Low Impact Development Effects on Aquifer Recharge Using Coupled Surface and Groundwater Models

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ABSTRACT

Low impact development (LID) is promoted as a sustainable management practice for stormwater in urbanized catchments. While the positive effects of LID features on surface water hydrology and water quality have been investigated, less is known regarding their effects on aquifer recharge. The hydrologic model PCSWMM was coupled with the groundwater model MODFLOW, to assess the influence of LID on aquifer recharge in a study area undergoing residential development. The coupled models were calibrated and validated with pre-development stream flows and groundwater levels from a predominately forested catchment. PCSWMM was used to quantify net infiltration rates for conventional and LID stormwater practices for the development. Net infiltration rates were then coupled with MODFLOW, to determine aquifer recharge, and the potential effects on groundwater availability for the development. Results suggested that LID practices would help restore pre-development aquifer recharge conditions. This study demonstrated a novel approach for assessing the effects of LID stormwater practices on aquifer recharge and groundwater availability in new residential developments.

INTRODUCTION

Urbanization has been shown to have a negative effect on landscape water balances (DeFires and Eshleman 2004). While the definition of an “urbanized catchment” remains subjective (Elga et al. 2015), Mejia and Moglen (2010) have demonstrated that impervious surfaces change the hydrological regime of a catchment. Changes include more frequent bankfull events and increased stream channel erosion (Roesner et al. 2001). Schirmer et al. (2013) and Salvadore et al. (2015) also found that while leaking potable and wastewater infrastructure can be an additional source of recharge to groundwater, infiltration and aquifer recharge in urbanized settings tends to decrease with the increase of impervious surfaces.

Conventional stormwater management approaches are designed to collect and convey precipitation falling on a developed landscape towards detention structures as quickly and efficiently as possible. Storm runoff is typically directed to an engineered structure designed such that pre- and post-development peak flows are equivalent for specified design storms, according to regional regulations (Bedient et al. 2013). While the intention of conventional stormwater management is to reduce the risk of flooding and damage to people and property, it often fails to restore pre-development water balances. A new stormwater management approach, referred to as low impact development (LID), has emerged in the last 20 years. The purpose of LID is to emulate the pre-development water balance in post-development site conditions. This is achieved by providing opportunities for stormwater from small and frequent rainfall events to infiltrate and evaporate at the watershed, neighbourhood and individual lot scales (Stephens et al. 2012).

While the effects of LID on surface water systems have been documented, the influence on aquifer recharge is less understood, and was absent in recent reviews of current research on LID (Dietz 2007 and Ahiablame et al. 2012). The term recharge is more appropriately subdivided into “net infiltration” and “aquifer recharge” (Rivard et al. 2014). Net infiltration refers to the infiltrated water which reaches the water table . However, a portion of the water which reaches the water table may leave the saturated zone as lateral groundwater flow to streams, or as evapotranspiration to the atmosphere. Aquifer recharge would be the remaining water which actually contributes to groundwater storage.

The development of assessment tools and management strategies to mitigate the negative impacts of urban development on aquifer recharge has been identified as a critical need in North America (Lavoie et al. 2014; Holysh and Gerber, 2014; Sousa et al. 2014). A specific region where this issue has attracted attention is within the Halifax Regional Municipality (HRM), Halifax, Nova Scotia, Canada. Suburban developments located outside of municipal water service boundaries in the HRM typically rely on local groundwater for potable water supplies, and some developments have experienced water shortages in recent years (CBC, 2010).

The use of LID stormwater management strategies in new or existing developments could increase aquifer recharge and help mitigate water availability issues. However, the relative effects of LID on aquifer recharge would be site specific, and dependent on many factors such as soils, aquifer characteristics and the density of the development. The collection of field data to assess these factors would be time consuming and expensive, therefore the development of tools for explicit modeling of the effects of LID on aquifer recharge would be beneficial. The objectives of this study were to: (i) develop a modeling framework to be able to quantify the effects of alternative LID practices on aquifer recharge and groundwater availability, and (ii) assess the potential benefits of LID in terms of groundwater availability for a suburban development which relies on a local aquifer for potable water supplies. The modeling framework consisted of an urban hydrology model (PCSWMM-Personal Computer Stormwater Management Model) coupled to a numerical groundwater flow model (MODFLOW). The models were calibrated using pre-development surface water and groundwater data from the study site, and then used to simulate how the proposed development would impact groundwater resources with and without the use of LID.

METHODOLOGY

Study Site

The study area is located approximately 30 km east of Halifax, Nova Scotia, Canada (44°45’21” N, 63°17’29” W) (Figure 1). The study site consists of Phase I of a proposed residential development (Seven Lakes Development). The area that is to be developed is partially forested with some cleared areas, and partially occupied by an abandoned quarry. The post-development projected land-use was based on plans for the first phase of the Seven Lakes Development (Figure 2), and consisted of 100 residential units, each serviced by individual drilled wells. The average lot size was planned to be 1200 m^2 with 30% of the lots covered with impervious surface (drive way and roof area). In pre-development conditions, the catchment has 11.7 ha of impervious area and 82.7 ha of pervious area. Whereas, in post-development conditions, the impervious area of the catchment will be increased to a total of 15.4 ha, leaving 79 ha of pervious area. The impervious area in the pre-development condition was comprised of existing paved roads, and roofs and paved driveways of some existing residential properties within the catchment.

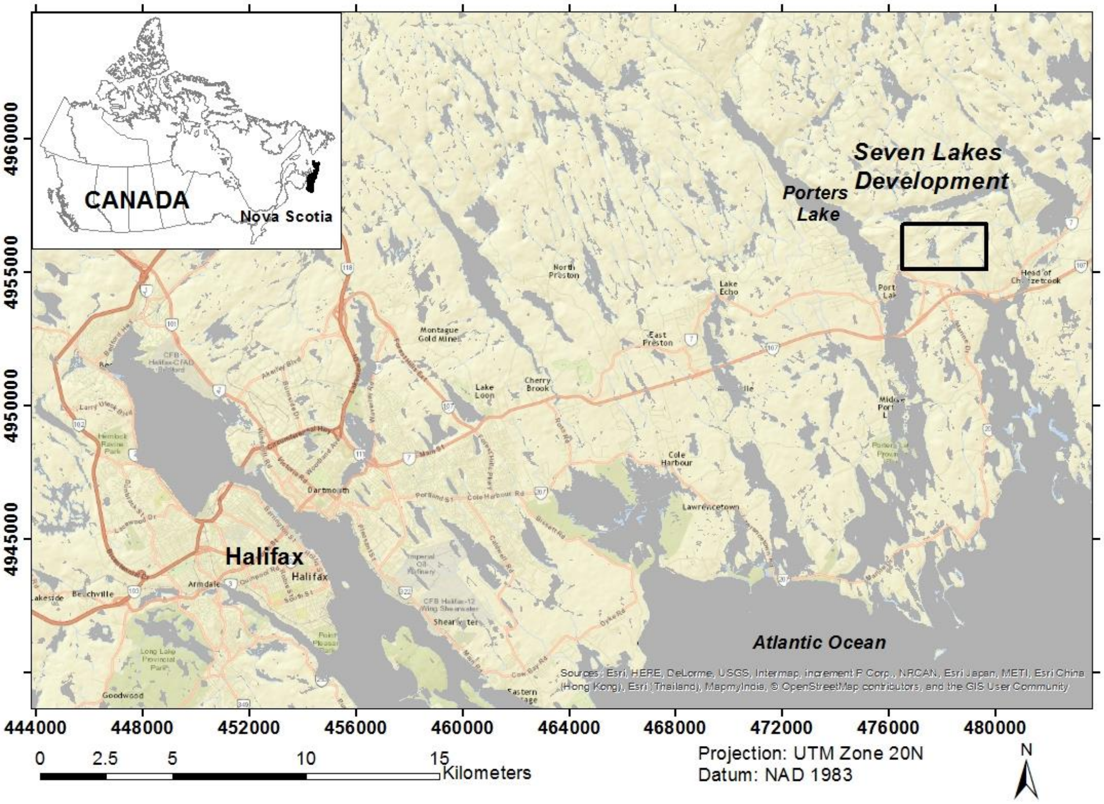

Figure 1. Study site location of Seven Lakes residential development east of Halifax, Nova Scotia, Canada.

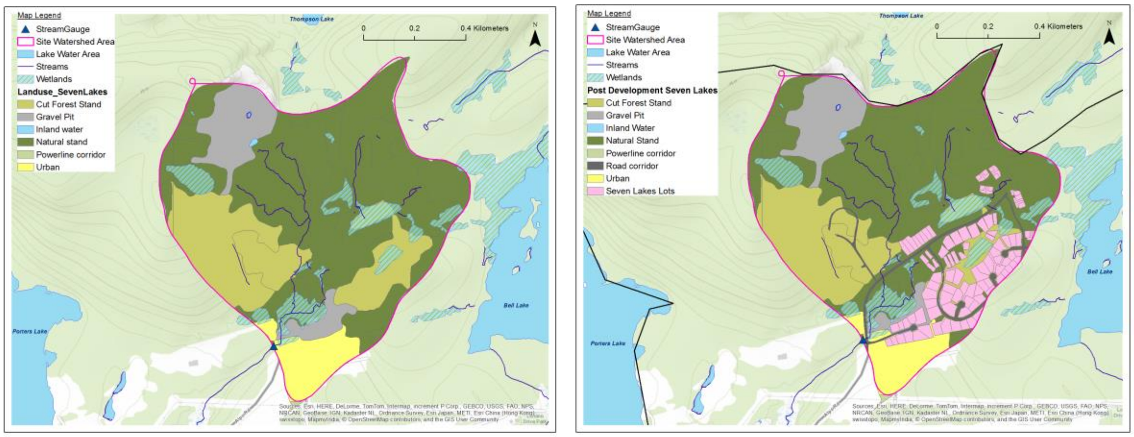

Figure 2. Study area showing (a) pre-development and (b) projected post-development land use.

The climate for the region is temperate and humid, whereby extreme temperatures are moderated by the influence of the Atlantic Ocean. Maximum daily temperatures of 22°C are typical in the month of August. Minimum daily temperatures of -9°C are common in January and February. Average yearly rainfall is 1261 mm and average yearly snowfall is 180 cm (Table 1) (Government of Canada 2017a).

Table 1. *Climate characteristics of the study site.*

Parameter	**Average**
Mean annual total precipitation	1423 mm
Mean annual lake evaporation	582 mm
Mean annual rain	1261mm
Mean annual snowfall	1800 mm
Minimum mean monthly precipitation (August)	92 mm
Maximum mean monthly precipitation (December)	141 mm
Mean annual temperature	6.9°C
Minimum mean monthly temperature (January)	-4.6°C
Maximum mean monthly temperature (August)	22.6°C

Note: Mean Annual Lake Evaporation as estimated by Environment Canada for the Kentville Climate Station using a Class A Evaporation Pan..

The study area is overlain by soils from the Halifax soil series, which is a brown sandy loam over yellowish sandy loam with good to excessive drainage (MacDougall et al. 1963). The bedrock which underlies the study area is of the Goldenville Formation of the Meguma group. The Goldenville formation is comprised of metasandstone, metasiltstone and slate (Keppie 2000) and is a metamorphic rock formation, which mainly yields water from the fracture network.

Modeling Approach

The modeling framework used in this study consisted of a combination of a land cover representation tool, a hydrologic model and a groundwater flow model. The land cover representation model, constructed in ESRI ArcGIS version 10.2 (ESRI, Redlands, California, United States) involved calculation of spatially weighted (i.e., lumped), land use characteristics for use in the hydrologic model, and the groundwater flow model. The hydrologic model was used to calculate net infiltration rates, which were then coupled with a groundwater flow model to determine: (i) steady state aquifer recharge, and (ii) the 3-D distribution of hydraulic head throughout the groundwater aquifer.

Hydrologic Model: Computational Hydraulics International's (CHI) PCSWMM (CHI, Guelph, Ontario, Canada) modeling software, a proprietary version of SWMM5, was used to predict net infiltration. PCSWMM treats each sub-catchment surface as a non-linear reservoir. The Curve Number method for estimating runoff was used to calculate infiltration. The degree-day model using a snow-cover depletion curve was used to model snow accumulation and melt. The option of selection of data from an external time series was chosen to model potential evapotranspiration with the Priestley Taylor (PT) method (Priestley and Taylor 1972). The PT method is semi-empirical and generally based on an energy balance which relies on solar radiation observations (Xu and Singh 2002). Net solar radiation was calculated from observations made as part of Environment Canada's Canadian Weather Energy and Engineering Dataset (CWEEDS) (Government of Canada 2017b). This dataset ends December 31, 2005, after which net solar radiation was estimated using methods described by Allen et al. (1998).

PCSWMM uses a two-zone water budget to model water movement in the subsurface. An upper zone is characterized by variable moisture content, and a lower zone is assumed to be 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. Lateral groundwater flow was modeled using the Dupuit-Forchheimer assumption, which represents lateral groundwater flow to a channel as a function of the difference in groundwater and surface water heads.

In PCSWMM the water that is transferred to the saturated soil zone from the upper soil zone is termed "percolation", which is equivalent to what we have termed "net infiltration". PCWMM does not explicitly calculate percolation as a time series output; however, therefore it was calculated from model outputs for a given time step using the water budget equation for the unsaturated soil zone as per Equation 1: (James et al. 2010):

Equation 1

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

Where: TH2 is the end of time step upper zone moisture content (fraction); ENFIL is the infiltration rate; ETU is the upper zone evapotranspiration rate; PAREA is the pervious area divided by total area; PERC is the percolation rate; DELT is the time step value; D1 is the beginning of time step lower zone depth; D2 is the end of time step lower zone depth; TH is the beginning of time step upper zone moisture content (fraction); DWT1 is the beginning of time step upper zone depth; and DTOT is the total depth of upper and lower zone, which is equal to D1 + DWT1.

Solving Equation 1 for PERC provided a means for calculation of the net infiltration rate for each time step as per Equation 2.

Equation 2

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

Net infiltration was summed on an annual basis using a water year of October 1 through September 30 in order to account for any time delay in the arrival of water to the aquifer associated with snowmelt in the spring.

The study area subcatchment was delineated using Arc Hydro tools in ESRI ArcGIS to be 94.2 ha. Land use, soils and slope were derived using publically available geospatial data sets and ESRI ArcGIS. Land use was derived from the Nova Scotia Department of Natural Resources (NSDNR) Forest Inventory database (Province of Nova Scotia 2015). The percent impervious cover for each land use was assigned using values recommended by James et al. (2010).

Groundwater Model: Visual Modflow Flex (MODFLOW) version 2015.1 (32 Bit) (Waterloo Hydrogeologic, Kitchener, Ontario, Canada) was used to model groundwater flow. 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 was run in steady state mode using yearly net infiltration rates as calculated in PCSWMM. Aquifer recharge was determined by subtracting lateral groundwater flow and saturated zone ET from net infiltration. A continuum approach (spatially averaged flow properties) to modeling flow in fractured rocks was used to model the study area. It was assumed that the aquifer is isotropic in the horizontal direction and anisotropic in the vertical direction.

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 divides) boundaries. Figure 3 illustrates the extent of the groundwater model and the topography of the surface layer.

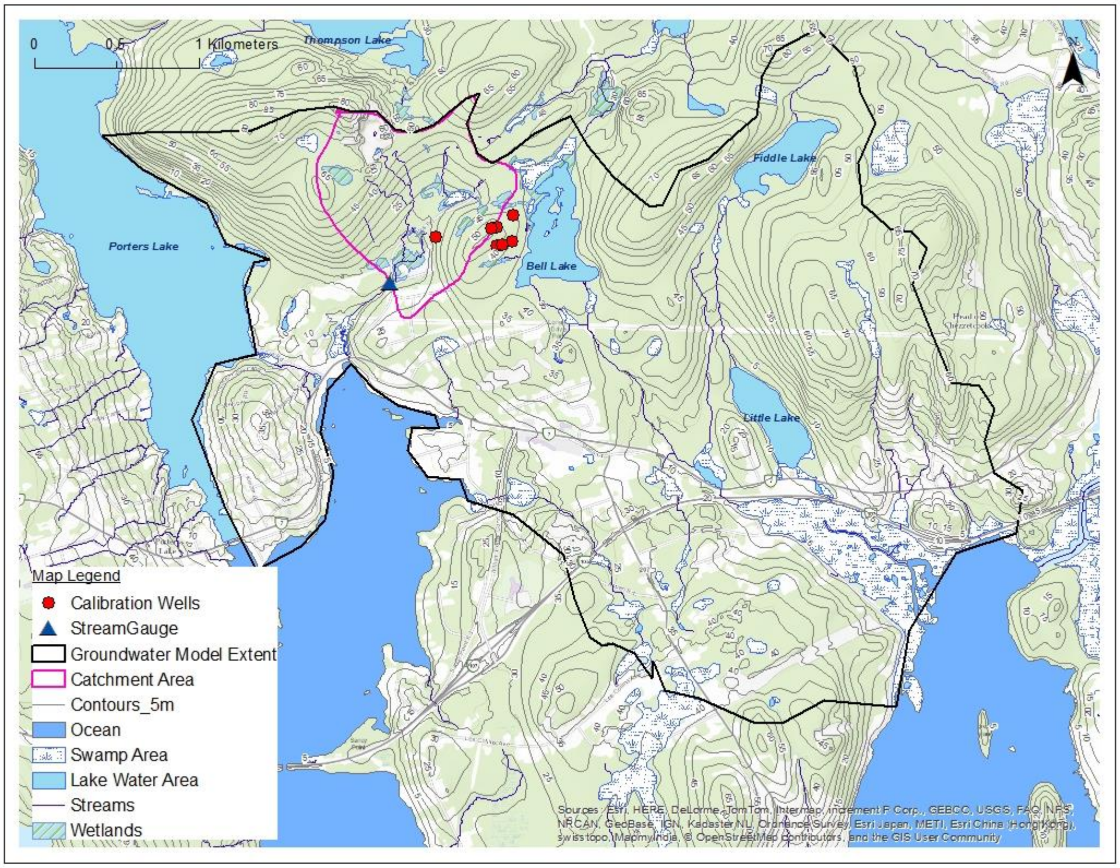

Figure 3. Spatial extent of the groundwater model. Constant head boundary conditions were applied to Porters Lake and the Ocean. No flow boundary conditions were applied to topographic divides. A drain boundary condition was used for the stream draining the hydrology catchment while lake boundary conditions were applied to Fiddle, Bell and Little Lake.

The surface of the model was built using a combination of a 20 m digital elevation model (DEM) published by NSDNR (Province of Nova Scotia 2006) and topographic survey data of the study site collected by a local consulting company. Where the datasets overlapped, the topographic survey data was preferentially used. A 40 m by 40 m grid mesh was assigned to the model domain in both the horizontal and vertical directions.

Six vertical layers were used to represent the groundwater system. Layer 1 represents the glacial till soil layer, with a variable thickness that was constructed in ESRI ArcGIS using the kriging interpolation tool. In areas where depths were not known, a thickness of 2 m was assumed. Layers 2 through 6 were each assigned a constant thickness ranging from 10 to 22.5 m. 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. In general, weathering processes of bedrock at or near the surface, result in increases in hydraulic conductivity and porosity from the movement of meteoric water through the rock discontinuities, freeze-thaw cycles and geochemical dissolution. In some terrains, this weathered bedrock zone may extend tens of meters in depth before reaching fresh (*i.e.*, un-weathered) bedrock (Rempe and Dietrich, 2014).

Constant head boundary conditions were applied to cells along the edge of the model domain, where it abutted the Atlantic Ocean, and Porter’s Lake. These cells were given head values of 0 m to represent sea level. Porter’s Lake has a direct hydraulic connection to the tidal estuary and the ocean; therefore it was assigned the same zero head boundary. 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.

A drain boundary was used to represent the gauged watercourse which drained the study area. The location of the drain was assigned using the surveyed length of the stream. Elevations were assigned to the headwater and outlet of the stream using values from the DEM.

Lake boundary conditions are different from the constant head boundary conditions in that they use the modeled water balance to update the lake stage as the model simulations progress (Merritt and Koniknow, 2000). Therefore, 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 location and surface area of the lakes (Bell, Fiddle and Little) were sourced from the NSTDB 1:10000 mapping (Figure 3). Lake stage of Bell Lake was assigned as 4 m, as determined from bathymetric mapping of the lake (CWRS, Progress report: baseline hydrological and hydrogeological assessment for the low impact development stormwater management project in Seven Lakes, Porters Lake, NS, unpublished report in 2013), Fiddle and Little Lakes were assumed to have stages of 6 m and 3.3 m respectively, based on their surface areas and the assumption that they are of similar bathymetry due to proximity to Bell Lake.

The recharge boundary condition was used to apply a uniform net infiltration depth over two different recharge zones: the catchment area of the study area (area to be developed), and the remainder of the groundwater model domain, which was undeveloped.

Wells were added to the model domain based on borehole logs from initial wells that have been drilled in the study area. All wells drilled in the study area have variable lengths of casing ranging from 6 to 12 m long. Wells that have yet to be drilled in the study area (future wells) were also added to each lot according to the proposed development plan. The depths of future wells were calculated in ESRI ArcGIS using kriging interpolation based on the depths of existing wells. A casing length of 10 m was assigned to each future well.

Observed Data

Three of the initial groundwater wells that had been drilled in the study site were instrumented in October 2013 to provide continuous water level measurements. HOBO U20 Water Level Loggers (Onset® Computer Corporation, Bourne, Massachusetts, United States) were installed in these wells and programmed to record pressure and temperature on an hourly time step. 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 measured barometric pressure. Corrected pressures were converted to a height of water above the sensor.

A stream gauging station was installed in the primary watercourse downstream of the study area. A HOBO U20 Water Level Logger (Onset® Computer Corporation, Bourne, Massachusetts, United States) programmed to log water level readings on a 15-minute time step 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.

Manual 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 (SonTek, San Diego, California, United States). The velocity-area method (Dingman 2002) was used to calculate flow across the stream section. A stage-discharge relationship was created for this location and used to covert the continuously measured water level to flow.

Climate data from Environment Canada (Government of Canada 2015) was used to run PCSWMM and to calculate potential daily ET. The nearest Environment Canada weather station to the study area is the Shearwater Station (Climate IDs 8205090, 9205091, 9205093, 8205092), for which there are four different stations which have recorded data over the past 30 years. Where necessary, data from these stations was combined.

A total of 10 surficial soil grab samples were collected from the study area from below the organic soil horizon. Sieve and hydrometer analyses were 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).

In-situ saturated hydraulic conductivity of soils was measured at 16 locations using 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 (Elrick and Reynolds 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).

The Guelph permeameter (Soilmoisture Equipment Corp., 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. The Guelph Permeameter K_{sat} Calculator (version 3) published by Soil Moisture was used to calculate soil parameters (Soilmoisture Equipment Corp., 2008).

PCSWMM Sensitivity Analysis/Calibration

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. Relative sensitivity, a normalized measure of sensitivity, was used to provide a valid means for comparison of the sensitivity of multiple model parameters (McCuen 1973). The relative sensitivity was ranked into classes ranging from negligible to very high following the scheme presented by Lenhart et al. (2002).

Although the Nash-Sutcliffe efficiency (NSE) is typically used to evaluate the fit of 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 (Moriasi et al. 2007). Krause et al. (2005) present a metric to dampen this effect by reducing the sensitivity of NSE to extreme values. Krause et al. (2005) propose that the NSE is calculated with logarithmic values of calculated and observed data. By using Equation 3, the influence of the low flow values is increased in comparison to the flood peaks which results in an increase in sensitivity of lnNSE to systematic over or under prediction. Equation 3 is given by Krause et al. (2005):

Equation 3

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

Where: n is the number of data points in the set; O is the observed data; and P is the predicted or modeled data.

MODFLOW Calibration and Sensitivity Analysis

MODFLOW calibration goodness of fit was evaluated using two metrics: the root mean squared error (RMS) and the normalized root mean squared error (NRMS). The average measured groundwater elevation in two wells that were continuously monitored, as well as the static water levels recorded in 5 additional wells when they were drilled, served as the observed data. Static water levels from the 5 wells were selected based on the depths to which they were drilled (< 50 m).

The mean groundwater outflow from PCSWMM was used to calibrate the drain boundary leakance parameter, where goodness of fit was assessed based on the percent difference between the groundwater flows predicted by PCSWM vs drain flows predicted by MODFLOW. Once calibrated, a sensitivity analysis was conducted in place of model verification. Calibrated values of hydraulic conductivity, net infiltration and leakance 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 (Lenhart et al. 2002).

Modeled Scenarios

The calibrated models were used to simulate two scenarios: pre- and post-development under both mean and drought precipitation conditions. In the post development model scenarios, the household wells were pumped at rate of 1.35 m^3/d, which would be a design water usage for a single family dwelling (CBCL, 2004)

Based on the time period considered (1990 to 2016), 1997 was determined to be the drought year, and 2003 the average year based on annual total precipitation depths of 925 mm and 1200 mm, respectively. For each precipitation scenario, two stormwater management strategies were simulated: conventional and LID.

Under post-development conditions with conventional stormwater management, precipitation falling on any additional impervious area was routed directly to the subcatchment outlet, following the assumption that stormwater from each lot would be directed to ditches that flow to the watercourse which drained the study area.

Under post-development conditions with LID stormwater management, precipitation falling on any additional impervious area was directed to a rain garden on each lot. Rain gardens were modeled as bio-retention cells; which 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 the rain gardens reached capacity, flow was directed to the subcatchment outlet via the ditched stormwater system.

Bio-retention areas were sized to capture 7 mm of precipitation falling on the impervious area of each lot using Equation 4 and Equation 5. The size and configuration of the bioretention cells were based on the dimensions of a demonstration bio-retention cell which was constructed in the study area by the developer. The demonstration cell had a surface area of approximately 50 m^2 and a total storage volume representing 7 mm of runoff from the impervious areas of each lot, The other input parameters for the bioretention cell are provided in Table 2. Default PCSWMM values of physical and hydraulic parameters for bioretention cell media were used. A flow chart illustrating the sequence of steps involved in the modeling framework in provided in Figure 4.

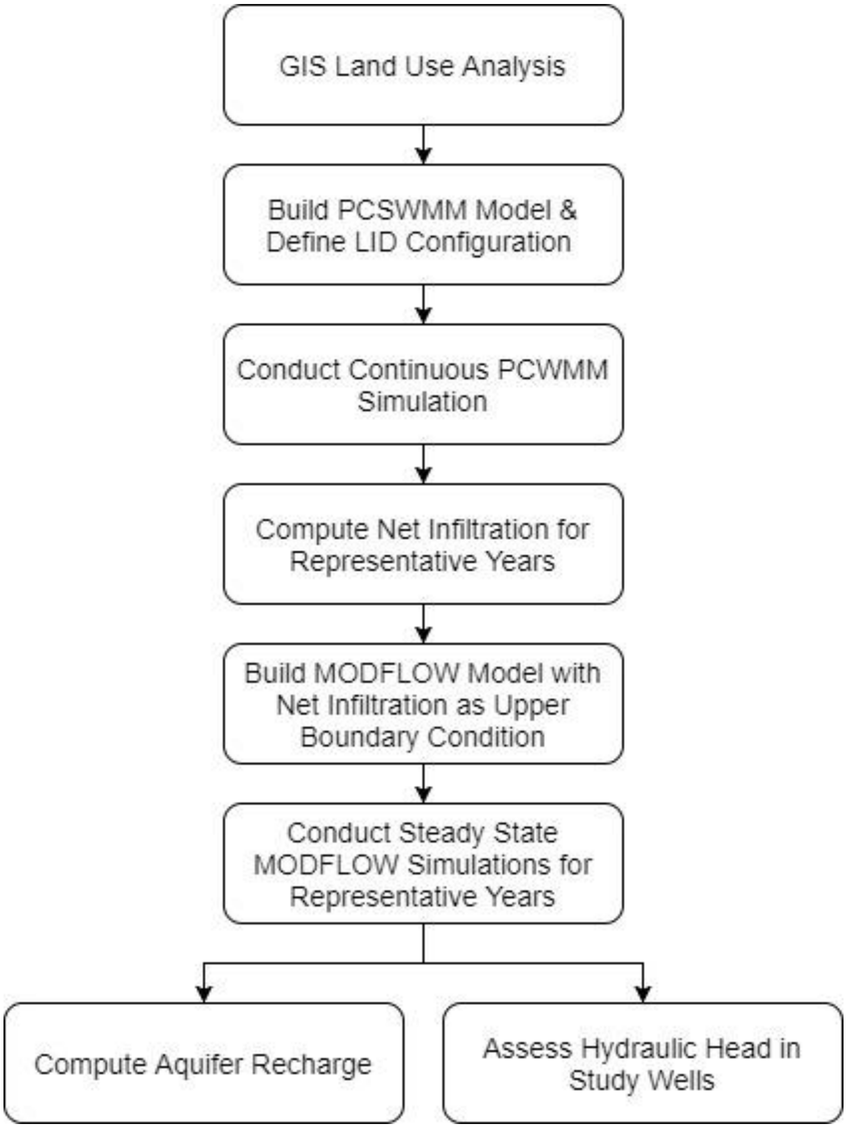

Figure 4. Flow chart illustrating the sequence of steps in the modeling process.

Table 2. *PCSWMM LID parameter descriptions (James et al. 2010).*

Parameter Name	**Description**	**Value**
Berm height (mm)	Maximum depth to which water can pond.	100
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

RESULTS AND DISCUSSION

Site Characteristics

The soil texture of the study area was characterized as sandy loam. This finding agrees with the soil mapping reported by MacDougall et al. (1963). Rawls et al. (1983) report hydraulic conductivity values for sandy loam textured soils to be 2.8 x 10^{-6} m/s or 10 mm/hr, and agrees reasonably well with the mean value of hydraulic conductivity measured across the study area in this study, 5.6 x 10^{-6} m/s.

PCSWMM Sensitivity Analysis and Calibration

The results of the sensitivity analysis (Table 3) show that mean total streamflow was moderately sensitive to the Upper Evaporation Fraction. Decreasing this fraction caused an increase in the stream flow as less infiltrated water would be available for evapotranspiration in the upper zone; this would ultimately generate more lateral flow to a channel. However, this parameter did not have a significant impact on net infiltration rates. Net infiltration was very sensitive to the curve number and had a medium sensitivity to the depth of depression storage on pervious areas. The curve number is the main parameter used 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 remaining model parameters.

The fact that most model parameters were not found to be sensitive may be attributed to the fact that the applicable objective functions for this study were net infiltration and mean stream flow. If alternative objective functions were of interest, such as peak stream flows or time to peak of storm hydrographs, it would be expected that other parameters would be sensitive, such as flow width and Manning's roughness coefficients.

Table 3. *PCSWMM sensitivity analysis results.*

Parameter	**Calibrated Value**	**Low Input**	**High Input**	**Sensitivity Class (Lenhart et al. 2002)**	
				Mean Total Streamflow	**Net Infiltration**
Curve number	64	60	85	neg	very high
Pervious depression storage (mm)	20	2.5	25	neg	medium
Upper evaporation fraction	0.5	0.35	0.6	medium	neg

Note neg = negligible

Calibrated model parameters shown in Table 4 were deemed satisfactory based on the mean monthly lnNSE value of 0.63 for the calibration period of November 2014 to October 2015. The model performance decreased during the validation period, with a mean monthly lnNSE of 0.42 for the validation period of October 2015 to August 2016.

Table 4. *Calibrated PCSWMM model parameters.*

Parameter	**Calibrated Values**
Catchment width (m)	75
Manning's n impervious area	0.017
Manning's n pervious area	0.772
Depression storage Impervious area (mm)	1.3
Depression storage pervious area (mm)	20
Curve number	64
Soil wilting point	0.15
Soil field capacity	0.4

MODFLOW Calibration and Sensitivity Analysis

MODFLOW was calibrated in steady state mode for the year 2014 using a net infiltration depth of 468 mm and drain flow of 446 m^3/day (0.0052 m^3/s). The drain flow was calculated as lateral groundwater flow using PCSWMM output. The goodness of fit parameters for the calibrated model were a RMS of 4.36 m and NRMS of 20.2%.

Table 5. *MODFLOW calibrated saturated hydraulic conductivities.*

Layer No.	**Thickness (m)**	**K_x and K_y (m/s)**	**K_z (m/s)**
1	Variable	2 x10^{-5}	2 x10^{-6}
2	10	8 x10^{-6}	8 x10^{-7}
3	20	2 x10^{-6}	2 x10^{-7}
4	20	4 x10^{-7}	4 x10^{-8}
5	22.5	8 x10^{-8}	8 x10^{-9}
6	22.5	8 x10^{-8}	8 x10^{-9}

Calibrated hydraulic conductivity values in the horizontal direction (K_x and K_y) of layers 1 through 6 ranged from 2 x10^{-5} m/s to 8 x10^{-8} m/s (Table 5). The hydraulic conductivity in the vertical direction (z) of layers 1 through 6 ranged from 2 x10^{-6} m/s to 8 x10^{-9} m/s.

Leakance was calibrated to be 3.6x10^{-4}/d for all lakes. The calibrated drain flow was found to be 5.6x10^{-3} m^3/s, or 9% greater than the observed flow using a leakance value of 1.5 /day.

MODFLOW outputs were found to be sensitive to hydraulic conductivity and net infiltration (Table 6). All other parameters were classified as having negligible influence on the model results. Variation of 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 40 m and decrease by 15.2 m, respectively. Variation of the net infiltration by -75 to 75% caused the mean hydraulic head in wells to decrease by 3.7 m and increase by 3.1 m, respectively. Conversely, variation of the drain leakance parameter by -99 and 99% caused the mean hydraulic head in wells to range between 1.5 m and 0.9 and was not considered sensitive.

Table 6. *MODFLOW sensitivity analysis results for a calibrated mean head of 33.1 m.*

	Range of % Change		**Mean Head (m)**		**Change (m)**		**Sensitivity Class (Lenhart et al. 2002)***
	Min.	Max.	Min.	Max.	Min.	Max.	
K in x,y,z directions	-70	150	73.1	17.9	40.0	-15.2	high
Net Infiltration	-75	75	29.4	36.2	-3.7	3.1	medium
Drain Leakance	-99	99	34.6	32.2	1.5	-0.9	negligible
Lake Leakance	-99	99	32.6	33.4	-0.5	0.3	negligible

*"High" Relative Sensitivity = 0.2 to 1.0, "Medium" Relative Sensitivity = 0.05 to 0.2, "Negligible" Relative Sensitivity = 0 to 0.05

Impact of LID on Net Infiltration and Groundwater

Net infiltration was calculated for all scenarios (Table 7). For pre-development scenarios net infiltration ranged from 185 mm, in the drought year, to 479 mm in the mean year. For the drought year, the post-development with conventional stormwater management net infiltration was 168 mm, whereas it was 189 mm in the LID scenario. For the mean hydrologic year, the post-development with conventional stormwater management net infiltration was 438 mm, and was 466 mm in the LID scenario.

From these results it can be seen that the impervious area added to the catchment area decreases net infiltration and that LID can be used to offset this effect with the provision of opportunities to enhance infiltration.

Aquifer recharge and the mean hydraulic head in the wells for pre- and post-development scenarios, under both mean and drought hydrologic conditions, are shown in Table 7 and Figure 5.

Table 7*. Net infiltration, aquifer recharge, mean head and change in mean well heads associated with pre-development hydrology, post-development land use with conventional stormwater management, and post-development land use with LID stormwater management, all under post development groundwater pumping conditions.*

Scenario	**Net infiltration (mm/year)**	**Aquifer recharge (mm/year)**	**Evapotranspiration (mm/year)**	**Mean head (m)**	**Change (m)**
Pre-development (1997)	185	174	548	17.4	--
Post-conventional (1997)	168	160	531	17.1	-0.3
Post-LID (1997)	189	172	538	17.3	-0.1
Pre-development (2003)	479	305	578	29.5	--
Post-	438	276	558	29.1	-0.4

conventional (2003)					
Post-LID (2003)	466	290	564	29.4	-0.1

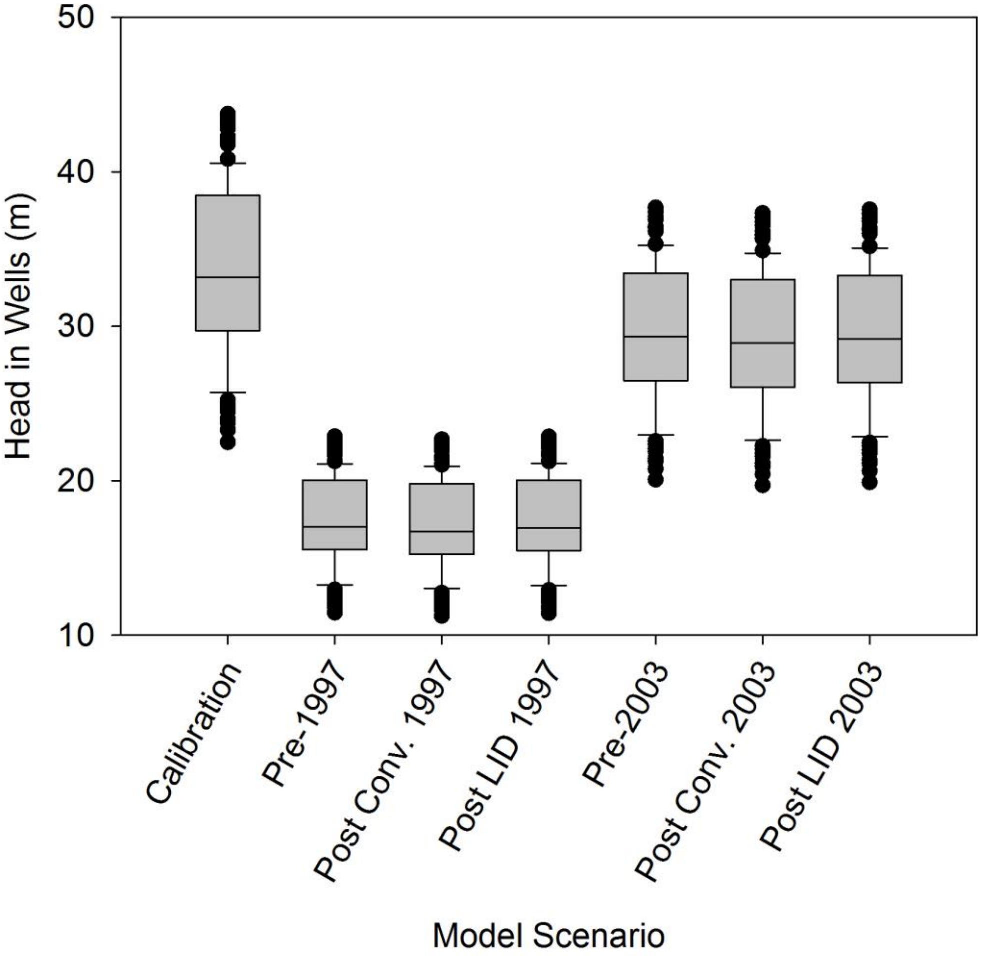

Figure 5. Distribution of hydraulic head in wells across the study area for each of the modeled scenarios and the calibration period.

Pre-development aquifer recharge values were found to range from 174 to 305 mm/year for drought and mean hydrologic conditions, respectively. For the drought year, post-development with conventional stormwater techniques caused the aquifer recharge to decrease to 160 mm/year. Conversely, LID practices caused an increase in aquifer recharge to 172 mm/year. For the mean hydrologic year, post-development resulted in aquifer recharge of 276 mm/year and 290 mm/year for conventional and LID stormwater techniques.

Under drought conditions net infiltration and aquifer recharge were close in value (*e.g.*, pre-development 185 to 174 mm/year, respectively). In this scenario the elevation of the water table was simulated to be below that of the stream for a portion of the year, and therefore lateral groundwater flow was decreased. Under such conditions, the outflowing stream would likely be ephemeral in nature. Under mean hydrologic conditions, aquifer recharge was 150+ mm lower than net infiltration due to the elevated water table which leads to larger amounts of lateral groundwater flow to the stream.

The implementation of LID practices was predicted to have a modest impact on groundwater levels under the projected groundwater pumping scenario (Table 7). The development of the landscape, and alteration of net infiltration, resulted in lower average hydraulic head throughout the study area under a groundwater pumping scenario. LID implementation was predicted to reduce the groundwater drawdown due to impervious area by 0.2 to 0.3 m. This effect of the LID practices may seem modest, but it should be noted that the conventional stormwater scenarios in this study were only predicted to produce additional drawdowns of <0.5 m even during drought conditions. In comparison Marchildon and Kassenaar (2013) modeled the impact of LID on groundwater recharge in a dense residential development in the Oak Ridges region of Ontario and determined that conventional stormwater practices would result in a groundwater elevation drawdown of greater than 4.5 m. They predicted that implementation of distributed LID features into the residential development was predicted to reduce groundwater drawdown to 1 m. Future studies could focus on examining a range of development scenarios, in varying geological environments, to identify specific situations in which LID would have significant positive benefits on groundwater availability.

Limitations of the Modeling Framework

The modeling framework presented in this paper provides a practical approach to evaluate the potential impacts of LID on groundwater processes. Coupling of the two models is straightforward but does require some intermediate processing of PCSWMM outputs in order to produce appropriate inputs to MODFLOW. PCSWMM is a versatile software tool that allows for explicit representation of a suite of LID features, but does have some limitations. PCSWMM is a semi-distributed watershed model, where individual residential lots would be simulated as lumped spatial entities. Hydrologic processes that would be occurring at smaller scales, such as groundwater mounding beneath LID features and internal lot drainage issues cannot be examined. Endreny and Collins (2009) and Gobel et al. 2004 both identified potential risks associated with groundwater mounding and building drainage when LID features are not properly sited. A fully distributed surface water-groundwater model would need to be used in order to evaluate these processes. In this study we predicted that net infiltration rates would actually be slightly higher in the LID development scenario versus the predevelopment scenario under drought conditions (Table 7), which may not be realistic given issues such as groundwater mounding and clogging of LID features.

There are also limitations associated with the use of PCSWMM for predicting net infiltration rates as it utilizes a relatively simple two-zone representation of the subsurface environment. Simple conceptual models are also employed to simulate evapotranspiration and the redistribution of water in the subsurface, which can also produce uncertainty in net infiltration estimates. In cold climates, such as those experienced in most of Canada and the Northern United States, alterations to soil hydraulic conductivity due to freezing and thawing would also have an impact on LID performance; these processes are not yet represented in PCSWMM.

The spatial distribution of net infiltration, and subsequently aquifer recharge, was simplified and not accounted for within our study. The PCSWMM model extent could be further discretized into more subbasins based on land-use and soils, to generate spatially varying net infiltration rates for input into MODFLOW. In this study, we also only performed steady state simulations of the groundwater system using MODFLOW. It would be useful to extend the modeling approach to conduct transient simulations of the groundwater system, and to examine intra-annual variability in aquifer recharge and groundwater levels.

CONCLUSIONS

This study provides the first comprehensive analysis of LID impacts in pre-and post-development conditions in the context of groundwater availability in a water-scarce aquifer region informed with substantial long-term baseline pre-development monitoring datasets. A novel approach to modeling LID effects on groundwater availability using two industry standard software packages is presented. The modeling framework consisted of a hydrologic model, PCSWMM, used to estimate net infiltration rates, which were then used as inputs to a groundwater flow model, MODFLOW. The calibrated models were used to simulate post-development conditions using either conventional stormwater management or LID features, , with the assumption that each residence would extract groundwater from private wells for domestic purposes.

Results of the study demonstrated that the inclusion of modestly sized LID features can be used to help restore aquifer recharge, which could be especially important for suburban developments which rely on groundwater for domestic water supplies in water scarce and low yield aquifers. Continued monitoring of the study area after development will allow for model validation of post-development conditions, and for assessment of the effects of LID features on other watershed characteristics such as surface water and groundwater quality.

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