Quantifying groundwater–surface water interactions at the hillslope scale, Havelock, Québec

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ABSTRACT
This paper presents preliminary results of a groundwater-surface water interaction study at the hillslope scale. Topographic, geologic, hydrogeologic and climatic data were analysed and a conceptual model for groundwater flow was developed. Characterization of the study area will contribute to the development and verification of representative coupled numerical models for simulating groundwater - surface water interactions.

RÉSUME
Cet article présente l'acquisition et l'analyse de données destinées à une étude des interactions entre les eaux de surface et les eaux souterraines à l'échelle locale. Des données topographiques, géologiques, hydrogéologiques et climatiques sont analysées et un modèle conceptuel pour l'écoulement souterrain est obtenu. La caractérisation du site à l'étude contribuera au développement de modèles numériques couplés représentatifs pour la simulation des interactions entre les eaux de surface et les eaux souterraines.

1 INTRODUCTION

The permanent interaction between surface water and groundwater are an important part of the water cycle at global and local scales. At the hillslope scale, the major groundwater–surface water (GW-SW) interaction processes are infiltration of precipitation or stream water, subsurface vertical and/or lateral flow through the vadose zone, recharge to the aquifer and subsequent groundwater seepage, and discharge through the hyporheic zone to local stream and lake beds. The magnitude of these processes and the flow dynamics in both downward and upward directions are controlled by the occurrence of pressure gradients and by the spatial distribution of the hydraulic conductivity (K) in the local media. With rapid urban development, the explosion of new wells, and increased use of groundwater for domestic, industrial and irrigation purposes, knowledge of the GW-SW interactions becomes a necessity for better management of water resources.

Sophocleous (2002) stressed the importance of multidisciplinary characterization of the GW-SW processes in order to represent their complexity. Comprehensive knowledge of the geology, topography and climate is thus fundamental for the identification and quantification of GW-SW interactions. Winter (1999) demonstrated the need to develop a regional physiographic framework with emphasis on climate, geology and water-table configuration impacts on GW-

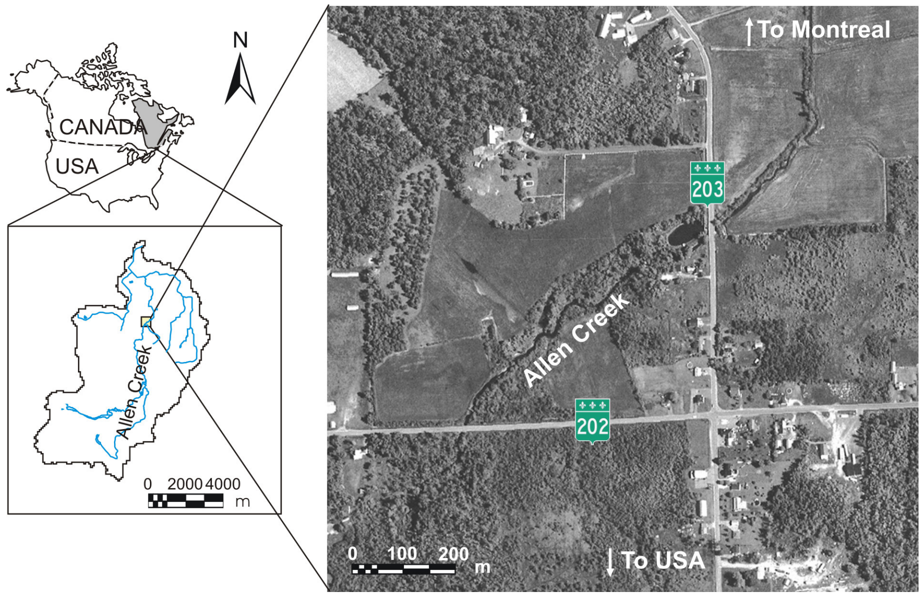

Figure 1. Study area location

SW interactions. Woessner (2000) also explained the relation between stream stage, stream geometry, channel orientation and groundwater exchange in the fluvial plain. A common theme in all of these reports was the need for a better understanding of GW-SW interactions.

Mathematical models of varying complexity for GW-SW flow have been developed in tandem with advances in field characterization of the interacting processes. For example, Fan and Bras (1998) proposed analytical solutions for hillslope subsurface storm flow and saturation overland flow. Recently more complex models for simulating flow and also contaminant transport in integrated surface-subsurface flow systems have been presented (e.g., VanderKwaak and Loague 2001; Panday and Huyakron 2004; Kollet and Maxwell 2006; Therrien and Sudicky 2006; Qu and Duffy 2007).

The present study focuses on quantifying recharge and stream flow at the hillslope scale from precipitation and temperature data through numerical modeling. Preliminary results are presented. The study area is described and stratigraphy and hydrogeological properties are characterized. Preliminary recharge results are obtained by analysis of in-well water levels and hydrograph separation. Finally, a conceptual model of groundwater flow is developed that will be used in the subsequent mathematical simulations.

2 STUDY AREA

The study area is located on the slopes of Covey Hill, some 50 km south of Montreal near the American border (Figure 1). It covers ~0.2 km^2 in the municipality of Havelock at the intersection of provincial roads 202 and 203. In a more regional sense, the study area is located at the contact of two distinct physiographic provinces: the southern margin of the St. Lawrence Lowlands platform and north-western margin of the Champlain Lowlands in the north, and the north-easter piedmont of the Adirondack uplands in the south.

The study area is mainly used as pastureland for cattle and is partly forested. Allen Creek, a small, moderate gradient stream, separates the study area into approximately equal halves and represents the local discharge zone (Figure 1). The terrain is undulating and locally sloping towards the creek. The drainage basin of the Allen Creek makes up part of the more regional flow originating at the Adirondack uplands and is directed to the St. Lawrence River. In most of the study area, Allen Creek flows over coarse sand, gravel and cobble bed material. At the up-gradient side of the study area, the bedrock is outcropping to sub-outcropping.

The unconsolidated sediments consist of glacial till of the last glaciation. Tremblay (2008) defines these unsorted glacial sediment as typically well compacted, gray (sometimes reddish), and carbonated. The grain size analyses show high silt content with varying portions of clay, sand, gravel and blocks. The fine silty matrix contributes to the relatively low hydraulic conductivity varying from 10^{-8} to 10^{-6} m/s (Tremblay 2008). At altitudes of approximately 160 meters above sea level (masl), the upper portion of the till was reworked by the Champlain Sea waves. It is identified as littoral sand and gravel with high capacity of retention and infiltration of precipitation water. In this case, the thickness and the compaction of the underlying intact till control the rate of water infiltration. These zones of reworked till are often left as pasture lands or shrub as they are not suited for agriculture.

The regional aquifers are found in the fractured Paleozoic sandstones (Nastev et al. 2007). The Covey Hill Formation of the Potsdam Group is composed of interbeds of locally conglomeratic fine to commonly coarse-grained quartz (>50%) and feldspar (<50%), with some mudrock and pebbles (Clark 1996). Compact beds are massive with a thickness of usually several tens of centimetres to a metre, but can also reach 2 m. In many places but mostly in lower beds, it can be conglomeratic with quartz pebbles as large as 2.5 cm and feldspar as large as 1.2 cm. This rock has many varieties: white, gray to reddish-brown due to the presence of iron minerals in the cementing materials. These minerals influence the groundwater quality as well. The cementation in Covey Hill sandstones varies from loose to strong, and rocks can occasionally be very poorly consolidated and friable. Its average regional hydraulic conductivity was defined in the range of $2x10^{-5}$ m/s with a log-variance of almost one order of magnitude, i.e. of 0.72 (Nastev et al. 2007)

3 FIELD WORK

Updated soil, surficial sediments and bedrock maps, a three dimensional stratigraphic model of the quaternary sediments, hydraulic transmissivity, and recharge estimates were evaluated at the 1:50000 scale during a recent regional hydrogeological study (Coté et al., 2006). Additional refinement of the available data was thus needed to account of the local site conditions. Field campaigns were carried out in summers 2006 and 2007. Field work consisted of geodetic surveying, soil and geological investigations, and installation of various monitoring equipment combined with digital data loggers. In this way, the study area was transformed into a field laboratory for testing and measurement of various parameters influencing the GW-SW interaction processes.

The geodetic surveys were carried out using a high-precision GPS-RTK (Real Time Kinematics) system. It provides a precision of ±1 cm in the vertical direction. More than 2000 point coordinates were measured on the slopes and along the creek. At inaccessible areas and areas where communication between the fixed station and the mobile receiver could not be established (dense shrub and woods, and deeper portions of the creek), altitudes were extracted from the existing regional Digital Elevation Model (DEM) with 10x10 m grid cell size.

Fourteen boreholes, with depths ranging from 2.5 to 13.0 m, and 7 shallow (≤ 2 m) test pits were excavated (Figure 2). They were used to define the stratigraphy of the unconsolidated sediments. Twelve boreholes, PZ1 through PZ6, were drilled along a NW-SE transect parallel to the assumed groundwater flow direction (perpendicular to the streamflow). Note that at five locations more than one borehole were drilled. The remaining two boreholes, PZ7 and PZ8, together with PZ5 form the second SW-NE transect parallel to the stream flow.

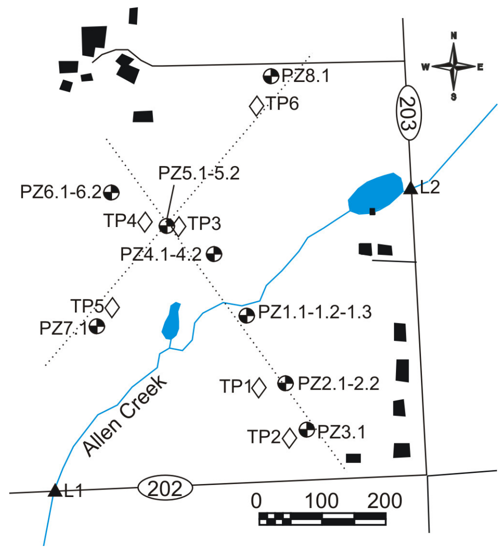

Figure 2. Test pit, borehole and limnimeter locations on the Havelock site. L stands for limnimeter, PZ stands for piezometer, and TP stands for test pit. Dashed lines show transect orientations.

All boreholes were transformed into piezometers for monitoring of the fluctuations of groundwater levels. At certain locations, piezometric nests were installed containing two (PZ2, PZ3, PZ4, PZ5 and PZ6) to three piezometers (PZ1). In this case, the different levels are indicated with additional numbers (starting from the greatest depth) 1, 2 and 3. The piezometers consist of 1.5 " PVC screened at the base over 1.5 or 3 m. Depending on the depth of the borehole, the piezometers intercept the unconsolidated sediments, the interface between sediments and bedrock, or the upper bedrock strata. For long-term monitoring, the digital water-level loggers installed in each piezometer were programmed to record on an hourly basis. Slug tests were also conducted to determine the hydraulic conductivity of the sediments adjacent to the screened section. Due to the small diameter of the PVC tubing, special 3/4" equipment for slug-testing had to be designed. The most representative drawdown curves were used for hydraulic conductivity computation.

Water level fluctuations in Allen Creek were monitored with two limnimeters installed upstream and downstream of the study area (Figure 2). To obtain flux data, rating curves were developed with velocity measurements. To avoid damage from frost, the digital dataloggers dedicated to each limnimeter were removed during the winter period. In this way representative stream-flux data were obtained only from mid April to October.

An on-site meteorological station was installed to monitor hourly temperature, atmospheric pressure and precipitation data.

In addition, two thermocouple chains for energy transfer measurements were installed in the streambed of Allen Creek. They will be used for temperature time-series analysis which should reveal more information on the seepage rate through the riverbed sediments. Six time domain reflectometry (TDR) probes were installed near PZ5 at depths varying from 15 to 100 cm for soil moisture measurements. Data from these sensors has not yet been collected and will not be discussed here. A Guelph permeameter campaign will be conducted in summer 2008 for better characterization of the permeability properties and infiltration in the top portion of the surficial sediments (0 to 30 cm).

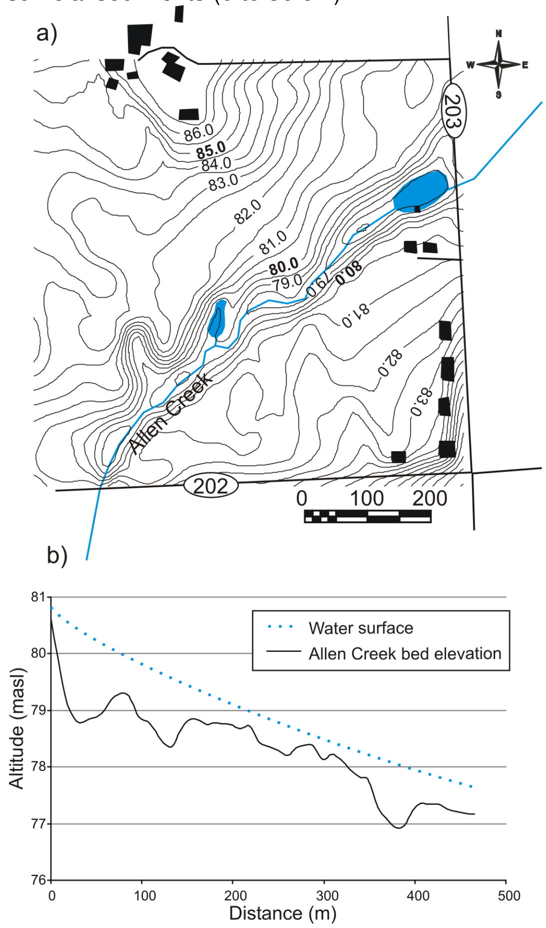

Figure 3. a) Digital Elevation Model of the study area b) Vertical profile along Allen Creek.

4 RESULTS

Interpretation of the collected field data is the first step towards building reliable numerical models to simulate GW-SW interactions at the study area.

4.1 Topography

A digital elevation model (DEM) was produced from the GPS measurements. The interpolation was carried out using the ordinary kriging with a linear variogram model. The grid cell size was fixed at 5x5 m. Kriging is a linear unbiased estimation method that honours the observed values where the quality of the interpolation depends on the distribution and the reliability of the measured data. Topographic isocontours obtained from the DEM are shown in Figure 3a. The altitudes in the study area vary between 76.9 and 88.0 masl. Allen Creek enters the study area at 80.5 masl, and the outlet is at 77.2 masl (Figure 3b). Stream flow slows down gradually as it approaches the outlet side. The total reach length is 480 m, which gives a moderate gradient of the surface water flow of 0.7%. The average hillslope gradient in the study area is 4.7% to the northwest, and 2.2% to the southeast. These are the slopes that runoff water takes to reach Allen Creek during significant precipitation events.

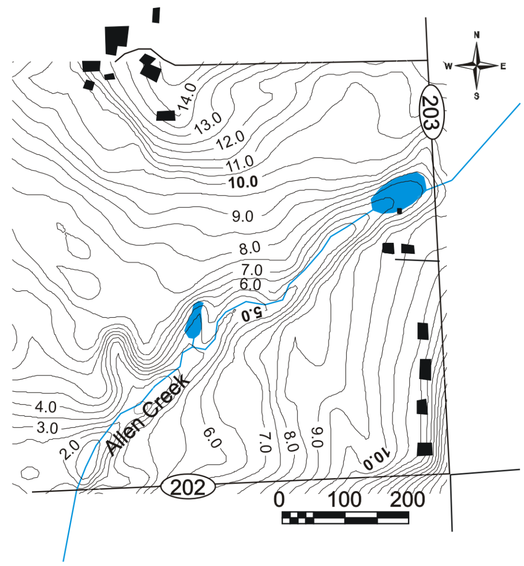

Figure 4. Thickness of unconsolidated sediments

Very little quantitative information on bedrock elevation was obtained from the boreholes reaching the bedrock (6) and from occasional rock sub-outcrops along upstream Allen Creek (2). Thus, only eight points were considered with known altitudes. Additional indirect information was obtained from Nastev et al. (2007), where Covey Hill sandstones were referred to as horizontal to sub-horizontal strata with average slopes of 1~2 %. This fact was used during the interpolation of the bedrock topography. A bilinear regression model was used because of the scarcity of known altitudes as it provides a smooth interpolation surface.

Once the bedrock surface was obtained, the thickness of the unconsolidated sediments was calculated by a simple extraction of the bedrock topography from the DEM of the ground surface (Figure 4). The deposit thickness is closely correlated to the DEM and extends from 0~0.5 m upstream of the downstream limnimeter to 14.5 m to the north. Based on the observed groundwater levels, the lower part of the sediments is permanently saturated, whereas the upper part is considered the vadose zone although during spring snowmelt it can also be under saturated conditions.

4.2 Stratigraphy

The stratigraphy controls the vertical and lateral flow of water. Test pits and boreholes confirmed the ubiquitous presence of glacial till. Soil observations are detailed in Table 1, whereas the simplified stratigraphic model is shown in Figure 5. Silt and sand matrix contain 20% to 80% of Potsdam sandstone fragments. The drainage capacity is generally good except for test pit P2 where poor drainage and shallow gleysol was encountered.

Table 1. Test pit results

Test pit	Soil type	Drainage	Gleysol depth (cm)
P1	Loam	Good to average	80
P2	Sand lying on silt	Poor	20
P3-P4	Sand lying on silt	Good	80
P5	Deep sand	Average	80
P6	Loam	Good	110

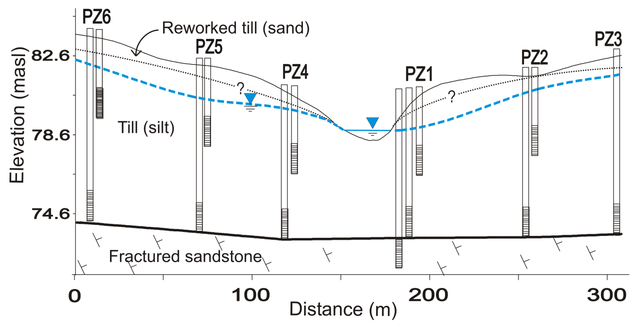

Figure 5. Simplified stratigraphy and observed piezometric levels on August 1st 2007

4.3 Hydraulic conductivity

Time-drawdown curves measured during the slug tests were analysed using the Bouwer-Rice and/or Hvorslev equations for unconfined aquifers (Kruseman and deRidder 1994). The Bouwer-Rice method applies to isotropic and homogenous aquifers with negligible specific storage and with small displacement when perturbed by a slug test. The Hvorslev equation assumes that the aquifer has infinite extent, horizontally and vertically. Both methods give similar results with a geometric average of the hydraulic conductivities (K) of 2×10^{-6} m/s for the glacial deposits, while the two tests conducted in Potsdam sandstone yielded a geometric average of 1×10^{-7} m/s. K values as a function of depth are presented in Figure 6. Glacial sediments show a wide variation in K. In the study area, the fractured sandstone appears to be less permeable than the overlying sediments.

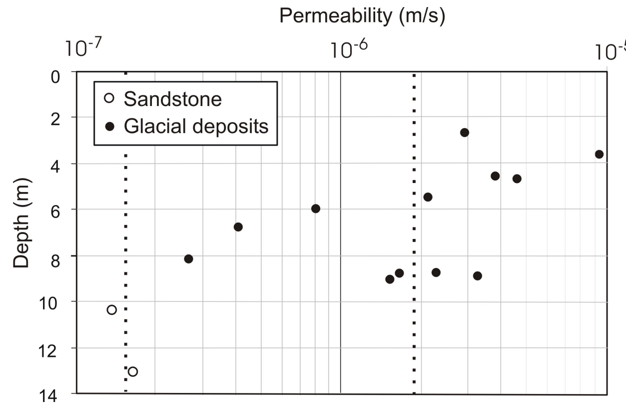

Figure 6. Hydraulic conductivities obtained from slug tests as a function of depth. Dashed lines are geometric averages.

4.4 Piezometry

The piezometric levels observed on August 1st 2007 are shown in Figure 5. The groundwater levels closely drape the topographic surface. Piezometric data for the rest of the year show similar patterns, which suggests that Allen Creek is a strictly gaining stream in the study area.

Water level fluctuations in monitoring wells intercepting the unconsolidated sediments are shown in Figure 7. Rainfall data are also presented for the same period. All records show an almost instant reaction to rainfall events which suggests relatively good infiltration characteristics of the surficial sediments. The only exception is PZ6.2, which shows a different behaviour. This is mainly due to the local lens of low permeability materials in which this piezometer is installed. The comparison of the measured groundwater levels in the piezometric nests indicates a general upward flow from the top of the bedrock to the ground surface. At the same time, shallow piezometers indicate water levels close to the ground surface and downward flow of infiltration water.

4.5 Preliminary recharge results

At this stage of the study, preliminary conclusions regarding the recharge on the study area are drawn using the Water Table Fluctuation method (Healy and Cook 2002). This method assumes that the rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Recharge is then calculated according to Eq. 1.

$$R = S_y dh / dt = S_y \Delta h / \Delta t \qquad [1]$$

where, S_y is the specific yield, h is the water table height and t is time. This equation has two unknowns, the recharge rate and the specific yield. For this study, the value of 4% was used for the specific yield. This method applies to dynamic and quick responding unconfined aquifers. For this reason, data from PZ6.2 was not used for recharge calculations as the water level fluctuations in this well are hardly related to precipitation.

Fluctuations of water levels with time were determined graphically from the data shown in Figure 7. Recharge was calculated individually for the four remaining piezometers of Figure 7. Average total recharge for the months of July and August 2007 is 127 mm with a standard deviation of 42 mm.

This method gives a rough first approximation of the recharge and introduces great uncertainty due to the estimated specific yield value and because the graphic interpretation is rather imprecise. The hydrograph separation method, which consists of separating measured stream flow into runoff and baseflow, will be used to calibrate the specific yield value. Also, the numerical simulations will provide another approximation of the recharge.

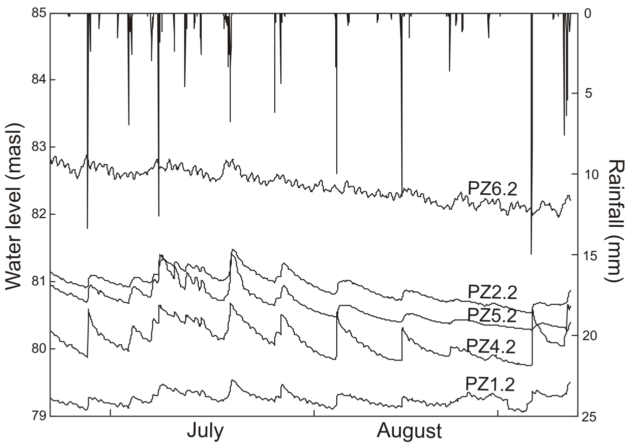

Figure 7. Fluctuation of groundwater levels and rainfall data in summer 2007

5 CONCEPTUAL MODEL FOR THE GROUNDWATER FLOW

The parameters discussed above helped develop a conceptual model for the groundwater flow system shown in Figure 8. Two aquifer units exist at the study area: bedrock and unconsolidated sediments. The groundwater flow in the bedrock makes up part of a more regional flow system which is recharged on Covey Hill, upgradient of the study area. In the unconsolidated sediment, local scale groundwater flow occurs. Observed piezometric levels suggest local infiltration of precipitation water (Figure 7). Thus, groundwater infiltrates the sediments more or less vertically from below (bedrock) and above (precipitation), it then flows laterally towards Allen Creek (Figure 8).

This conceptual model will have implications for subsequent simulations of the GW-SW interactions. The boundary conditions in the bedrock should be determined based on the regional piezometric levels. Boundary conditions in the unconsolidated sediments can be defined from the local water divides and observed groundwater levels.

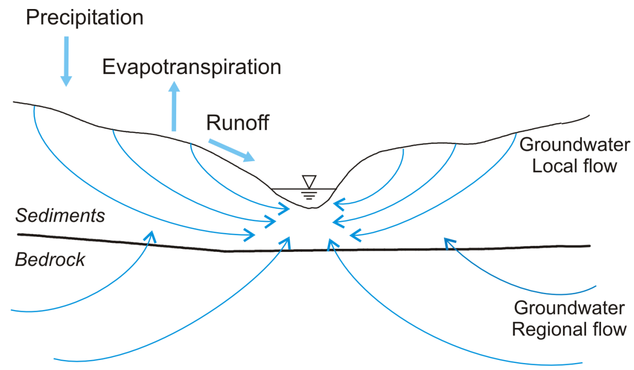

Figure 8. Conceptual model for groundwater flow

6 CONCLUSION

A local scale surface water–groundwater interaction study is underway at a hillslope study site in the municipality of Havelock, 50 km south of Montreal. It covers approximately 0.2 km^2 and consists mainly of Potsdam sandstones covered by glacial till. A DEM has been built based on detailed surveying of more than 2000 points. Fourteen piezometers were installed to monitor the fluctuation of the groundwater levels. Water levels in the creek, which represents a local discharge zone, are measured with two limnimeters installed up gradient and down gradient of the study area. At the same time, soil and geological investigation has been conducted based on test pits and boreholes observations.

Two aquifer units exist at the study area: bedrock and unconsolidated sediments consisting of reworked till at the surface and compact till at the base. Hydraulic tests indicate higher average hydraulic conductivity for the unconsolidated sediments (2×10^{-6} m/s) than for the sandstone rocks (1×10^{-7} m/s). Piezometric data indicate that Allen Creek is a gaining stream in the study area. The groundwater flow in the bedrock makes up part of a more regional flow which is recharged on Covey Hill, upgradient of the study area. In the unconsolidated sediment groundwater flow occurs locally. The developed conceptual model for groundwater flow suggests that groundwater infiltrates the sediments more or less vertically from below (bedrock) and above (precipitation). Groundwater then flows laterally towards the Allen Creek.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Lise Lamarche, a PhD student at INRS-ETE. The help of the local residents during the course of the field work is also gratefully acknowledged.

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