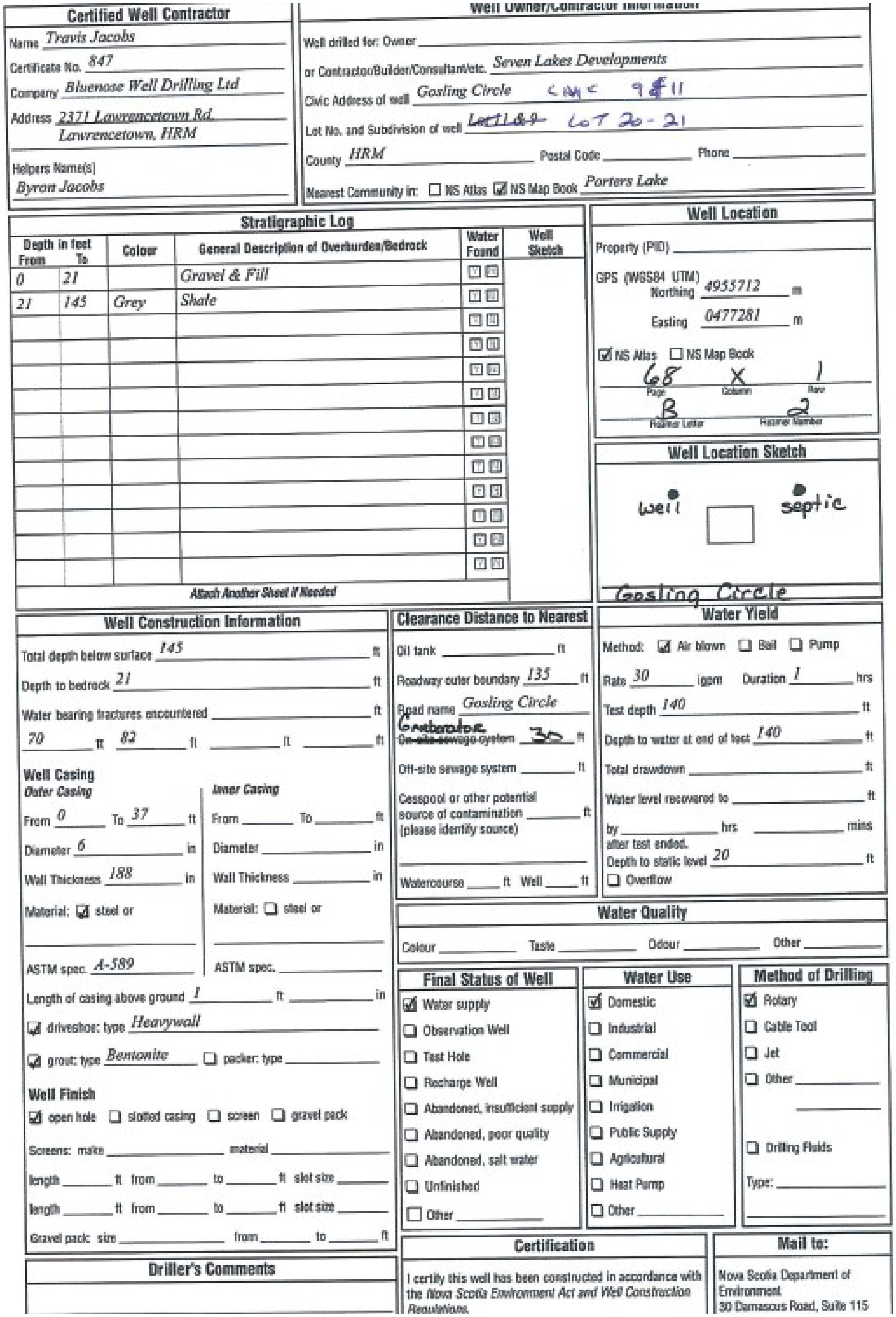
Driller's Comments

Certification

I certify this well has been constructed in accordance with the *Nova Scotia Environment Act and Well Construction Regulations.*

Mail to:

Nova Scotia Department of Environment
30 Damascus Road, Suite 115



Certified Well Contractor

Name *Travis Jacobs*
Certificate No. *847*
Company *Bluenose Well Drilling Ltd*
Address *2371 Lawrencetown Rd.*
Lawrencetown, HRM
Helpers Name(s)
Byron Jacobs

Well Owner/Contractor Information

Well drilled for: Owner
or Contractor/Builder/Consultant/etc. *Seven Lakes Developments*
Civic Address of well *Gosling Circle* CIVIC 9 & 11
Lot No. and Subdivision of well ~~Lot 1&2~~ LOT 20-21
County *HRM* Postal Code ____ Phone ____
Nearest Community in: ☐ NS Atlas ☑ NS Map Book *Porters Lake*

Stratigraphic Log

Depth in feet From	To	Colour	General Description of Overburden/Bedrock	Water Found	Well Sketch
0	21		Gravel & Fill	Y N	
21	145	Grey	Shale	Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	
				Y N	

Attach Another Sheet If Needed

Well Location

Property (PID) ____
GPS (WGS84 UTM) Northing *4955712* m
Easting *0477281* m
☑ NS Atlas ☐ NS Map Book
68 Page X Column 1 Row
B Hazard Letter 2 Hazard Number

Well Location Sketch

well septic
Gosling Circle

Well Construction Information

Total depth below surface *145* ft
Depth to bedrock *21* ft
Water bearing fractures encountered ____ ft
70 ft *82* ft ____ ft ____ ft

Well Casing

Outer Casing
From *0* To *37* ft
Diameter *6* in
Wall Thickness *188* in
Material: ☑ steel or
ASTM spec. *A-589*

Inner Casing
From ____ To ____ ft
Diameter ____ in
Wall Thickness ____ in
Material: ☐ steel or
ASTM spec. ____

Length of casing above ground *1* ft ____ in
☑ driveshoe: type *Heavywall*
☑ grout: type *Bentonite* ☐ packer: type ____

Well Finish

☑ open hole ☐ slotted casing ☐ screen ☐ gravel pack
Screens: make ____ material ____
length ____ ft from ____ to ____ ft slot size ____
length ____ ft from ____ to ____ ft slot size ____
Gravel pack: size ____ from ____ to ____ ft

Clearance Distance to Nearest

Oil tank ____ ft
Roadway outer boundary *135* ft
Road name *Gosling Circle*
[illegible]
~~On-site sewage system~~ 30 ft
Off-site sewage system ____ ft
Cesspool or other potential source of contamination ____ ft
(please identify source)
Watercourse ____ ft Well ____ ft

Water Yield

Method: ☑ Air blown ☐ Bail ☐ Pump
Rate *30* igpm Duration *1* hrs
Test depth *140* ft
Depth to water at end of test *140* ft
Total drawdown ____ ft
Water level recovered to ____ ft
by ____ hrs ____ mins
after test ended.
Depth to static level *20* ft
☐ Overflow

Water Quality

Colour ____ Taste ____ Odour ____ Other ____

Final Status of Well

- ☑ Water supply
- ☐ Observation Well
- ☐ Test Hole
- ☐ Recharge Well
- ☐ Abandoned, insufficient supply
- ☐ Abandoned, poor quality
- ☐ Abandoned, salt water
- ☐ Unfinished
- ☐ Other ____

Water Use

- ☑ Domestic
- ☐ Industrial
- ☐ Commercial
- ☐ Municipal
- ☐ Irrigation
- ☐ Public Supply
- ☐ Agricultural
- ☐ Heat Pump
- ☐ Other ____

Method of Drilling

- ☑ Rotary
- ☐ Cable Tool
- ☐ Jet
- ☐ Other ____
- ☐ Drilling Fluids

Type: ____

Driller's Comments

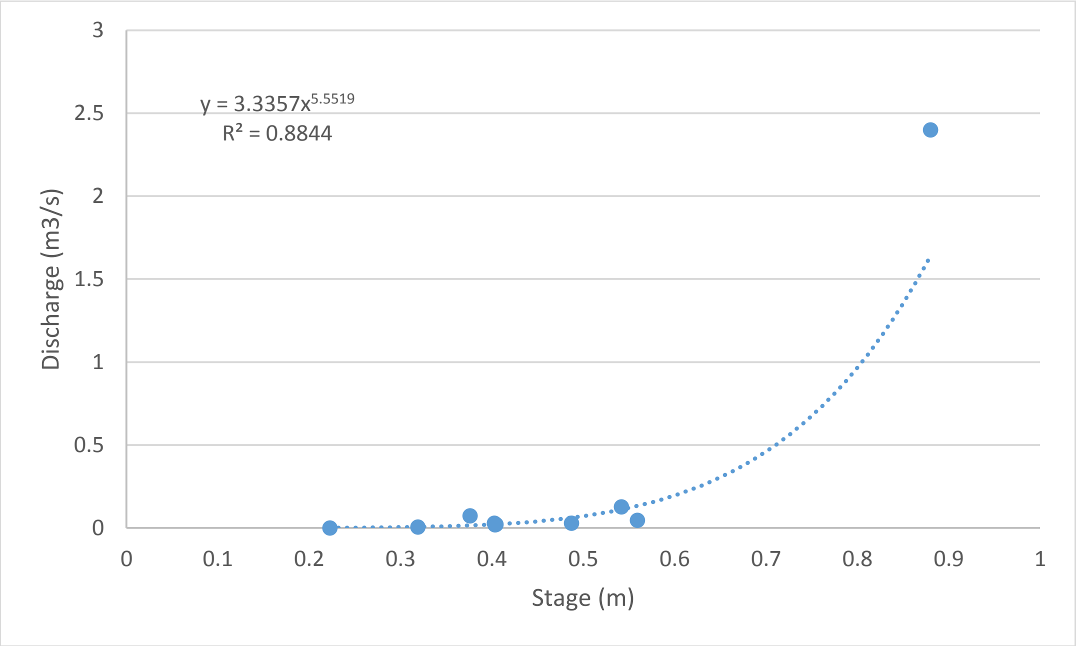
Certification

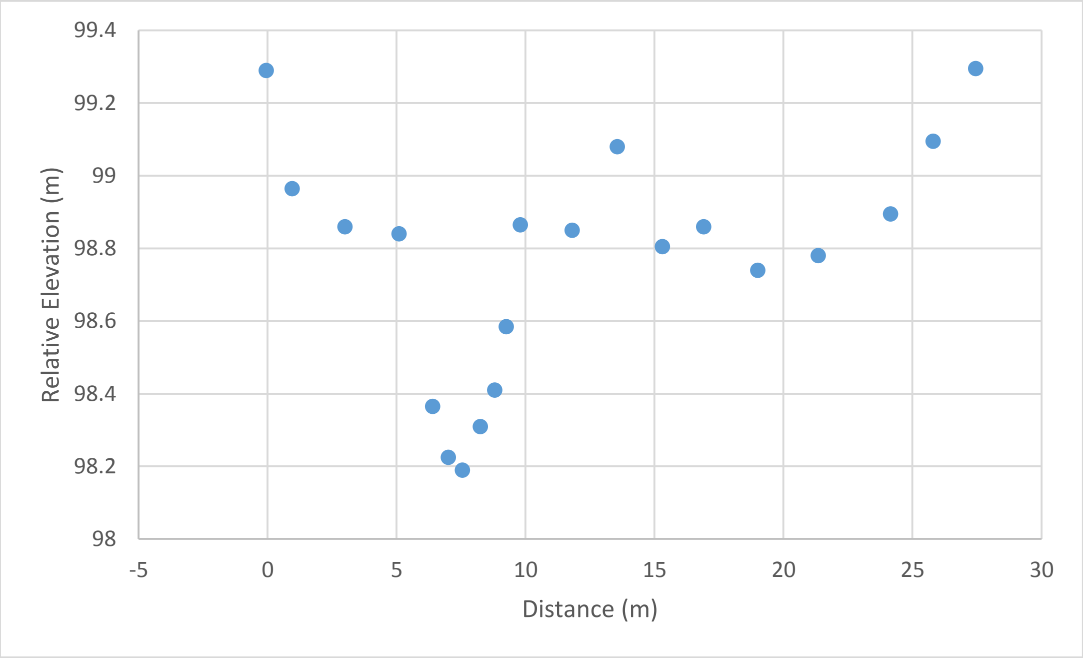
I certify this well has been constructed in accordance with the *Nova Scotia Environment Act and Well Construction Regulations.*

Mail to:

Nova Scotia Department of Environment
30 Damascus Road, Suite 115

APPENDIX C STREAM STAGE-DISCHARGE CURVE





APPENDIX D EVAPOTRANSIPIRATION MATLAB CODE

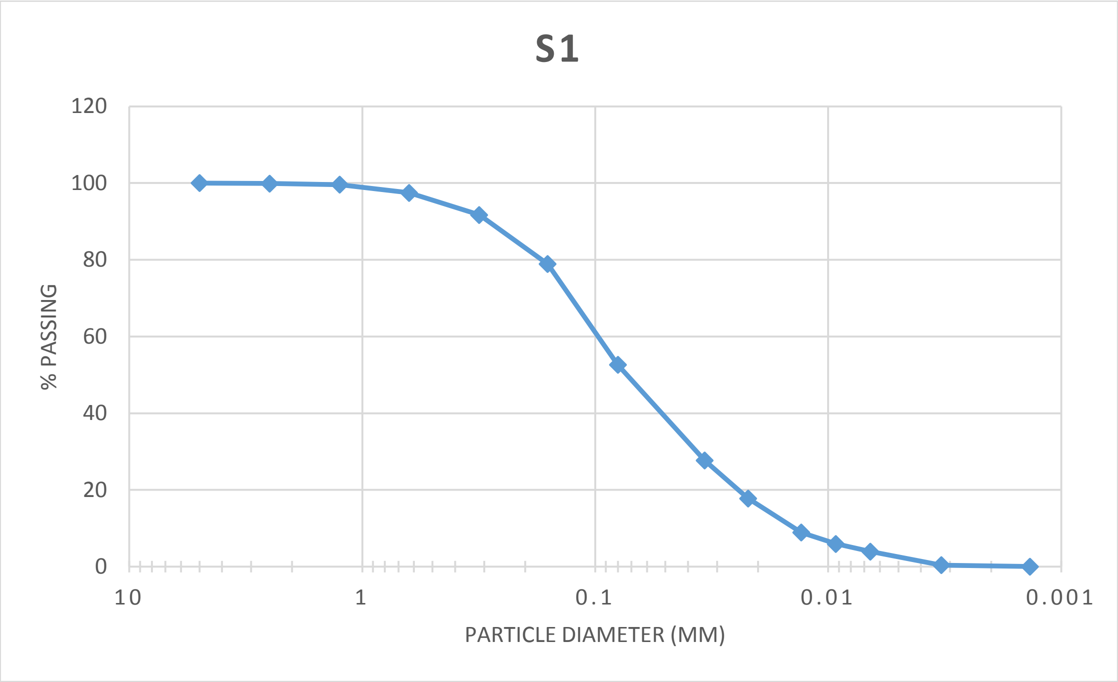
```
% Daily Evapotranspiraton Model using the
% Priestly Taylor Method
% February 3, 2016
% Data Input is from Shearwater RCS Station
% Combination of EC hourly and daily data


ln = @log;
load('RCS3.csv') % loading csv file

%Input Constants
lat = 44; % degrees
z = 24; % Shearwater RSC Station Height (m) Environment Canada
Cp = 1.013; % specific heat of moist air units kJ/(Kg*C)
E = 0.622 ; % ratio of molecular weight of water vapour/dry air

% Constants related to Priestly Taylor simulation
alphacoef = 1.26; % calibration coefficient

%Parameters related to the loop
simlength = 2963;
deltat = 1; %units in days
t = 1; %this is day one of the simulation subject to change
tstore = 0:simlength;
time(1)=t;
i = 2;

while t < simlength %calculates values for each day of the
simulation

    % unload the csv file with all of the recorded data

    julianday = datenum(RCS3(t,2),RCS3(t,3),RCS3(t,4));%go get
the
                                                            %
julian date
    day_now = RCS3(t,4);
    month_now = RCS3(t,3);
    year_now = RCS3(t,2);
    Ta = RCS3(t,7); %go get mean temperature
    Td = RCS3(t,9); %go get dew temperature
    Tmin = RCS3(t,6); %go get min temperature
    Tmax = RCS3(t,5); %go get max temperature
    uz = RCS3(t,8); %go get average wind speed
    Pnow = RCS3(t,10); %go get Daily Atmospheric Pressure kPa

%go get Ra and Rs in Ra function
[Ra,Rs] = get_Ra(julianday,lat);
```

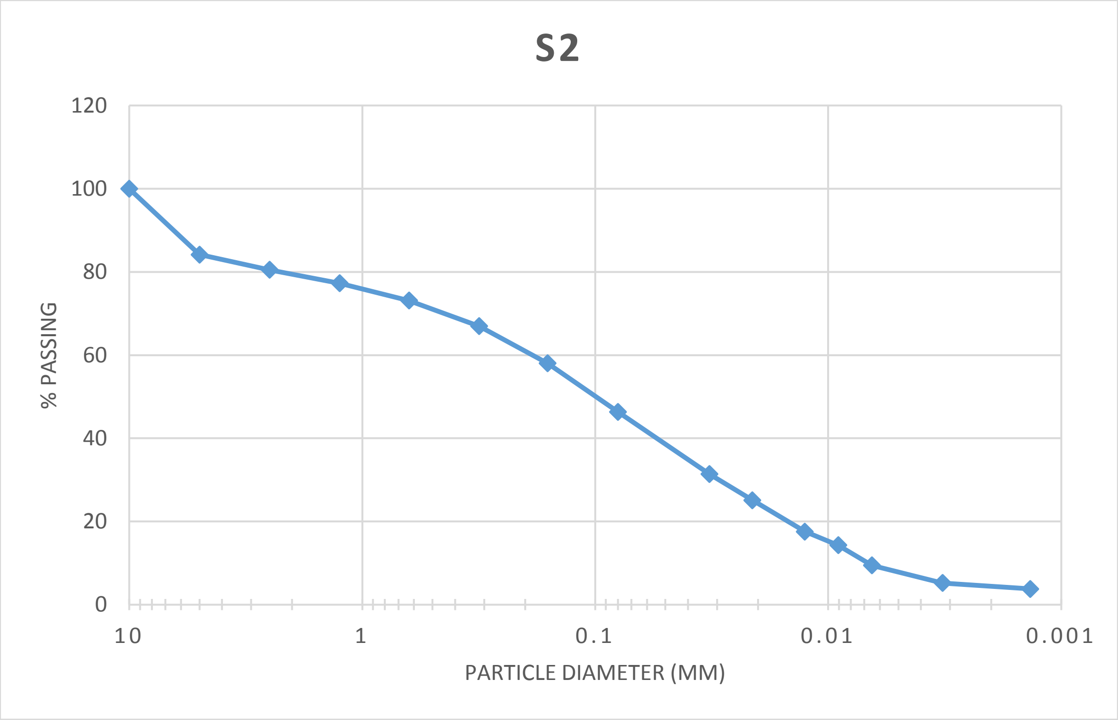
```
% Latent heat of Vapourization
lamda = 2.501 - (2.361.*10.^-3).*Ta; %units MJ Kg-1

% % Atmospheric Pressure %you know have this measured
% P = 101.3.*((293-0.0065.*z)./293).^5.26; % units kPa

% Saturation Vapour Pressure
VPsat = 0.611.*exp(17.27.*Ta./(Ta + 237.3)); % units kPa

% Actual Vapour Pressure
VPact = 0.611.*exp(17.27.*Td./(Td + 237.3)); % units kPa

% Slope Vapour Pressure Curve
delta = 2504.*exp(17.27.*Ta./(Ta + 237.3))./(Ta +
273.3).^2;%units of kPa/C

% Psychrometric Constant
Psy = (Cp.*Pnow./(E .* lamda)).*0.001;

% Short Wave Radiation on a Clear-Sky Day
Rso = (0.75 + 2.*10.^-5.*z).*Ra; %units MJ/m2*d

% Net Shortwave Radiation
alpha = 0.23; %albedo or canopy reflection coefficient for
               % grass dimensionless (Xu and Singh, 2002)

Rns = (1 - alpha).*Rs; %units MJ/m2/day

% Net Longwave Radiation
sigma = 4.903 * 10.^-9; % stefan-boltzmann constant units
MJ/K^4/m^2/day
Rnl = sigma*(((Tmin+273.16).^4 + (Tmax+273.16).^4)./2).*...
        (0.34-0.14.*(VPact).^(0.5))*(1.35.*Rs./Rso-0.35);

%Net Radiation
Rnet = Rns - Rnl;

%Soil heat flux assumed to be negligible (Allen at al 1998)

u2 = uz * (4.87 ./ (ln(67.8.*z - 5.42))); % calculate wind speed
at z

% Calculate ET using Priestly Taylor Equation
ET_PT_now = alphacoef .* (delta ./ (delta + Psy)) .* (Rnet ./
lamda);


t = t + deltat; %step forward in time

% check to see if we should store the variable for this time
```

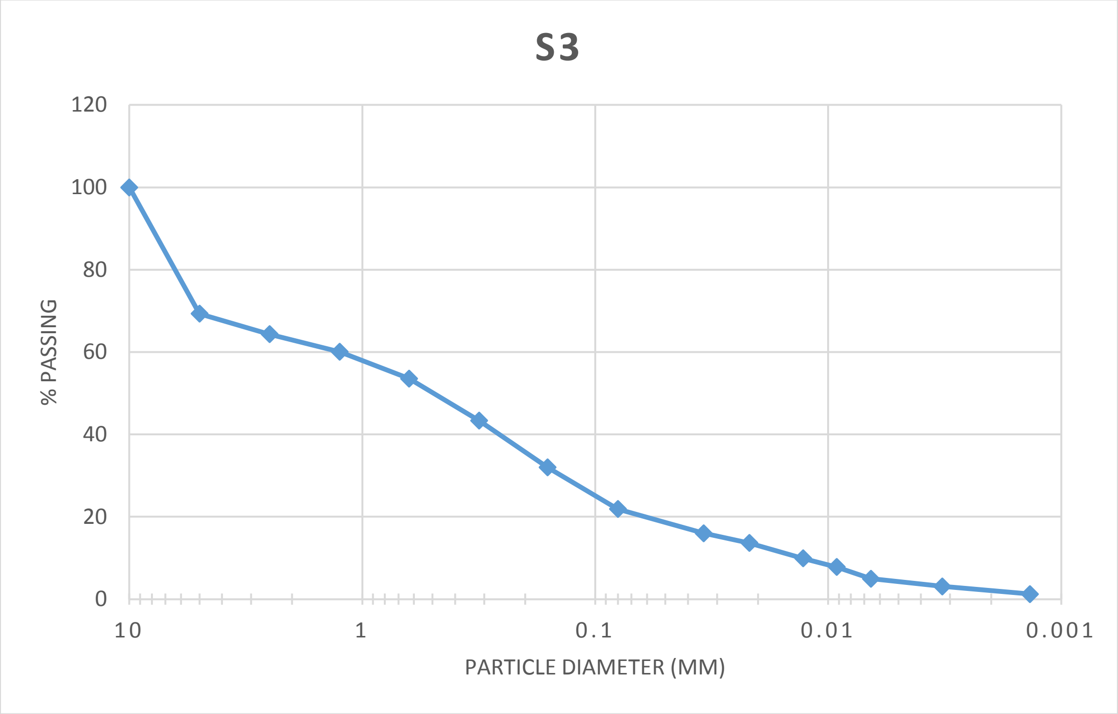
```
if t>=tstore(i)
    time(i) = t;

    year(i) = year_now;
    month(i) = month_now;
    day(i) = day_now;
    Td_now(i) = Td;
    Tmean(i) = Ta;
    Tmin_now(i) = Tmin;
    Tmax_now(i) = Tmax;
    Ra_calc(i) = Ra;
    Rs_calc(i) = Rs;
    ET_PT(i) = ET_PT_now;
    P(i) = Pnow;
    uz_now(i) = uz;
    u2_now(i) =u2;

    i = i + 1;
end

end


T =
[month;day;year;Td_now;Tmean;Tmin_now;Tmax_now;P;uz_now;u2_now;Ra
_calc;Rs_calc;ET_Har;ET_PT;ET_PM];
TransposeT = transpose(T);
dlmwrite('RCS3_Out.txt',TransposeT);


function[Ra,Rs,delta1,delta2,delta3]=get_Ra(julianday,lat)
% Calculating the Ra, extraterrestrial radiation
% Function to be called on from the main code

% Variables to be passes in
% t in Julian Days
% latitude in degrees

% for that day calculate Ra and Rs and send it back to the main
file

latrad = lat.*pi/180; % convert to radians

% solar constant
Gsc = 0.0820; % units MJ/m/min

%Inverse relative distance Earth-Sun
dr = 1 + 0.033*cos(2*pi/365*julianday);

% Solar declination
```

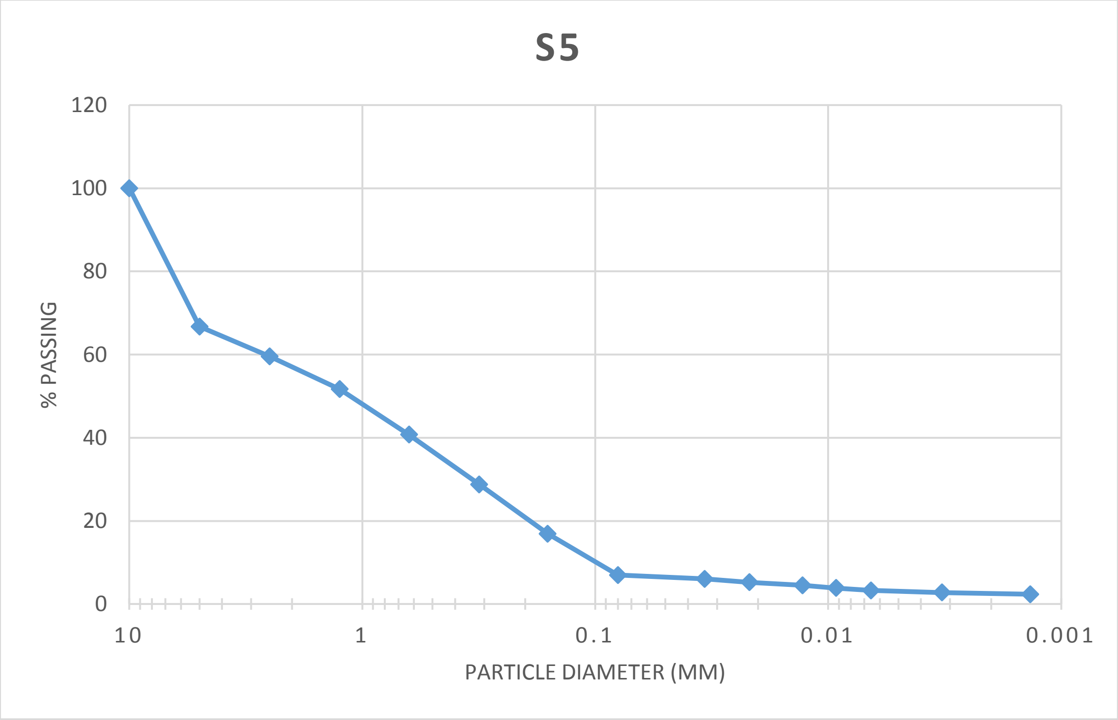
```
delta = 0.5*sin(2*pi./365*julianday -3.5);  %changed 0.5 and -3.5

% Sunset hour angle
ws = acos(-tan(latrad).*tan(delta));

Ra_now = 24*60/pi * Gsc * dr * (ws*sin(latrad)*sin(delta) +...
        cos(latrad)*cos(delta)*sin(ws));

Ra = Ra_now;

% Now Calculate Rs incoming solar radiation

N = 24/pi*ws; % max possible daylight hours
n = N; % actual bright sunshine hours
www.currentresults.com/weather/
           %  /canada/cities/sunshone-annual-average.php 0.43%
as = 0.25; % recommended place holder from FAO
bs = .3; % recommended place holder from FAO
% n is actual duration of sunshine in hours and should be fed
into the
% function
Rs = (as + bs*n/N)*Ra ;
end
```

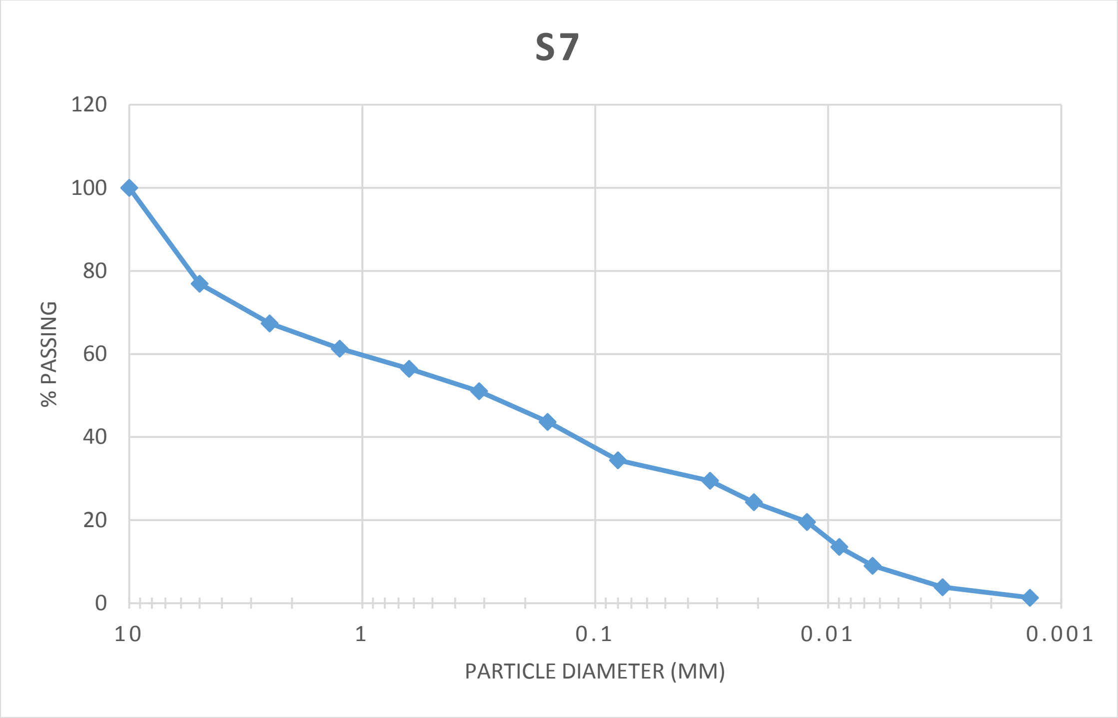
APPENDIX E SOIL PARTICLE SIZE DISTRIBUTION CHARTS

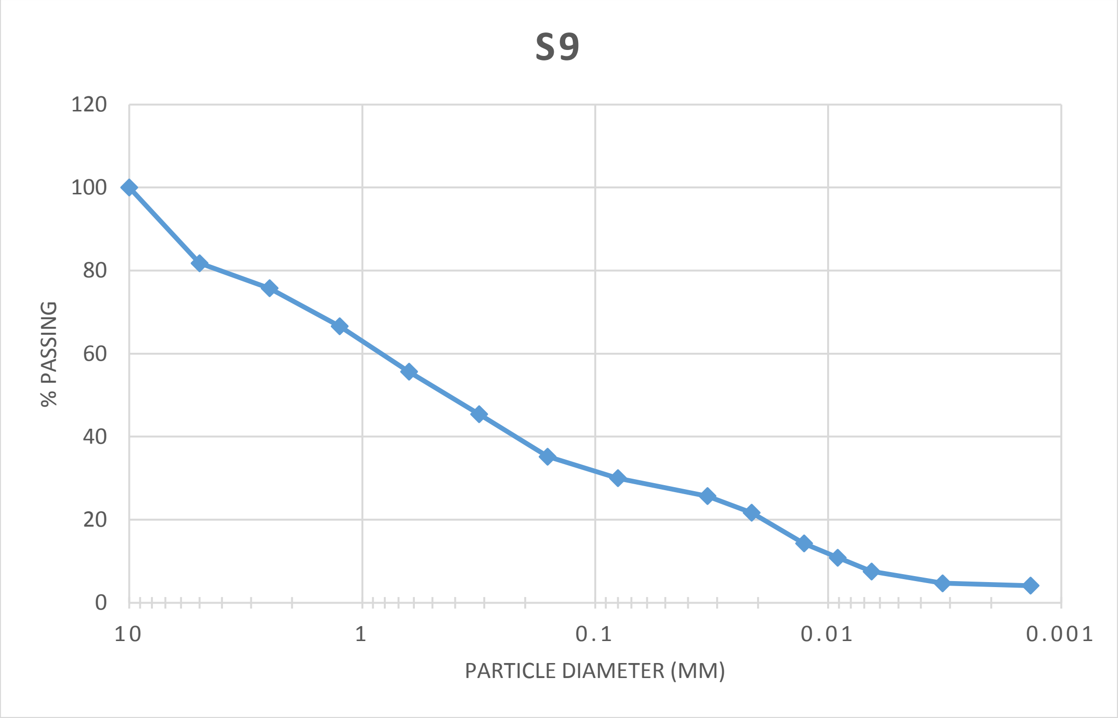


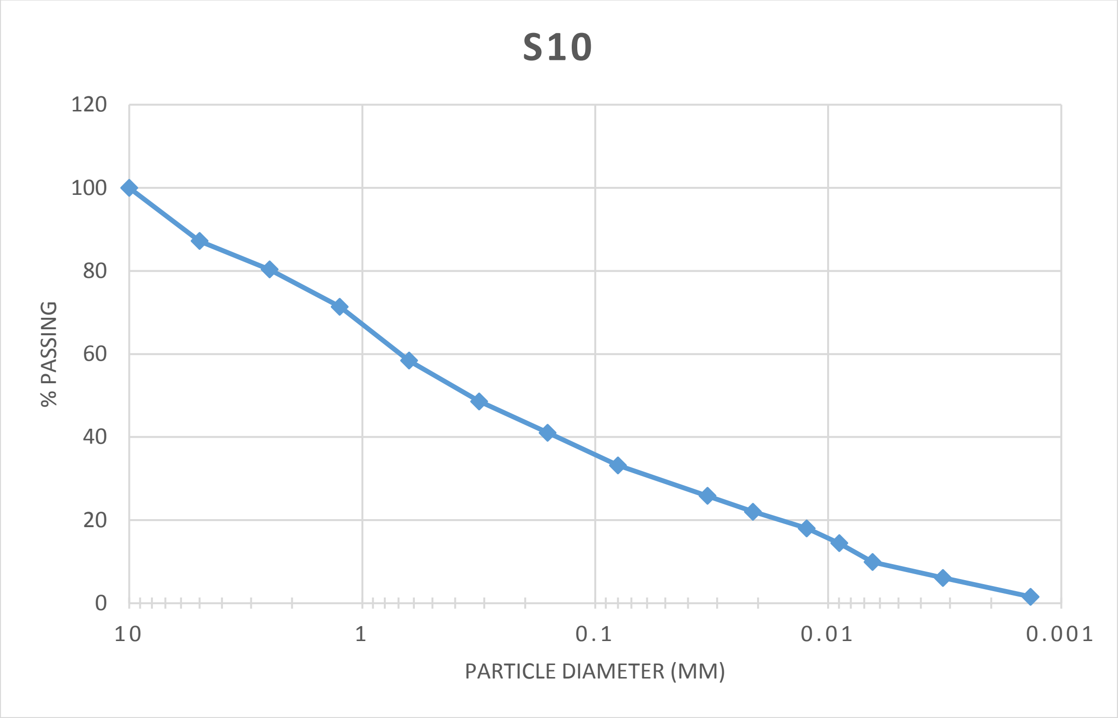


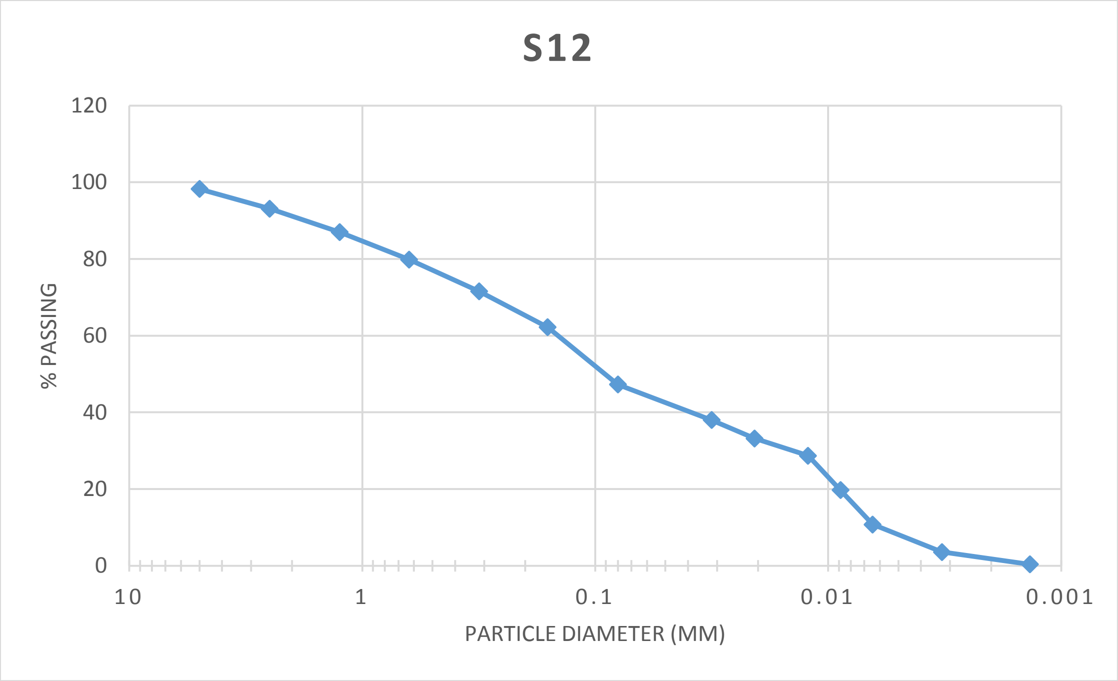

S3
120
100
80
60
40
20
0
% PASSING
10
1
0.1
0.01
0.001
PARTICLE DIAMETER (MM)

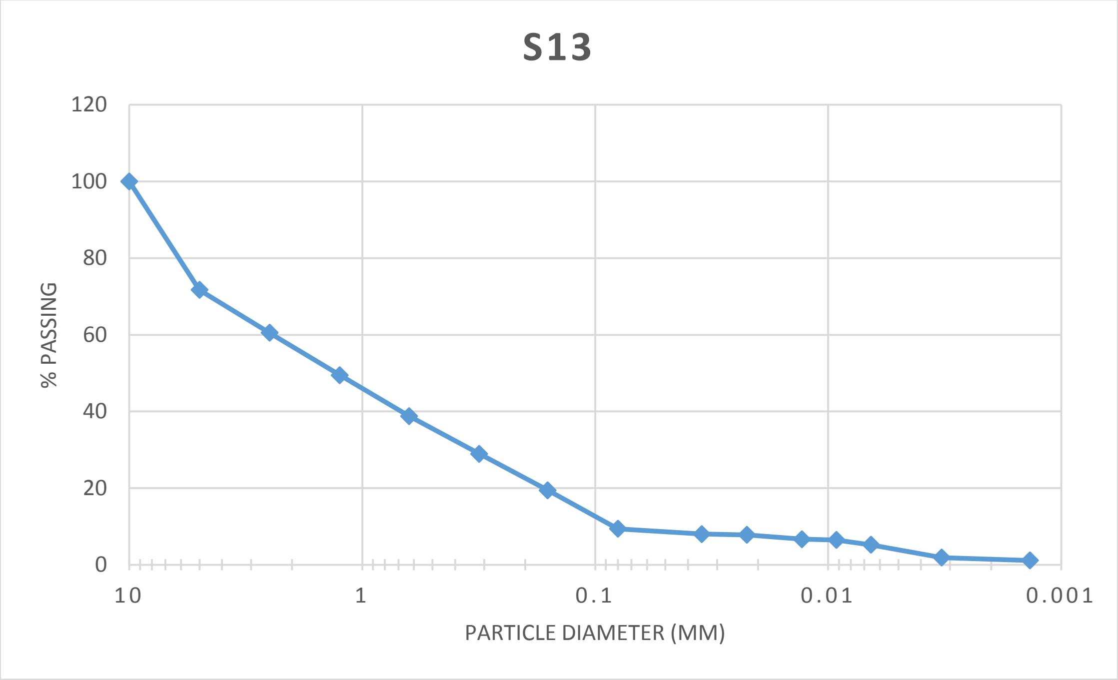

S5
120
100
80
60
40
20
0
% PASSING
10
1
0.1
0.01
0.001
PARTICLE DIAMETER (MM)

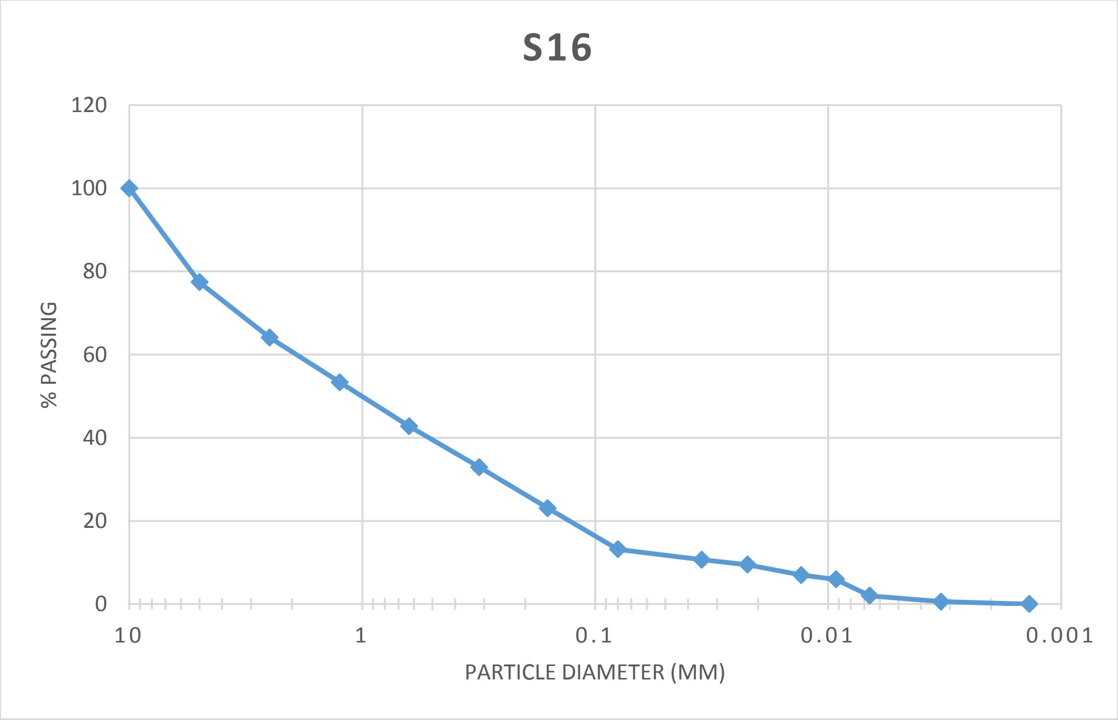

S7
120
100
80
60
40
20
0
% PASSING
10
1
0.1
0.01
0.001
PARTICLE DIAMETER (MM)


S9
120
100
80
60
40
20
0
% PASSING
10
1
0.1
0.01
0.001
PARTICLE DIAMETER (MM)


S10
120
100
80
60
40
20
0
% PASSING
10
1
0.1
0.01
0.001
PARTICLE DIAMETER (MM)


S12
120
100
80
60
40
20
0
% PASSING
10
1
0.1
0.01
0.001
PARTICLE DIAMETER (MM)


S13
120
100
80
60
40
20
0
% PASSING
10
1
0.1
0.01
0.001
PARTICLE DIAMETER (MM)


S16
120
100
80
60
40
20
0
% PASSING
10
1
0.1
0.01
0.001
PARTICLE DIAMETER (MM)