Using geophysical data to assess groundwater levels and the accuracy of a regional numerical flow model

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Abstract

The use of geophysical data to accurately determine water levels is demonstrated for an aquifer within the Saint-Narcisse moraine in the Mauricie region of southeastern Québec, Canada. Two numerical simulations were conducted using FEFLOW, one based on regional piezometric data and the other using geophysical data; the data were acquired through transient electromagnetic (TEM), electrical resistivity (ERT), and ground-penetrating radar (GPR) surveys. The three-dimensional geological and groundwater flow model was based on data from 94 boreholes, 5 stratigraphic cross-sections, and 20 TEM, 6 ERT (~1.44 km) and 4 GPR (~0.97 km) surveys. Both numerical analyses confirmed the simulated water levels, and the root mean square errors obtained from the piezometric data and the multiple geophysical techniques were similar at 3.81 m and 2.76 m, respectively. Through a discrete modeling approach, this study shows that groundwater levels estimated using geophysical tools and methods and those determined by direct observation are comparable. The outcome illustrates how geophysical data can complement direct observations to provide additional hydraulic information to hydrologic modellers. Geophysical surveys provide an extensive set of soft data that can be leveraged to improve groundwater flow models and determine groundwater levels, particularly in areas characterized by limited direct piezometric information.

Keywords: Canada, numerical modeling, geophysical methods, aquifer properties, groundwater monitoring

1. Introduction

Using three-dimensional (3D) groundwater flow models is now standard practice for managing water resources and visualizing flow scenarios through Quaternary deposits. Numerical modeling provides a cost-effective tool for several areas (e.g., engineering, environment, mining, water management; Shi and Polycarpou 2005; Dunlap and Tang 2006; Chesnaux et al. 2013; Lévesque et al. 2016; Lévesque et al. 2017) and can be used to improve the protection of aquifers and adequately manage groundwater resources (Calvache et al. 2009; Preisig et al. 2014; Hudon-Gagnon et al. 2015; Cui et al. 2021). The construction of 3D hydrogeological models is usually not a simple task and remains particularly challenging when attempting to accurately characterize the complex architecture of regional aquifers (Ross et al. 2005). Building a reliable 3D model of an aquifer ideally relies on combining multiple avenues of investigation, e.g., borehole data, geophysical data, and sedimentology. Various simplifications of the stratigraphic reconstruction and parameters (e.g., the complex entanglement of the stratigraphic units, grain size variation, anisotropy, and materials properties) are often necessary. However, groundwater flow models must aim to provide the highest level of representativity of the natural system being modeled (Allen et al. 2008), although the targeted accuracy of a numerical model relates directly to its primary purpose and use (Hudon-Gagnon et al. 2011, 2015). Regardless of model complexity, validating model performance is crucial for groundwater models because recharge, hydraulic conductivity, and other model inputs cannot be measured accurately (Hill 2006). Only after a proper validation against observational data can numerical models provide adequate information and be used as a decision-making tool to properly manage groundwater resources (Doherty 2003). A major problem for groundwater management using computer models is that the final model is undermined by uncertainty. If the model parameters (e.g., hydraulic conductivity, recharge) are uncertain, so are model predictions (Gallagher and Doherty 2007). Consequently, a significant difficulty encountered by modelers is the lack of availability of observational data to confirm a model's reliability in representing actual aquifer conditions. Observational data—obtained mainly from boreholes and piezometric data—are used to validate the model's performance; however, the limited availability and scarcity of these data, given the time-consuming and expensive nature of borehole drilling campaigns, often renders modeling inaccurate. Moreover, boreholes are generally limited in number with considerable distance between sites, hindering the establishment of a correlation among sites. Boreholes are also often located along roads and near accessible and urbanized areas. This non-uniform distribution can result in a poor distribution of data sites, further complicating the validation of a numerical model.

Because of the potential to have a relatively dense spatial coverage, geophysical surveys can provide a large set of soft data to help model these aquifers (Slater 2007). Furthermore, geophysical surveys can efficaciously investigate subsurface sediments and provide a non-invasive, inexpensive, and effective means of characterizing the internal dimensions of the aquifers and their stratigraphic variability. Geophysical techniques have proven their ability to improve the geological framework and hydrostratigraphic characterization of aquifers, including hydraulic properties, spatial extension, and flow paths (McClymont et al. 2010; Marker et al. 2015; Greggio et al. 2018; Kalisperi et al. 2018; Pondthai et al. 2020; Lévesque et al. 2021). Over the past decade, many studies have been conducted using geophysical data to improve the accuracy of numerical modeling by incorporating additional data. The extensive literature studying these hydrogeophysical approaches is reviewed by Binley et al. (2010) and briefly summarized here, highlighting what one might expect to be the dominant factors linking geophysics and hydrological model development. Some of these past studies use calibration to adjust hydrological model parameters to minimize the misfit between measured geophysical data and simulated variables (Gallagher and Doherty 2007; Huisman et al. 2010; Claes et al. 2020). Some authors go further and calibrate a physical-mathematical model of water flow to identify hydraulic properties and parameters of the vadose (unsaturated) zone (Binley and Beven 2003; Huisman et al. 2003; Farmani 2008; Binley et al. 2010; Yu et al. 2021). Several studies also demonstrate the ability of ground-penetrating radar (GPR) methods to enhance the estimation of the parameter distributions in the shallow subsurface (Kowalsky et al. 2004; Busch et al. 2013) or to estimate hydraulic parameters and propose approaches to validate if numerical experiments assume erroneous initial conditions (Tran et al. 2014; Yu et al. 2021). The ERT and GPR methods can also provide accurate hydrogeophysical parametrization for flooding events (Huisman et al. 2010) or capture heterogeneous soil properties and system states to assess and predict subsurface flow and contaminant transport (Kowalsky et al. 2005). Finally, some authors simply convert geophysical properties to observed hydrologic properties (e.g., water content) through a petrophysical relationship (Hinnell et al. 2010; Tran et al. 2014; Lévesque et al. 2021). Few of these studies apply multiple combined geophysical approaches to improve the accuracy of numerical modeling and, to the best of the authors' knowledge, water levels derived from multiple geophysical techniques have yet to be used to validate the reliability of a numerical hydrogeological model. Lévesque et al. (2021, 2022) recently developed methods to locate the water table more accurately by improving the geophysical interpretation of regional stratigraphy and piezometric levels. These new methods represent an effective means of augmenting the amount of data available to validate the numerical model's performance. In fact, when only one or a small number of geophysical methods are used to enhance numerical modeling, the information may be far from complete.

This study's main goals are to (1) accurately assess water levels and provide additional information to flow models by combining multiple geophysical techniques; and (2) demonstrate that groundwater levels obtained through direct observation and from geophysical data are comparable. Indeed, the combination of geophysical methods can provide a valid alternative to geological and piezometric data obtained from direct methods (drilling). The first validation of the model's performance (with boreholes) confirms the model's reliability for representing actual aquifer conditions and for subsequent simulations to evaluate the accuracy of geophysics-estimated data to confirm simulated water levels. The model's performance using both data sets is also compared through the root mean squared (RMS) error. Geophysical data were collected from the Saint-Narcisse moraine in eastern Mauricie (Québec, Canada) during the summer of 2020 and 2021. This data collection formed part of the *Groundwater Knowledge Acquisition Program* (PACES; Walter et al. 2018), sponsored by the Québec Ministry of the Environment (MDDELCC). Multiple surficial geophysical investigations, i.e., transient electromagnetic surveys (TEM), electrical resistivity tomography (ERT), and ground-penetrating radar (GPR), were applied to characterize this area of the Saint-Narcisse moraine aquifer. In addition to these collected geophysical data, the study included 94 boreholes, 5 stratigraphic cross-sections, and 26 piezometric surveys from the PACES spatial reference geodatabase for the study region (Chesnaux et al. 2011) to build the 3D geological model and validate reliability of the 3D flow model in representing real aquifer conditions.

2. Study area and geological overview

2.1. Basement geology

The study area is located in the southeastern portion of the Mauricie region, situated between Montréal and Québec City (Fig. 1), and is characterized by the Saint-Narcisse moraine cutting across the region. The study area overlies both the St. Lawrence Lowlands and the Grenville Province and is characterized by a relatively flat topography. To the north of the moraine lies the Grenville Province, the youngest province of this Precambrian Canadian Shield, comprising high-grade igneous and intrusive metamorphic rocks (Rivers et al. 1993). The lithologic composition of the Grenville Province varies depending on the area; anorthosite, mangerite, charnockite, orthogneiss, paragneiss, migmatite, and marble are the main rocks found near the study area (Cloutier et al. 2013; Légaré-Couture et al. 2018). St. Lawrence Platform, i.e., St. Lawrence Lowlands, composed of Paleozoic sedimentary rocks, lies in the southern portion of the study area. These Paleozoic rocks are composed of shales (Utica and Lorraine groups), carbonate (Trenton group), and Ordovician sandstone (Black River group), deposited in a marine environment (Occhietti 1977; Légaré-Couture et al. 2018). The St. Lawrence Platform is bordered to the southeast by the Appalachians and by the Canadian Shield to the northwest.

2.2. Quaternary sediment deposits and the Saint-Narcisse moraine

During the last glacial maximum (LGM), the LIS covered most of eastern Canada and produced glacial deposits composed mainly of diamicton, i.e., tills, by crushing, removing, and transporting rocks and sediments (Dyke 2004; Margold et al. 2015; Lévesque et al. 2019). Numerous frontal moraines produced during the deglacial phase record the often climate-related phases of LIS advance and retreat (Evans 2005; Benn and Evans 2010; Landry et al. 2012). The Saint-Narcisse morainic complex in eastern Canada is a remarkably well-preserved, discontinuous frontal moraine that is one of the longest documented frontal moraines in Canada (Daigneault and Occhietti 2006). This long ridge, composed of glacial sediments, extends nearly 1400 km (Daigneault and Occhietti 2006) with a thickness of up to 120 m, although it varies locally between 1 and 20 m (Occhietti 1977). Quaternary surface deposits associated with the Saint-Narcisse moraine in the Mauricie region are related to the last glaciation, i.e., Wisconsinan glaciation and consists of various sedimentary facies that make up its stratigraphic sections: proximal and distal glaciomarine deposits, juxtaglacial and fluvioglacial deposits, i.e., ice-marginal outwash, subglacial or melt-out tills, and till wedges (Occhietti 2007).

During deglaciation, the isostatic depression caused by the Laurentide ice sheet (LIS) combined with a rapid global rise in sea level led to a marine transgression and the incursion of the Champlain Sea into the southern Mauricie region. The sea flooded the valleys of the St. Lawrence Lowlands and led to deposits reflecting both shallow and deep marine environments, i.e., proximal and distal glaciomarine deposits. This marine transgression reached an elevation of about 200 m asl (i.e., above present-day sea level; Parent and Occhietti 1988; Parent and Occhietti 1999) and lasted over 1800 years (13–11.2 cal. ka BP). During the early Holocene, the isostatic rebound triggered a marine regression, and the Champlain Sea deposited regressive sands during its retreat. During this regression, the Champlain Sea also deposited a thick layer of clay covered by regressive sand in low-lying areas around the moraine. During the Younger Dryas readvance of the LIS, the Champlain Sea reworked the glacial tills set down during the LGM and deposited proximal glaciomarine sediments on the sides and on top of the moraine, i.e., at higher elevations (Dyke and Prest 1987; Parent and Occhietti 1988; Daigneault and Occhietti 2006; Occhietti 2007). The till and fluvioglacial deposits were reworked by waves and currents to form visible terraces on the seaward side of the moraine (Fig. 1). These terraces are essentially composed of coastal and sublittoral sands deposited in the shallowest areas of the Champlain Sea (Occhietti et al. 2001; Occhietti 2007; Légaré-Couture et al. 2018). This imposing glacial-sediment complex is partially confined on its sides by clay, thus retaining water inside the morainic system. This geological entity is a deposit known for its complex stratigraphy and heterogeneity; it is also known that the main depositional sequence resulted in a series of thick interbedded sand and sand-gravel layers overlying a discontinuous till over the bedrock.

Although the moraine extends over 1400 km, this project focuses on 8 km around the municipality of Saint-Narcisse, the moraine’s eponym. In this southeastern portion of the Mauricie region, the primary groundwater source is exploited locally to supply the surrounding municipalities, e.g., Saint-Narcisse, Saint-Prosper, and Saint-Maurice, attesting to the local aquifer capacity of the moraine.

3. Materials and methods

3.1. Data collection

Information for producing the 3D stratigraphic and 3D groundwater flow models for this section of the moraine aquifer relied on fieldwork and the compilation of existing regional data from the spatial reference database of the *Groundwater Knowledge Acquisition Program* (PACES; Chesnaux et al. 2011; Walter et al. 2018). Data from 94 boreholes and 26 piezometric surveys (from boreholes) were acquired from the existing geodatabase. Also, 5 stratigraphic cross-sections, 20 TEM surveys (i.e., 20 stations), 6 ERT surveys (~1.44 km), and 4 GPR surveys (~0.97 km) were obtained during the summers of 2020 and 2021.

3.2. Geophysical methods

3.2.1. Ground-penetrating radar (GPR)

GPR is a non-invasive geophysical method that uses electromagnetic waves to detect electrical discontinuities representing changes in subsurface materials (Beres Jr and Haeni 1991; Neal 2004; Reynolds 2011). In many aspects, GPR is analogous to sonar techniques and seismic reflection and works by the transmission, propagation, reflection, and reception of discrete pulses of high frequency (MHz) electromagnetic energy (Reynolds 1987; Davis and Annan 1989). This energy is transmitted into the ground, where it encounters materials of differing electrical properties, e.g., rock type, grain size, grain shape, porosity, pore-fluid electrical conductivity, and saturation. Variations in these properties lead to changes in the velocity of the propagating electromagnetic wave (Davis and Annan 1989; Baker 1991; Neal 2004). As the dielectric properties of unconsolidated sediments are primarily controlled by water content (Topp et al. 1980; Davis and Annan 1989), variations in porosity or the proportion of fluid occupying pore spaces significantly alter the velocity of the electromagnetic wave, thus producing reflections. GPR can provide accurate estimates (approximately to the meter) of water-table height (Neal 2004; Reynolds 2011). A sufficient contrast between the relative dielectric constant of unsaturated and saturated materials will cause a significant proportion of the energy emitted by the device to be reflected; the water table is displayed as a horizontal reflection having a large amplitude on radargrams. GPR data across the study area were collected in 2021 to locate the water table, covering approximately 0.97 km of completed surveys (Fig. 1).

For the GPR surveys, a MALÅ GX (Ground Explorer) GPR system manufactured by MALÅ Geoscience were operated (now ABEM/MALÅ) with a MALÅ Controller application and real-time interpretation support and cloud storage via MALÅ Vision. A 12-V battery powered the GPR, and two shielded antennae were used, i.e., MALÅ GX HDR antennae, at 160 and 500 MHz. A 160 MHz antenna was also used because it provided the depth range required to locate the water table (generally located between 1 and 5 m) in this area of the moraine and also offered the necessary vertical resolution (approximately 0.1 m). The 160 MHz antenna has a maximum depth penetration of 5 to 15 m, depending on the sediment's velocity. The GPR data were collected in a continuous recording mode with a real-time interpretation from MALÅ AI at two-way travel-time settings that varied between 50 and 200 ns. All radargrams were processed using the MALÅ Vision program, and mean velocity was assumed on the basis of the interpretation of the sedimentary facies described by Lévesque et al. (2021) for this area of the Saint-Narcisse moraine, $v = 0.065$ $\mathrm{m \cdot ns^{-1}}$ for saturated sand, and $v = 0.1$ $\mathrm{m \cdot ns^{-1}}$ for unsaturated sand. In fact, Lévesque et al. (2021) propose a stratigraphic calibration chart that links the sedimentary facies (i.e., clay, sand, sand-gravel), the associated electrical resistivity, and water content of the Saint-Narcisse moraine in Eastern-Mauricie. This chart, combined with the electrical resistivity values acquired using the TEM and the ERT, gives us a good overview of the type of sediment located on the subsurface. Consequently, it allows us to determine fairly accurate velocity data for most GPR sites.

3.2.2. Electrical resistivity tomography (ERT)

ERT is a geophysical method used to describe the intrinsic resistance of electric current flow in geological media and estimate the spatial distribution of the bulk electrical resistivity. The bulk electrical resistivity is mainly related to sediment/rock type, porosity, saturation, grain size, and pore-fluid electrical properties. This method detects the water table and the conductivity differences in water saturation below the ground surface (Loke 2000; Reynolds 2011). For this study, vertical electrical soundings (VES) of resistivity were undertaken using a Syscal Pro resistivity meter with a Wenner electrode configuration. The investigation depth of this instrument is about 45 m with 48 switchable electrodes, totaling 360 quadrupoles (Wenner arrays). Each resistivity profile consisted of a line of 48 electrodes, with 5 m spacing for a total length of 235 m. The least-squared inversion was processed using RES2DINV software to develop a model of subsurface resistivity, hereafter referred to as the true resistivity–depth profile (Loke and Barker 2006; Reynolds 2011). Outliers were removed from the data set before the final inversion (Loke 2006). The inversion required 3 to 5 iterations after the absolute error no longer changed significantly, and the results were less than 10%. The absolute error option displays the distribution of the percentage difference between the logarithms of the measured and calculated apparent resistivity values (Loke and Barker 1995, 2006; Loke 1999).

3.2.3. Transient electromagnetic induction (TEM)

TEM consists of a primary electromagnetic field (EMF) generated into a transmitter loop (Tx) of electrical wire deployed on the ground (20 × 20 m). As the primary field interacts with the subsurface geological materials, the decay of the EMF generates a secondary magnetic field that contains information about underground electrical properties. The TEM method does not involve direct electrical contact with the ground through electrodes and thus is effective in various environments, such as a glacial environment deposits (Parsekian et al. 2015; Kalisperi et al. 2018). The receptor loop (Rx; 5 × 5 m) is connected to a receptor that measures the rate of decay of the electromagnetic current, which is then inverted in electrical resistivity (Nabighian 1988; Fitterman and Labson 2005). Depth of investigation is determined by the size of the loop, the strength of the initial current, and the resistance of the subsoil. TEM surveys were undertaken using an NT-32 transmitter and a 32II multifunction GDP receiver (MacInnes and Raymond 2001). The NT-32 unit consists of a portable battery and a transmitter–receiver (TX-RX) console that operate a square-sized transmitter loop (Tx) and receiver loop (Rx; in-loop configuration) for the measured induced voltage. Once the data were acquired, they were inverted to deduce the subsurface apparent resistivity distribution. First, the raw data were averaged using TEMAVG Zonge software (MacInnes and Raymond 2001; MacInnes et al. 2001). This step also filtered inconsistent data points, i.e., outliers, that must be deleted before the inversion. The second step used STEMINV software (MacInnes and Raymond 2001; MacInnes et al. 2001) to produce a consistent 1D smoothed inversion model of electrical resistivity versus depth on the basis of the iterative Occam inversion scheme (Constable and Parker 1987). Finally, MODSECT software was used to build a 2D model using the 1D resistivity model acquired with STEMINV (MacInnes et al. 2001; MacInnes and Raymond 2001). MODSECT interpolates vertical columns with Catmul–Rom splines to visualize the geometry of the geoelectrical structure of each line.

For TEM and ERT surveys, the resistivity values were associated with unsaturated and saturated sediments, above and below the water table. The electric current circulates in the sediment, mainly by volume conduction (or electrolytic conduction) through the pore water of these sediments (Abu-Hassanein et al. 1996; Shukla and Yin 2006; Pandey et al. 2015). Consequently, above the water table, resistivity values are high and associated with unsaturated sediments, whereas below the water table, the associated resistivity values are much lower and are related to saturated sediments. The high contrast between different values of electrical resistivity (between unsaturated and saturated sediments) determines the location of the water table. When the resistivity values are greater than 1000 Ωm, the bedrock is reached because the electrical resistivity values of crystalline or sedimentary rocks are significantly higher than those of sediments. These rocks have resistivity values ranging between 1000 and 100,000 Ωm (Palacky 1993).

For ERT and GPR, the observed point-based locations were selected at the beginning and end of each 2D line. Additional observed points could also have been used at different distances along the 2D profile, but for a regional scale numerical model, these points being very close to each other, it was not necessary to add more. Indeed, the two extremities of a 2D profile (the greatest distance between the observation points) provided a suitable density of information. Each station serves as a location for the observed points for the TEM.

3.3. 3D modeling and model parameters

3.3.1. 3D groundwater flow model

The 3D groundwater flow was modeled using the FEFLOW® 7 modeling and simulating software. FEFLOW employs a finite-element numerical method, simulating groundwater flow by solving the basic balance equations in porous and fractured media for complex geometries (Diersch 2013). The finite-element method can easily incorporate properties such as anisotropy and heterogeneity or irregular and curved aquifer boundaries into the numerical model (Diersch 2013). Such particularities are typically observed in unconsolidated aquifers. This software allows modeling in 1D, 2D, or 3D in a steady or transient state and saturated (or not) conditions. In this case, the system is considered to be saturated. The simulations were undertaken using the free and movable surface mode and a steady-flow regime for an unconfined granular aquifer overlying the bedrock. The model also uses an adaptive grid, which allows the model surface to correspond to the elevation of the free surface, thus representing an unconfined aquifer.

3.3.2. *Stratigraphic reconstructions and the 3D geological model*

A discrete modeling approach was selected to build the 3D geological model and obtain an accurate and coherent computer representation of this Quaternary basin, covering an area of about 26 km^2. This stratigraphic reconstruction using Leapfrog Geo was necessary to provide a more detailed and realistic stratigraphic representation than possible via flow simulation software such as FEFLOW. This 3D geological model is easily exported from Leapfrog in interoperability mode with FEFLOW. The 3D geomodeling system Leapfrog Geo software package (ARANZ Geo Ltd.) was used for this part of the model development. This software is designed to build and analyze geologic objects and their properties. However, delineating confining layers and subsurface aquifers in these complex heterogeneous settings is challenging, and require an accurate stratigraphic reconstruction to build an accurate 3D flow model.

The modeling process began by determining the top boundary using a digital elevation model (DEM) produced with ArcGIS. Precise elevations (i.e., in meters) for each borehole, stratigraphic cross-section, and geophysical data were acquired, i.e., TEM, ERT, and GPR, to increase the precision in the top layers. To accurately determine the elevation, i.e., ~1 m, LiDAR, i.e., laser imaging detection and ranging data were used. Emphasized precise elevations are important to ensure that the obtained geophysical results and water-table elevations (acquired by piezometric surveys in the boreholes) were not erroneous and introduced bias and error into the numerical flow model. Then the upper surfaces of the sand and sand-gravel as the major units in the moraine were modeled (Fig. 2), a deposit known for its complex stratigraphy and heterogeneity. Simulated as a discontinuous layer between sand and bedrock, the till unit has a local maximum thickness of 25 m and an average thickness of 1 to 5 m (Occhietti 2007). A combination of bedrock and till units underlie this aquifer, although they are unevenly distributed. The sand unit directly overlies bedrock where there is no till. Each layer is constrained by an upper surface and a lower surface for a total of 4 layers (homogeneous), three of which are from Quaternary deposits, i.e., sand, tills, sand and gravel (Fig. 2). This stratigraphic reconstruction is simplified, and several critical parameters are not considered, including grain size variations and the complex entanglement of the stratigraphic units. Several authors as demonstrated that simplified models are often the most accurate, and modelers can simplify a model without significant loss of accuracy in the simulation (Benzaazoua et al. 2004; Hill 2006; Hudon-Gagnon et al. 2015; Doherty and Moore 2020). The hydraulic properties of the materials, i.e., hydraulic conductivity, porosity, and the grid, were integrated directly into Leapfrog Geo. Then, the hydrogeological limits were determined according to the boundary conditions necessary to build a numerical flow model, i.e., the Croche and Batiscan rivers to the east and west and two impermeable zones to the north and south (Fig. 1, Fig. 2). These impermeable zones are related to the thick layer of clay deposited by the Champlain Sea during the Holocene. A model layer comprised a grid of tetrahedral elements in both 2D and 3D, and the grid was refined at the model's edge for a total of 166,348 elements and 83,376 nodes. In Leapfrog, to build a 3D model, the modeler first needs to generate the meshing in a 2D model.

3.3.3. Model parameters and material properties

The parameters to calculate groundwater flow included the rate of groundwater recharge, the bottom and the top elevation of the aquifer, and the hydraulic conductivity, i.e., Kxx, Kyy, Kzz, respectively. Because many towns and villages in the southeastern Mauricie region use groundwater as a source of drinking water supply, there are a number of available hydrogeological consulting reports covering a large part of the region. These reports constitute an essential source of information regarding pumping test data, which have been used to assign hydraulic conductivity to the sediments/layers. The vertical hydraulic conductivity (Kzz) was set using 10% of the horizontal value (Kxx/Kyy; Table 1), according to a well-established rule of thumb (Hudon-Gagnon et al. 2015).

The recharge for the entire Saint-Narcisse moraine aquifer in southeastern Mauricie was set at 350 mm·year^{-1}. The recharge of the Mauricie region is well constrained because of the previous work of the PACES investigations in the Lanaudière and Mauricie regions of Québec (the PACES-LAMEMCN program; Chesnaux et al. 2011; Walter et al. 2018). An element investigated by PACES was the hydraulic connections between bedrock aquifers and the overlying granular aquifers. Boumaiza et al. (2022) calculated the recharge of the Mauricie region using a water budget approach (Steenhuis and Van der Molen 1986), which considers that the difference between the input and output fluxes of water in the aquifer system is equal to the change in water storage (Boumaiza et al. 2020, 2022). For this study area, the parameters used to calculate the recharge were the estimated vertical inflow from rainfall and snowmelt, the surface runoff (RuS), and the actual evapotranspiration (AET).

3.3.4. Boundary conditions

Boundary conditions are a crucial parameter for constraining the simulation. In FEFLOW, boundary conditions can be simulated according to various conditions: fixed-head boundary (Dirichlet conditions), fluid flux (Newman conditions), and fluid transfer (Cauchy conditions). In this study area, the model's northern and southern limits were considered impermeable (no-flow boundary related to clay) because the granular deposits, i.e., sand/sand and gravel, composing the moraine beyond these limits are not present in this area. The low flow of groundwater through the impermeable clay layer (i.e., in low-lying areas around the moraine, north and south) that overly the bedrock is considered unimportant for flow dynamics in the moraine aquifer system. The eastern and western boundaries of the model are considered fluid-transfer conditions, and the nodes are assigned/located along the Batiscan River to the east between 69 m and 11 m (i.e., elevation) and the Croche River to the west between 96 m and 52 m. The eastern and western limits are set at the Batiscan and Croche rivers, as the aquifer lies between these rivers and has a connection to them. Moreover, given the high contrast between hydraulic conductivity values in crystalline rock and granular deposits, the bedrock was considered as an impervious limit at the base of the moraine aquifer, which stretches across the whole model. A combination of bedrock and till units underlie this aquifer, and given that the till unit is discontinuous and unevenly distributed, the sand unit sometimes directly overlies the bedrock. The flow model did not consider groundwater pumping from municipal wells as these are not present in the study area. The private wells were not considered because of their negligible pumping rate at a regional scale, and their values are not precisely known.

4. Results

4.1. Geophysical results and the water table

All three geophysical methods clearly identified the water levels in saturated sediments (Fig. 3, Fig. 4, Fig. 5, Fig. S1 in the electronic supplementary material (ESM)). The water table elevation was often identifiable, as was the height of the bedrock when the survey was sufficiently deep. The uncertainty of water-level elevation was approximately 1 m when interpreted with the ERT raw data. From the diffusion equation related to electrical currents, the resolution of the resistivity method (ERT) decreases exponentially with depth (Loke and Barker 1995; Loke and Barker 1996; Loke 1999). However, it is nonetheless possible to determine a structure having a size of 1 m at a depth of less than 10 m (Loke and Barker 1995; Loke and Barker 1996; Loke 1999), a sufficient resolution to accurately determine water levels in this study.

The water table was clearly evident as a horizontal and continuous reflector on radargrams (Fig. 3, Fig. 4, Fig. 5, Fig. S1 in the ESM). The reflection arising from the water table may be seen clearly as a coherent reflection with a large amplitude in GPR12 and GPR13 (Fig. 5).

4.2. Modeling

4.2.1. Simulation results

A single groundwater model was developed for the unconfined aquifer of this section of the Saint-Narcisse moraine. The evaluation of model performance validates the quality and accuracy of a simulation performed by two flow models using observed and simulated results. The validation used regional groundwater level data determined through either borehole data or geophysical methods. To validate the performance of each model, a root mean square error (RMS; Equation 1) was calculated. In this study, the term "validate the performance of a model" (or "validation") means confirming the relevance of the results acquired from a numerical analysis using observed geophysical or piezometric data. In this study, geophysics-estimated groundwater levels also serve as observed data. The RMS acts as an indicator of modeling quality in terms of model precision and accuracy and indicates the reliability of the model in representing reality (Chesnaux et al. 2017; Dewar and Knight 2020).

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)} \tag{1}$$

where x is the difference between the simulated and observed groundwater levels, and n represents the number of observed values. The resulting numerical flow model from the simulation (Figs. 6 and 7) showed that the groundwater flows from the northwest topographic summit of the moraine toward the southeast. The hydraulic relationship between groundwater and rivers is strong, and the aquifer replenishes both the Croche and Batiscan rivers. The global water budget for the model produced a total regional flow of 17,684 $m^3 \cdot day^{-1}$ and an imbalance value (i.e., water mass balance) of -0.33 $m^3 \cdot day^{-1}$ for the study area. The imbalance value shows the numerical error of the mass transport for the specified subdomain over the entire simulation period. It is the difference between the change in model storage and net boundary fluxes by summing the mass amount of all boundaries, storage losses and gains, sources and sinks, and internal transfers. The imbalance value should be close to 0 (residual mass − balance error) to confirm that the simulation achieved good convergence and provided consistent results.

4.2.2. Comparison of numerical results with borehole data (piezometric surveys)

The study area contained a relatively high number (26) of piezometric surveys. The high number of boreholes for this relatively small area, i.e., 26 km^2, ensures a proper interpolation of static groundwater levels. The water table varied between 0 and 10.5 m below the ground surface, depending on the topographic elevation. An interpolated map of groundwater depth, i.e., piezometric map, of the Saint-Narcisse moraine in the Mauricie region was built by Lévesque et al. (2021), confirming the groundwater levels of this study. This map was created to define regional piezometry using a sizable number of evenly distributed piezometric surveys, i.e., 465 surveys, conducted on and around the Saint-Narcisse moraine. Then, the simulated hydraulic head, i.e., water-table elevation, was compared with the observed water levels from the 26 boreholes used to evaluate the model's performance and validate the quality and accuracy of the simulation (Table 2).

After validation, this model produced a RMS of 3.81 m (Fig. 8), a relatively low value indicating an acceptable degree of representativity (acceptable RMS value; Wise 2000; Chesnaux 2013; Chesnaux et al. 2017). The simulation results matched very well with the observational data (see Fig. 8 showing a good correlation between the simulated and observed values; $R^2 = 0.9994$). These results show the model's acceptable representativity to simulate the hydraulic head and underground flow within this portion of the Saint-Narcisse moraine.

4.2.3. Comparison of numerical results with geophysical results

Similar to the borehole data, the geophysical results produced a large amount of water depth–related data (Fig. 1, Fig. 3, Fig. 4, Fig. 5, Fig. S1 in the ESM). 33 inferences of groundwater depth were obtained through the three geophysical methods (Table 3). Access to some remote areas of the moraine was challenging to conduct geophysical surveys; therefore, the obtained survey data were not always evenly distributed, and the results contained gaps in the south–central and southwestern areas of the model.

After the validation of the quality and accuracy of the simulation (the model's performance), the simulated hydraulic head—compared with the water levels obtained using geophysics-estimated groundwater levels—produced a RMS of 2.76 m (Fig. 9), a low value indicating a reliable model, confirmed by the R^2 of 0.9989 for the correlation between the simulated and observed values. As observed with the borehole-based validation, the geophysical method–based model performance validation confirmed that the model represented reality and could be used to simulate the hydraulic head and underground flow in this region of the Saint-Narcisse moraine.

5. Discussion

5.1. Accurately assessing water levels using multiple geophysical approaches

In this study, geophysical data provided an excellent complement to direct observations (e.g., borehole logs, stratigraphic cross-sections, and piezometric surveys in wells) and were shown to be an effective alternative to borehole surveys for characterizing the internal structures of deposits, the water table, and flow directions. The coupling of the ERT and GPR results with the TEM results of Lévesque et al. (2021) allowed us to accurately estimate the groundwater level. Furthermore, these TEM surveys were validated using boreholes and piezometric surveys aimed at locating and delineating the aquifers of this portion of the Saint-Narcisse moraine and the associated water levels (Lévesque et al. 2021). The uncertainty of water-level elevation was approximately 1 m at a depth of less than 10 m for the ERT and TEM raw data (Loke and Barker 1995; Loke and Barker 1996; Loke 1999). All three geophysical methods identified the water levels in saturated sediments (Fig. 3, Fig. 4, Fig. 5, Fig. S1). By combining these different data sets, the uncertainty associated with the location of groundwater levels is significantly reduced and an additional tool to determine hydraulic heads for the numerical flow model is provided. Combining multiple geophysical techniques can significantly reduce the uncertainty inherent to geophysical methods, which are indirect observations of the subsurface. In the last decades, several contributions have used multiple geophysical techniques to complement direct observations. For example, Bowling et al. (2005, 2007) applied this approach to define conceptual geological models, and Bersezio et al. (2007) and Goutaland (2008) used multiple techniques to obtain a more complete analysis of sedimentary deposits and stratigraphic units. Combining multiple approaches allowed Costabel et al. (2017) and McClymont et al. (2011) to investigate the extent and depth of three freshwater lenses on North Sea islands and groundwater flow paths within proglacial moraine, respectively (McClymont et al. 2011; Costabel et al. 2017). Li et al. (2021) coupled TEM, nuclear magnetic resonance (NMR), and audio-frequency magnetotellurics (AMT) with stochastic groundwater modeling to predict the hydrological impact of a copper in situ recovery operation in the Kapunda region of South Australia (Li et al. 2021).

Combining multiple geophysical techniques to reduce uncertainty is critical because each method has its particular strengths and weaknesses. For example, TEM and ERT are often used; however, their resolution is sometimes not sufficiently fine to locate the water table precisely or characterize the sedimentary architecture. Thus, combining TEM and ERT with GPR allows us to reduce the amount of missing information between geophysical measurements, the water table, and sedimentary units. On the other hand, TEM and the ERT often provide information about the water table at greater depths, as well as the lithology of a sedimentary deposit, which the GPR cannot provide.

Unlike GPR, which is more suited to characterizing poorly conductive sediments, e.g., sands and/or gravels Bristow and Jol 2003), TEM and ERT produce a good resolution in conductive grounds but have the disadvantage of characterizing resistant soils with difficulty (Spies and Frischknecht

1991). Indeed, there is a loss of signal when electromagnetic waves generated by the GPR encounter conductive deposits such as clay, volcanic ash, and saline environments (Reynolds 2011; Pondthai et al. 2020). ERT works very well on resistive and conductive, e.g., silts and clays, sedimentary deposits (Baines et al. 2002), but contact with the electrodes can be problematic if the environment is highly resistant, e.g., dry sand, boulders, gravel, frozen ground, ice, or laterite. As observed by Reynolds (2011), “ERT relies on being able to apply current into the ground, and if the resistance of the current electrodes becomes anomalously high, the applied current may fall to zero, and the measurement will fail.” TEM and GPR may be more effective in this situation, as they operate without contact with the medium (Kalisperi et al. 2018). TEM and ERT can obtain results, i.e., water table summit depth, at greater depths because GPR surveys depend on the conductive property of the materials, and the maximum depths of investigation rarely go beyond 20 m (Beres Jr. and Haeni 1991; Asprion and Aigner 1997; Mari et al. 1998; Milsom 2003; Neal 2004; Gascoyne and Eriksen 2005). In contrast, TEM and ERT can be applied from a few to hundreds of meters in depth (Galazoulas et al. 2015; Kalisperi et al. 2018). The GPR and ERT methods provide vertical sections (2D) of the subsoil, but TEM profiles are produced through interpolations between 1D soundings, and the limitations of this approach bear uncertainty related to the interpolation and the smoothing. Moreover, TEM does not permit characterizing the top subsurface layers under the transmission/reception device, and a “blind” thickness of 1 to 3 m is present depending on the configuration of the sounding, i.e., the type of device used, the size of the coil, the intensity of the current injected (Goutaland 2008; Reynolds 2011). Geometric errors in transmitter–receiver positions and topographic effects can also skew TEM results (Reynolds 2011). For ERT, the closer the electrodes, the better the resolution (Reynolds 2011). To obtain a satisfactory resolution and desired depth, installing many electrodes over several hundred meters is necessary, but this approach requires greater resources and time.

Among these three geophysical approaches, the GPR was the most accurate for estimating the groundwater levels, given that the water table position was clear as a continuous, horizontal reflector having a large amplitude on radargrams (Figs. 3–5, Fig. S1 in the ESM). The reflection produced by the water table in GPR12 and GPR13 can be seen clearly as a coherent reflection with a large amplitude (Fig. 5). Thus, the water table and the sedimentary characteristics (e.g., sedimentary structures, lithologic limits, horizon with high organic matter content) generate radar reflections, and fine vertical decametric-scale resolutions are also visible on radargrams (Neal 2004). Because of the high dielectric permittivity of the water, the water table reflects a strong contrast between the propagation speeds of radar in saturated and unsaturated sediments. Reynold (2011), however, commented that the water table can be sometimes difficult to detect with GPR because a contrast in the relative dielectric constant is necessary to reflect a significant proportion of the energy. A thick capillary zone makes it more difficult to obtain a clear contrast between the unsaturated and saturated sediments, and the total reflected energy is diminished greatly; the resulting reflection amplitude is too low to clearly identify the water table.

The advantage of combining several geophysical methods is that the weaknesses of one method can be compensated by the other applied methods, especially if the complementary approaches are specifically chosen for this purpose. Multiple geophysical approaches—relying on various methods to collect data—and the amount of available geophysical data provided an opportunity to determine groundwater levels, and their combination significantly diminished the uncertainty of the results.

5.2. RMS and the validation of a numerical flow model with geophysical data

This study demonstrated that simulated water levels using multiple and combined geophysical approaches matched observed levels. The RMS obtained for the borehole-based validation of the model performance using piezometric data closely matched that of the geophysical method–based results at 3.81 m and 2.76 m, respectively. An ideal RMS value would theoretically be 0 m, signifying the model predicts exactly the observed water-level data with no difference between the observed and simulated water levels. The lower the RMS, the higher the accuracy of the model output to represent actual aquifer conditions. However, it is rare to obtain an RMS of 0 m because several parameters are to be considered, such as the uncertainties related to the seasonal variations in water levels at a regional scale, measurement errors, simplification of the stratigraphy, and the spatial heterogeneity of borehole distribution. For example, it is necessary to consider that the piezometric surveys were not all collected in the same season or during the same year, and there will necessarily be seasonal variations in water levels between spring and autumn or between different years. Indeed, northern regions (e.g., Québec and Canada) are characterized by high seasonal contrasts, and it is usual to observe water levels that vary by several meters depending on the season or the year.

In hydrogeology, an RMS better than a few meters cannot be expected and the results obtained for geophysical and borehole data are acceptable and represent well the natural variations of the water levels. For this reason, this steady-state model is considered to be of good quality. Nevertheless, even when a numerical model is accurate, modelers cannot expect to produce a true picture of the subsurface and hydrogeological processes because of the limitations and efficacy of the investigation tools. In reality, most models are too simple because they cannot represent the heterogeneity and the complexity of subsurface processes with perfect fidelity (Doherty and Moore 2020). Model success depends on the use and scale of the model in question, with the scale critical to the model’s required complexity and detail, "Learning how to define the optimal compromise between simplicity and complexity is one of the biggest challenges facing current modeling practice" (Doherty and Christensen 2011). A hydrogeological flow model at the local scale may require very precise data, whereas a regional-scale model can successfully determine water levels, confirm flow directions, or assess transit flows even with average deviations of a few meters. Theoretically, the larger the scale, the higher the RMS, given that the database must contain more data to fulfill the needs of the study (a larger surface to cover) and consequently, the numerical simulation will necessarily lose accuracy and precision. Therefore, larger-scale models naturally present greater possibilities of errors, inconsistencies, and uncertainty. For a steady-state numerical model at the regional scale such as this study model (~26 km^2), a deviation of 3 to 4 m is satisfactory and indicates the model's reliability in representing reality. The same RMS, however, may not be valid for more local applications.

To evaluate the reliability of the geophysical data to represent actual aquifer conditions, the same steps as for boreholes were used: a numerical simulation was conducted using FEFLOW® software and validate whether this model is suitable using multiple geophysical data sets (i.e., TEM, ERT, and GPR). The low RMS, i.e., 2.76 m, obtained after simulation with geophysically estimated data, suggests that the model is reliable in terms of accuracy and precision and is also consistent with the first validation of the model’s performance carried out using borehole data, i.e., a RMS of 3.81 m. Consequently, geophysical data are an excellent addition for validating a flow model to provide additional hydraulic information and complement direct observations (i.e., boreholes and piezometric surveys).

5.3. Available approaches to constrain a numerical flow model with geophysical data

Geophysical methods offer indirect observations of the subsurface. Consequently, they must be validated to confirm the subsurface information (in this case, groundwater depth). Several approaches are available to develop representative groundwater flows model and correctly locate the water levels using geophysical data. The first approach, as mentioned in section '*Accurately assessing water levels using multiple geophysical approaches'*, is detecting water levels using various geophysical techniques. In such a case, the acquired results related to groundwater depth from one geophysical method are compared with those obtained from another (or multiple) method for the same location. The second approach involves acquiring existing data from piezometric surveys (mainly from boreholes and private and municipal wells). As suggested by Lévesque et al. (2021), only a few boreholes and/or piezometric surveys are required to validate geophysical results and the true location of the water table. This validation approach involves comparing the stratigraphic and piezometric information with the geophysical results to derive an empirical and local petrophysical relationship. This correlation between direct and indirect observations allows extrapolating the results, i.e., water levels, over a larger area, even for zones lacking observational information. For example, borehole data—stratigraphy—can be correlated with electrical resistivity values acquired with TEM or ERT surveys for unsaturated and saturated Quaternary deposits. Then, the resistivity values associated with each class of sediment can be transposed to the geophysical data acquired in areas having no or limited drilling or piezometric surveys and thus extend the coverage of groundwater level estimates (Lévesque et al. 2021). If there are sufficient piezometric data from boreholes to validate the model directly, geophysical approaches can also provide an additional tool to acquire water levels, especially in remote areas. Geophysical data can therefore improve the accuracy of a numerical model by increasing the total data set, i.e., boreholes and geophysical data, to validate the simulated water levels. As mentioned by Hill (2000) in her "Guidelines for effective model calibration," the most important steps to develop a high-quality model are to apply the principle of parsimony (i.e., start very simple and build complexity slowly) and use a broad range of information (soft data) to constrain the problem (Hill 2000; Boumaiza et al. 2021). Indeed, using more data to validate the quality and accuracy of the simulation and eventually perform a calibration makes it easier to identify a model's shortcomings and improve and even correct these weaknesses. Correcting these shortcomings and improving the model's accuracy will necessarily affect the results, such as the flow direction, the hydraulic head, the global water budget, and the water balance. The results will be more accurate; the water mass balance will be closer to 0 to confirm that the simulation achieves good convergence and provides consistent results. The hydraulic head, the flow directions, and the global water budget will also be more accurate and more representative of reality.

Finally, for TEM, ERT, and GPR methods, a chart of electrical resistivity values (or relative dielectric permittivity for GPR) for saturated and unsaturated sediments can be helpful to detect the water levels in Quaternary deposits. Abrupt variations in electrical properties are generally associated with the boundary between saturated and unsaturated sediments, thereby identifying the water table. These charts link the sedimentary facies, i.e., clay, tills, sand, sand and gravel, and gravels, the associated electrical resistivity, and the water content (Reynolds 1987, 2011; Neal and Roberts 2000; Neal 2004; Lévesque et al. 2023). Lévesque et al. (2022) also demonstrated that although overlap of the electrical resistivity exists in the distributions between sediment classes, saturated and unsaturated sediment overlaps minimally for a given sediment class. Consequently, TEM and ERT can accurately identify the presence of water in Quaternary deposits and provide valuable information regarding water levels.

Moreover, the water table observed in radargrams, i.e., via GPR, is often clearly detectable as a coherent horizontal reflection with a large amplitude (Fig. 5; Reynolds 2011). If the capillary zone is thin, there is a sharp contrast in the relative dielectric constant between saturated and unsaturated sediments to reflect a significant proportion of the energy. Consequently, the reflection arising from the water table is clearly visible (Fig. 5; Reynolds 2011). Occasionally, the radargram reveals oblique reflections, i.e., stratification, associated with interfaces between sandy and clayey sediments or sandy layers of different grain sizes. Such southward-dipping reflectors were frequently observed in the Saint-Narcisse moraine (Fig. 5). These oblique reflections often indicate the flow directions at the origin of these structures (Cojan and Renard 2013) and can also be used to validate flow directions obtained from the numerical simulation. The dipping reflectors recorded in these surveys (Fig. 5) suggest that the current trend is from northwest to southeast, confirming the results from numerical modeling.

6. Conclusion

This study illustrated the relevance of using geophysical data to accurately assess water levels and provide additional information for flow models. Geophysical data can provide hydraulic information and a larger set of soft data to validate simulated water levels, especially in areas having limited direct piezometric observations. The need to ensure that model outputs match field measurements is often limited by cost, as acquiring field data in hydrogeology is expensive and time-consuming, particularly hard data such as boreholes and piezometers. Geophysical methods, including TEM, ERT, and GPR, provide an inexpensive, non-destructive, fast, robust, and effective means of characterizing the water levels, the internal dimensions, and stratigraphic variability of unconfined aquifers in data-sparse regions. This contribution provides the groundwater modeling community with a set of new tools to improve regional numerical flow models, which are essential for properly managing groundwater resources worldwide.

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FIGURE CAPTIONS:

Fig. 1 Regional topography of the study area and location of geophysical surveys and boreholes, i.e., piezometric surveys, acquired from the Saint-Narcisse moraine. The *dashed black line* represents the maximum extent of the numerical model proposed in this study; GM: 3D groundwater model, TEM: transient electromagnetic survey, ERT: electrical resistivity surveys, GPR: ground-penetrating radar surveys. The blue rectangle in the North America map (top left) represents the approximate location of the study area (not at scale).

Fig. 2 A simplified 3D geological model of the unconfined aquifer of the study area within the Saint-Narcisse moraine, southeastern Québec, depicting four layers of stratigraphic architecture. The model covers approximately 26 km². The vertical exaggeration 15×

Fig. 3a The interpreted 2D TEM Section TEM08 acquired from the study site along the Saint-Narcisse moraine, southeastern Québec. The surface deposit elevation was obtained from LiDAR data. The *blue dashed line* represents the projected water table obtained from direct observations (boreholes, piezometric surveys); **b** True resistivity–depth profile of ERT26 for the same location and water table (*blue dashed line*)

Fig. 4a The interpreted 2D TEM Section TEM16 acquired from the study site along the Saint-Narcisse moraine, southeastern Québec. The surface deposit elevation was obtained from LiDAR data. The *blue dashed line* represents the projected water table acquired from direct observations (boreholes, piezometric surveys); **b** True resistivity–depth profile of ERT20 for the same location and water table (*arrowheads*); **c** Radargram GPR01 acquired using 160 MHz antennae with a MALÅ GX (Ground Explorer) system for the same location. The water-table reflection is clearly visible at about 1 m depth (*arrowheads*)

Fig. 5 Radargrams acquired from the study site along the Saint-Narcisse moraine, southeastern Québec, using 160 MHz antennae and a MALÅ GX (Ground Explorer) system. The water-table reflection is clearly seen at about 4 m depth (*flat-lying reflection, arrowheads*) and multiple oblique southward-dipping reflectors

Fig. 6 The 3D flow model of the Saint-Narcisse moraine unconfined aquifer, southeastern Québec. Equipotential lines represent the simulated hydraulic head. The simulation results show a maximum hydraulic head in the northwest with a general southeastern flow

Fig. 7 Simulated equipotential lines of the hydraulic head over the study area along the Saint-Narcisse moraine in southeastern Québec. The simulation results show a maximum hydraulic head in the northwest with a general southeastern flow

Fig. 8 Root mean square error (RMS) of the hydraulic head from the numerical results (*simulated values*) and the borehole-based observed values (*observed values*) for the study site along the Saint-Narcisse moraine aquifer, southeastern Québec. The observed values were acquired from 26 boreholes (piezometric surveys). The *orange line* represents the line of perfect fit.

Fig. 9 Root mean square error (RMS) of the hydraulic head from the numerical results (*simulated values*) and the geophysical method–based observed values (*observed values*) for the study area along the Saint-Narcisse moraine aquifer, southeastern Québec. The observed values were acquired from 33 observations of water levels derived from transient electromagnetic (TEM), electrical resistivity (ERT), and ground-penetrating radar (GPR) surveys. The *orange line* represents the line of perfect fit.

Table 1 Properties of materials in the groundwater model of the Saint-Narcisse moraine. ø means that the bedrock was considered as an impervious limit at the base of the moraine aquifer.

Geological layer	Kxx and Kyy (m/d)	Kzz (m/d)
Sand and gravel	18.72	1.87
Sand (littoral and fluvioglacial)	4.72	0.47
Tills	1.52	0.15
Bedrock	ø	ø

Table 2 Hydraulic head in the study area acquired from 26 piezometric surveys of boreholes (observed) and numerical results (simulated)

Site ID	Borehole	Date of drilling	Observed head (m)	Simulated head (m)
1	S769	15-09-1981	112.04	114.49
2	S770	15-09-1981	114.64	115.70
3	S967	15-09-1983	103.81	105.23
4	S969	27-07-1982	77.75	75.13
5	S1012	23-09-1990	108.61	114.15
6	S1527	18-12-1987	84.89	86.14
7	S2067	26-05-2005	84.75	88.23
8	S2123	06-06-2005	61.54	65.28
9	S3050	17-04-2017	105.79	112.45
10	F2240	26-09-1990	112.42	115.21
11	F2241	26-09-1990	112.8	115.62
12	F2425	01-01-2002	117.46	119.54
13	F2426	01-01-2002	111.38	118.70
14	F2427	01-01-1987	116.12	117.13
15	F2430	01-01-1987	106.61	113.40
16	F2433	01-01-1987	105.97	113.22
17	F2424	01-01-1987	111.64	116.98
18	F2435	29-03-2007	115.35	117.34
19	F2438	29-03-2007	110.7	115.07
20	F2439	30-03-2007	114.21	115.94
21	F2440	30-03-2007	113.94	117.72
22	F2429	23-05-1985	116.79	114.56
23	YL017	21-08-2020	114	116.90
24	YL018	22-08-2020	109	109.71
25	YL022	23-08-2020	118	118.68
26	YL020	24-08-2020	115	113.84

Table 3 Hydraulic head in the study area as acquired from 33 observations of the groundwater depth on the basis of TEM, ERT, and GPR geophysical methods (observed) and numerical results (simulated). For each geophysical survey, the water level has been estimated to be at approximately the same elevation

Site ID	Station	Date of survey	Observed head (m)	Simulated head (m)
1	ERT20_1	21-08-2020	108	111.15
2	ERT20_48	21-08-2020	108	111.16
3	ERT23_1	22-08-2020	111	112.37
4	ERT23_48	22-08-2020	111	110.03
5	ERT25_48	14-10-2020	116	114.64
6	ERT26_1	14-10-2020	76	78.83
7	ERT26_48	14-10-2020	76	70.74
8	TEML8_1	14-08-2020	76	79.91
9	TEML8_2	14-08-2020	76	77.02
10	TEML8_3	14-08-2020	76	74.11
11	TEML8_4	14-08-2020	76	71.56
12	TEML13_2	22-08-2020	117	114.71
13	TEML13_3	22-08-2020	117	114.04
14	TEML14_1	22-08-2020	109	108.76
15	TEML14_2	22-08-2020	109	109.26
16	TEML14_3	22-08-2020	109	110.15
17	TEML15_1	15-10-2020	109	113.59
18	TEML15_2	15-10-2020	109	114.12
19	TEML16_1	15-10-2020	108	111.04
20	TEML16_2	15-10-2020	108	110.85
21	TEML16_3	15-10-2020	108	110.87
22	TEML16_4	15-10-2020	108	111.28
23	TEML17_1	16-10-2020	110	110.89
24	TEML17_2	16-10-2020	110	109.81
25	TEML17_3	16-10-2020	110	109.23
26	GPR1A	11-10-2021	108	111.95
27	GPR1B	11-10-2021	108	111.76
28	GPR4A	11-10-2021	118	117.09
29	GPR4B	11-10-2021	118	115.50
30	GPR12A	12-10-2021	79	76.64
31	GPR12B	12-10-2021	79	82.02
32	GPR13A	12-10-2021	84	88.60
33	GPR13B	12-10-2021	84	83.82

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