WATER BUDGET ANALYSIS OF THE PALEO-DELTAIC SAINT-HONORE AQUIFER IN THE SAGUENAY LOWLANDS

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ABSTRACT
The Saint-Honore aquifer consists of a deltaic flat plateau deposited on top of the Precambrian crystalline bedrock, either directly or over a thin layer of clay or glacial till. This aquifer is an important source of water supply for domestic, municipal and industrial purposes. It is also feeding numerous streams and surface water bodies. An hydrogeological study is conducted, including water budget and numerical flow analysis, in order to obtain a estimate of the water supply capacity of the Saint-Honore aquifer. The difference between *P* and *ET* is considered as a first estimate of recharge in this unconfined sandy aquifer, since overland flow is presumably very low. A water budget analysis is carried out for a large portion of the aquifer, using GIS and field data. A numerical flow model is being developed in order to analyse different scenarios of groundwater withdrawal rate under different recharge conditions. The model calibration is carried out using water level measurements in several piezometers, both in steady-state and transient regimes. Comparisons are made between simulated and estimated values of flow rate at outlet streams, allowing the extension of water budget analysis to the simulation results.

RÉSUMÉ
L'aquifère de Saint-Honoré consiste en un plateau deltaïque qui repose sur le socle cristallin Précambrien, soit directement ou sur une mince couche d'argile ou de till. L'eau de cet aquifère constitue une importante ressource utilisée à des fins domestiques, municipales et industrielles. Cette eau souterraine alimente aussi de nombreux cours d'eau et des lacs. Une étude hydrogéologique est actuellement en cours, incluant l'analyse du bilan hydrique et des simulations numériques, afin d'obtenir une estimation de la capacité de l'aquifère de Saint-Honoré. En première approximation, la différence entre *P* et *ET* est considérée comme la recharge de cet aquifère sablonneux à nappe libre, le ruissellement de surface étant présumé très faible. Un bilan hydrique est réalisé pour une grande portion de cet aquifère, en utilisant les données de terrain et des méthodes géomatiques. Un modèle numérique de l'écoulement dans cet aquifère a été développé dans le but d'analyser différents scénarios d'exploitation sous différentes conditions de recharge. Le modèle a été calé sur les niveaux d'eau mesurés dans plusieurs piézomètres, tant en régime permanent qu'en régime transitoire. La comparaison entre les valeurs simulées et mesurées du débit des cours d'eau drainant l'aquifère permet d'étendre l'analyse du bilan hydrique aux résultats des simulations.

1. INTRODUCTION

Determining a safe and sustainable yield of an aquifer requires the development of a water budget based on sound data on inflow and outflow quantities, and on a valid conceptual model of the aquifer. Unfortunately, most of the components of the water budget are either highly variable or affected by a high level of uncertainty; these components include evapotranspiration, aquifer storage, overland flow and groundwater discharge to surface streams (Alley *et al.*, 1999; Scanlon *et al*, 2002).

The Saint-Honore aquifer is a regionally important source of water supply for domestic, municipal and industrial purposes. Concerns about the quality and availability of this groundwater resource have motivated an hydrogeological study focusing on a water budget analysis. Such a study requires field measurements of key parameters of the water budget components, including precipitation, piezometric level and groundwater discharge rate. The particular geomorphology of this aquifer consisting of a flat sandy plateau demands that flow rate be measured at numerous stream outlets distributed around the downstream boundary of the aquifer. A well-calibrated numerical flow model allows the extension of a water budget analysis to different scenarios of groundwater recharge and withdrawal rates.

This paper 1) describes the study area, 2) explains the conceptual model based on geological and hydrological data, 3) presents a water budget analysis using GIS tools, and 4) reports on the development and the calibration of a numerical flow model of the Saint-Honore aquifer.

2. DESCRIPTION OF THE STUDY AREA

The study area is located in the northern part of the Saguenay lowlands between the town of Saint-Honore and the Valin River (Figure 1). This figure also shows the boundary of the vertical recharge area of the aquifer model developed in this study and presented below.

2.1 Physiography, vegetation and land use

A large portion of the study area is occupied by a flat sandy plateau that slopes gently to the southwest, and ends as a steep slope at its southern boundary. The primary land uses in this area are agriculture, sand pit extraction, an airport infrastructure and low-density residential zones. Together, those activities cover about 40% of the study area. Vegetation, mostly forest, covers the remaining land.

2.2 Geology and hydrogeology

Hydrogeological data on the Saint-Honore aquifer are provided by borehole logs for water supply investigations including CIE (1976), STES (1977), Hydrogeo-Sol (1999), and Laboratoires S.L. (2000). Recent additional data are provided by Laboratoires S.L. (pers. comm., 2003)

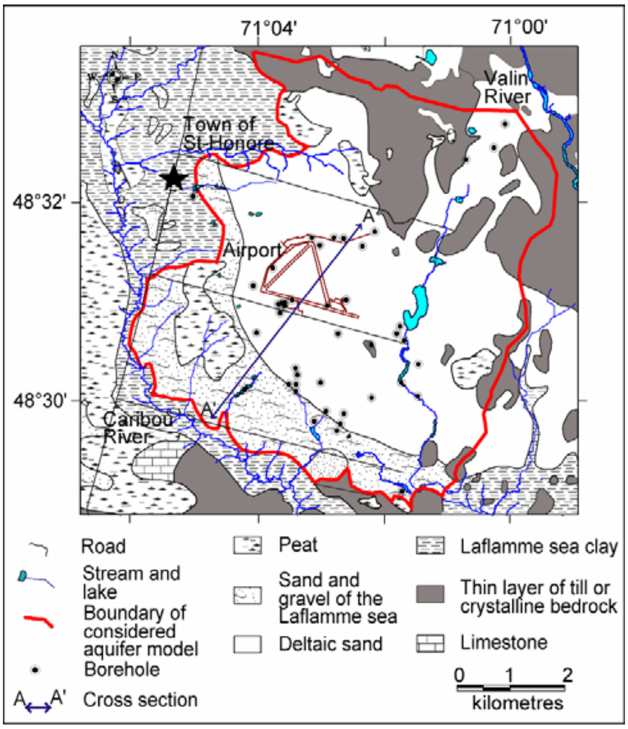

Figure 1. Map of the Quaternary deposits of the Saint-Honore aquifer, showing borehole locations (adapted from Lasalle and Tremblay, 1978).

The aquifer substratum is mainly composed of crystalline Precambrian bedrock, with a presumably low fracture density. Remnant layers of Ordovician limestone do outcrop at a few places at the southwest border of the study area. However, no borehole information indicates, as of yet, the presence of limestone on top of the crystalline bedrock underlaying the sandy aquifer.

The main body of the aquifer consists of a Quaternary deltaic structure deposited on top of the Precambrian crystalline bedrock, either directly or over a thin layer of clay or glacial till. The delta was created by a river flowing from the north, and discharging into the Laflamme Sea which has covered a large portion of the Saguenay lowlands at the end of the last glaciation.This structure is up to 50 m thick locally and it is primarily composed of unconsolidated sand and gravel. It was formed by a prograding delta, as suggested by the general spatial distribution of particle size, which tends to coarsen upward and to decrease from the north to the south (Figure 2). Important lateral variations are the results of a number of local-scale paleo-environments such as braided channels.

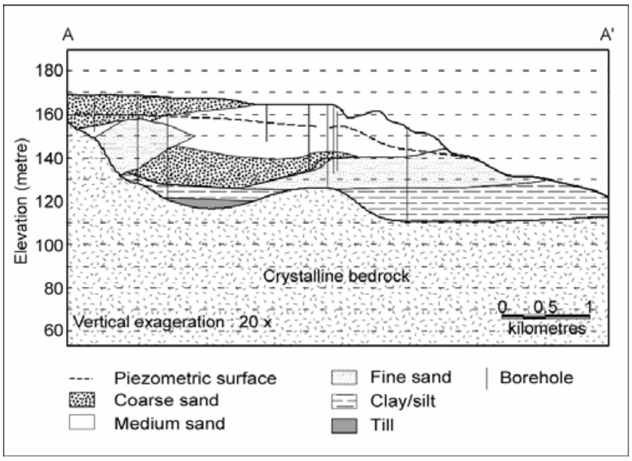

Figure 2. Schematic NE-SW cross section of the aquifer; location is shown in Figure 1.

2.3 Drainage features and streamflow

The plateau is bordered on three sides by valleys with the bottom occupied either by clay layers or by outcropping crystalline bedrock. The Caribou River is located to the west and the south of the plateau, and the Valin River (only partly show in Figure 1) to the east; these rivers discharge to the Saguenay River located three kilometres to the southeast of the study area. The plateau aquifer feeds numerous streams and surface water bodies; most of them located within the watershed of the Caribou River (Figure 1).

3. AQUIFER CONCEPTUAL MODEL

We have developed a conceptual model of the Saint-Honore aquifer in order to carry out a water budget analysis and groundwater flow simulation. This model is based on geological and borehole log data as described above, and on periodic field measurements of piezometric level and stream flowrate over a period of more than two years (Laboratoires S.L., pers. comm.). A geographic information system (GIS) that includes *MapInfo* (MapInfo, 2001), *Vertical Mapper* (NTI and MML, 2001) and *Discover* (Encom, 2001) has been used for the development of the conceptual model and for creating grids, which have been further imported in the numerical flow model described below.

3.1 Aquifer boundary

The Saint-Honore aquifer is constituted by a largely unconfined sand plateau that is draining in many directions, as described above. Our conceptual model considers a portion of this aquifer on which the available data allows a reasonable estimate of inflow and outflow parameters. This control portion of the aquifer covers a surface area of about 41.6 km^2 (Figure 1). The boundary of this area is the assumed lateral limits of recharge by vertical infiltration in the control portion of the aquifer. This boundary corresponds to the water divide of the watershed on the north and east sides, while on the south and west sides the limit is drawn at the contact line between the sand units and the underlying clay deposit which is considered impervious (Figure 1). The sand aquifer is also underlain in places directly by the crystalline bedrock or by a thin layer of glacial till. As a first approximation, it is assumed that no groundwater exchange is taking place either through the bedrock or with adjacent aquifer portions.

3.2 Piezometric surface

Water level measurements are periodically taken in about seventeen piezometers distributed over the control portion of the aquifer (Laboratoires S.L., pers. comm.). The general direction of groundwater flow is from northeast to southwest. The depth to the water table varies from less than one metre below the floor of sand pits to more than ten metres near the edge of the plateau. The piezometric surface is estimated for any given series of water level measurements, using a geostatistical interpolation method. An example of the resulting map of piezometric contours is presented below along with the results of numerical simulation.

The change in water storage in the aquifer between two dates corresponding to two series of water level measurements is estimated from the resulting piezometric surfaces. The change in saturated volume of aquifer is first estimated by substracting the piezometric surface at the beginning, from the surface at the end of the considered period. Then the change in water storage is estimated assuming an average value of the effective porosity of the aquifer material.

3.3 Recharge

Data on precipitation and potential evapotranspiration are obtained from the weather station at the Bagotville airport, located 15 km to the south of the study area. The average annual precipitation is 951 mm over the 30-year period from 1971 to 2000 (EC, 2003). The average value of potential evapotranspiration for the same 30-year period is about 514 mm, as estimated from the Thornwaite formula (EC, 2003). Actual evapotranspiration and its estimated values are discussed below, as a component of the water budget.

3.4 Discharge

The discharge from the Saint-Honore aquifer occurs in different ways, including evapotranspiration as mentioned above, spring discharge to streams and withdrawal at pumping wells.

Stream flow measurements are taken periodically at fourteen stations located at the western and southern border of the aquifer (Laboratoires S.L., pers. comm.). These outlet streams capture spring discharge from the aquifer as well as overland flow. As a first approximation, overland flow is assumed negligible over the flat sandy plateau of this aquifer; consequently, the summation of flow rate measured at the outlet streams provides an estimate of the total spring discharge from the aquifer. The yearly discharge at a given stream is obtained by integrating the data hydrograph over a 12-month period.

Groundwater withdrawal data from the Saint-Honore aquifer were provided by personal communications from the main users of this water resource, i.e. Niobec Mine, the Municipality of Saint-Honore and the City of Chicoutimi.

4. WATER BUDGET ANALYSIS

The water budget for the Saint-Honore aquifer can be written as:

$$P = ET + D + W + \Delta S \qquad [1]$$

and

$$\Delta S = S_{end} - S_{init} \qquad [2]$$

where P is precipitation; ET is the actual evapotranspiration; D is spring discharge through streams fed by both groundwater from the aquifer and a presumably negligible amount of overland flow; ΔS is the change in water storage in the aquifer; S_{end} is the stored volume at the end of the period; S_{init} is the stored volume at the beginning of the period; and W is groundwater withdrawal. All of the components of the water budget are expressed as a uniform depth of water over the surface area of the considered aquifer model (41.6 km^2).

The water budget analysis is carried out for two consecutive 12-month periods, from September 2001 to August 2002, and from September 2002 to August 2003. The values of the water budget components for these two 12-month periods are respectively (Table 1) 813 and 814 mm for total precipitation (P), 324 and 296 mm for total discharge to streams (D), 128 and 150 mm for groundwater withdrawal (W), and -42 and -59 mm for the change in groundwater storage (ΔS) assuming an effective porosity value of 30%.

The actual evapotranspiration (ET) is the only unknown in equation [1]; it is estimated at 403 and 427 mm respectively for the first and the second year of this water budget exercice. These estimated values of actual evapotranspiration are to be compared to the 30-year average estimate of potential evapotranspiration (514 mm) discussed above. The estimated values of *ET* are lower than the potential evapotranspiration; an expected result since the later neglects water scarcity periods that occurs every summer.

Table 1. Water budget components estimated from field measurements and computed from simulation results, expressed as water depth (mm).

Water budget component	Simulated		Estimated	
	First year	Second year	First year	Second year
Inflow:				
Precipitation	813	814	813	814
Outflow:				
Discharge to streams	404	283	324	296
Change in storage	-148	-7	-42	-59
Groundwater withdrawal	128	150	128	150
Actual evapotranspiration	429	388	403	427
Inflow – Outflow	0.03	0.02	0	0
Discrepancy (%)	10^{-4}	10^{-4}	0	0

5. GROUNDWATER FLOW SIMULATION

A numerical flow model of the Saint-Honore aquifer has been developed in order to analyse different scenarios of groundwater withdrawal rate under different recharge conditions, using both steady-state and transient flow regimes.

5.1 The numerical model

Annual average values are used in the steady-state simulations for the groundwater recharge rate, for potential evapotranspiration, and for the withdrawal rate at pumping wells; whereas the transient simulations consider monthly values of the same parameters. The simulations were carried out using *Visual MODFLOW v. 3.0.0* (WHI, 2002).

5.1.1 The grid and the boundary conditions

The numerical model considers a rectangular domain of about 9 km per 9 km. The model grid consists of five layers, each layer containing 11664 cells. The cell dimension varies from about 660 m² to 5950 m²; the smallest cells are located in two zones containing important pumping wells. The topography of the ground surface and of the bedrock topographies have both been imported from GIS created grids. The four upper layers represent the sand and clay units, whereas the bottom layer simulates the crystalline bedrock. The cells located at the border of the model and out of the aquifer bassin are designated as inactive cells.

5.1.2 Input values of hydraulic properties

The model domain was subdivided into five hydro-stratigraphic units corresponding to five zones of different hydraulic conductivity values (*K* zones): the crystalline bedrock, the Laflamme Sea clay, and three sand units, i.e. a coarse sand unit, a medium sand unit and a fine sand unit (Figure 3). The bottom low hydraulic conductivity boundary is consistant with the assumption of no significant groundwater exchange taking place through the Laflamme Sea clay or the crystalline bedrock. The input hydraulic conductivity values of the Laflamme Sea clay and the crystalline bedrock were fixed to $2x10^{-11}$ and $9x10^{-9}$ m/s, while the input specific yields of the same units were both assigned to 3%. The main aquifer body, i.e. the deltaic sand complex, is discretized into four model layers, except for a local clay lense located in layer 2 in the northwest part of the aquifer (Figure 3).

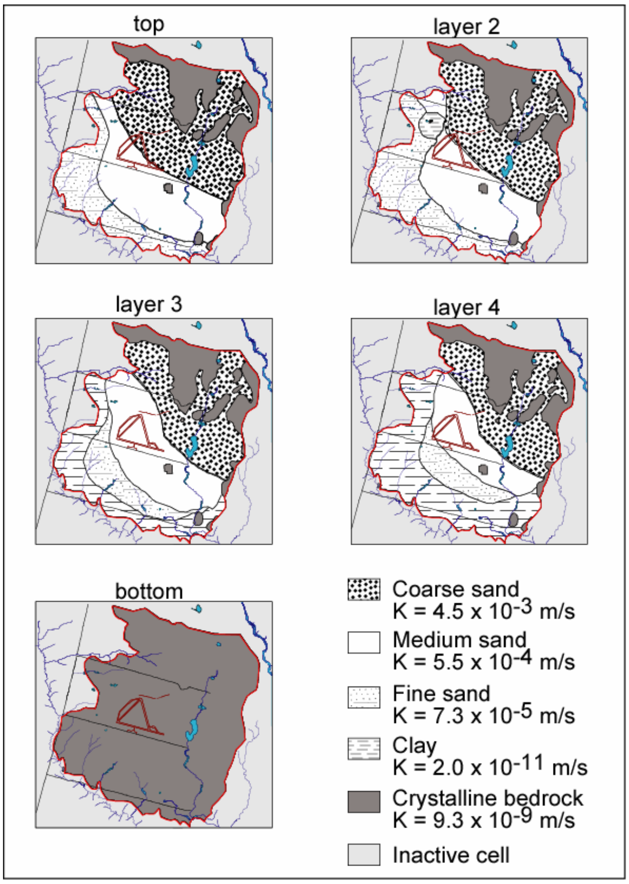

Figure 3. Distribution of hydraulic conductivity values in the five layers of the model.

Input values of hydraulic conductivity for the three sand units, as estimated from pumping test results (CIE, 1976; STES, 1977; Laboratoires S.L., 2000; Laboratoires S.L., pers.comm.), range from $5x10^{-6}$ to $3x10^{-3}$ m/s and input values of specific yield for the sand units were both assigned to 30%.

5.1.3 Aquifer recharge and discharge

Precipitation (*P*) and evapotranspiration (*ET*) rates for the steady-state simulation were set to the 30-year average values of *P* and potential *ET*, i.e. 951 and 514 mm per year respectively. Whereas the transient simulation made use of the actually measured values of *P* and the estimated values of potential *ET*, for every one-month stress period of the considered 24-month simulation period.

The aquifer discharge to streams was represented using the *Drain* package (McDonald et Harbaugh, 1988) by setting drains in stream channels where springs do occur. The drain conductance was estimated by model calibration.

Groundwater well withdrawals were simulated using the *Well* package (McDonald et Harbaugh, 1988). Groundwater withdrawal rates were set to the average annual rates for the steady-state simulation, whereas monthly rates were applied for every one-month stress period for the transient simulation.

5.2 Model calibration

Model calibration was carried out by varying the hydraulic conductivity values and the spatial distribution of the *K* zones corresponding to the sand units, in order to obtain a reasonable fit with observed values of hydraulic head and flow rate at outlet streams. The level of refinement of the *K* zoning is considered suitable to the available field data; the resulting calibration accuracy, as shown in Figure 3, appears appropriate for the purposes of this study. Different calibration procedures were adopted for the steady-state and for the transient flow regimes simulations.

5.2.1 Steady-state simulation

The purpose of the steady-state simulation was to reproduce the average flow conditions for one year.

A calibration criterion included matching water level measurements in thirty-one observation wells. The resulting calibration was considered adequate, as the residual mean and the absolute residual mean are respectively 0.45 and 1.40 m; the normalized root mean squared error is 5.71%. A linear regression analysis of the simulated and observed values of hydraulic head for all of the observation wells yields a coefficient of correlation of 0.98 (Figure 4). Most of the points are located into or on the edge of the 95 % confidence interval.

5.2.2 Transient simulation

The piezometric surface calculated from the steady-state simulation established initial conditions for the transient flow simulation. The calibration of the transient flow model was based on records of periodic water level measurements in seventeen piezometers over twenty-four months. Each month was considered as a stress period, with specified values of recharge and discharge rates, for a total of twenty-four stress periods. At the end of the two years transient simulation, the residual mean and the absolute residual mean are respectively 0.24 and 1.24 m, and the normalized root mean squared error is 5.38%. A linear regression analysis of simulated and observed values of hydraulic head for the seventeen observation wells yields a coefficient of correlation of 0.98.

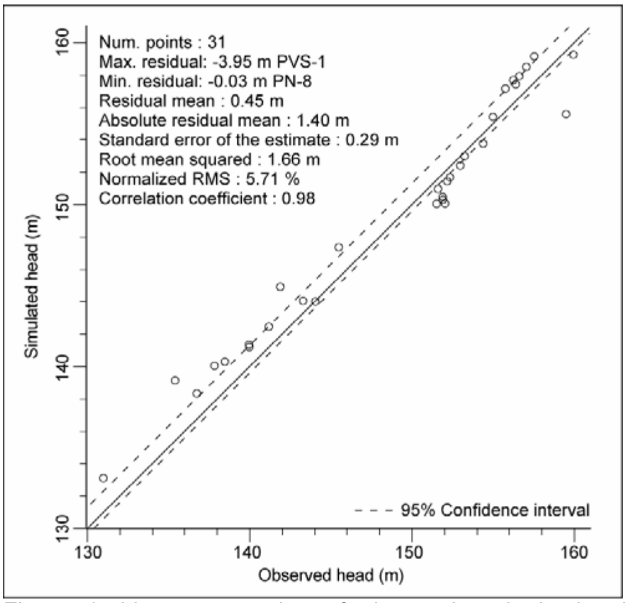

Figure 4. Linear regression of observed and simulated values of hydraulic head for all of the thirty-one observation wells

A second calibration criterion for the transient simulation was that the simulated piezometric surface and the hydraulic gradient match the estimated average values obtained by geostatistical interpolation from field data. Figure 5 presents a comparison between the piezometric surface calculated at the end of the two-year transient simulation period, and the piezometric surface estimated by geostatistical interpolation from field data collected at the corresponding time in the seventeen considered observation wells. This figure shows an acceptable correspondence between the transient simulation results and the piezometric surface estimated from field data, particularly for the contours lines ranging from 135 to 160 m. As expected, the areas of the aquifer that are equipped with piezometers show a better match between the piezometric surfaces than areas without information such as the area of outcropping crystalline bedrock in the northern part of the simulated domain.

A third calibration criterion consisted of reproducing the time-varying hydrographs for seventeen observation wells from the two years records of water level measurements. Three of those seventeen observation wells, P-7, PZ-16 and PZ-1, are located in Figure 5. The general trend of the simulated hydraulic head matches reasonably well that of the measured hydrographs, as shown in Figures 6, 7 and 8. Both the simulated and the measured hydrographs show a general decrease of the water table level during the two-year period considered in this study. This general decrease of the level of the water table could be related to the precipitations being lower than the 30-year average during the two considered consecutive 12-month periods.

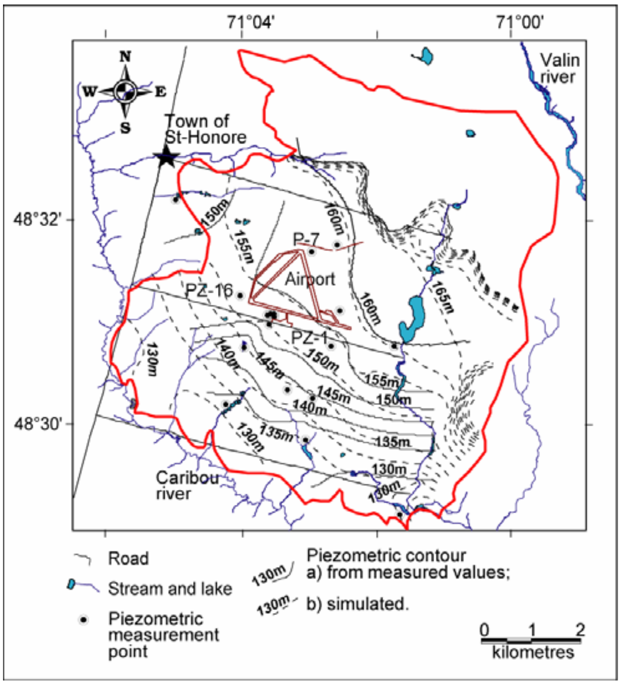

Figure 5. Comparaison between the simulated piezometric surface at the end of the two-years transient simulation period, and the piezometric surface estimated at the corresponding time by geostatistical interpolation from field data.

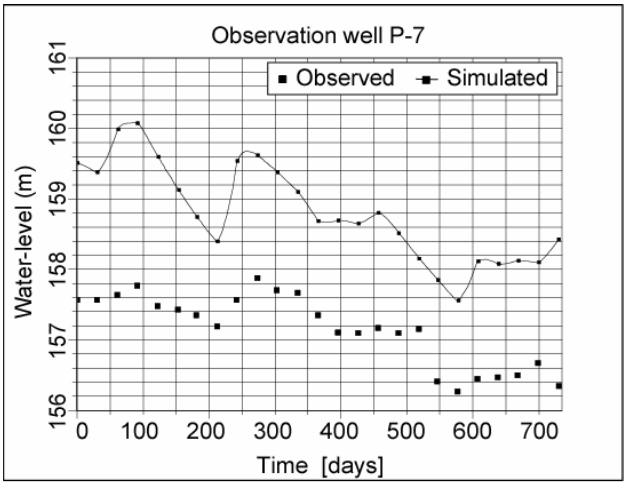

Figure 6. Hydrographs showing the simulated and the observed water level at piezometer P-7

The hydrographs of piezometer P-7 (Figure 6) show a good correlation between the observed and simulated general trends, in spite of a systematic overestimation of the simulated water level. This systematic overestimation may be due to the proximity of an important pumping zone. This observation suggests that a further grid refinement could improve the calibration results for this sector. The hydrographs of piezometers PZ-16 et PZ-1 (Figures 7 and 8) show that a better correlation between numerical results and field data are obtained away from pumping wells. All of the simulated hydrographs show fluctuations with a higher amplitude than the observed ones. This discrepancy could be due to the low accuracy of the specific storage values used in the simulations.

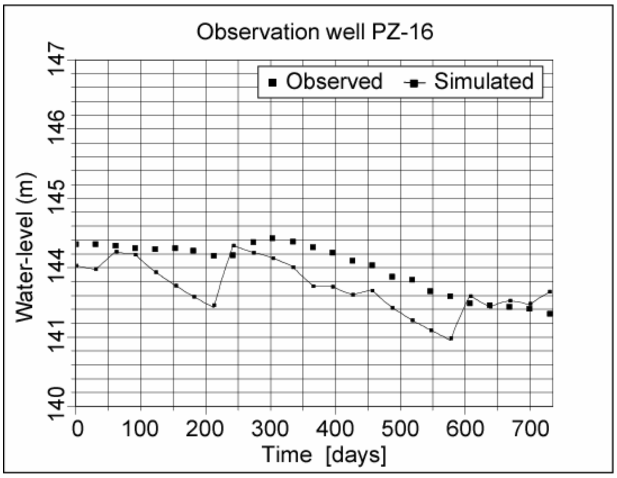

Figure 7. Hydrographs showing the simulated and the observed water level at piezometer PZ-16

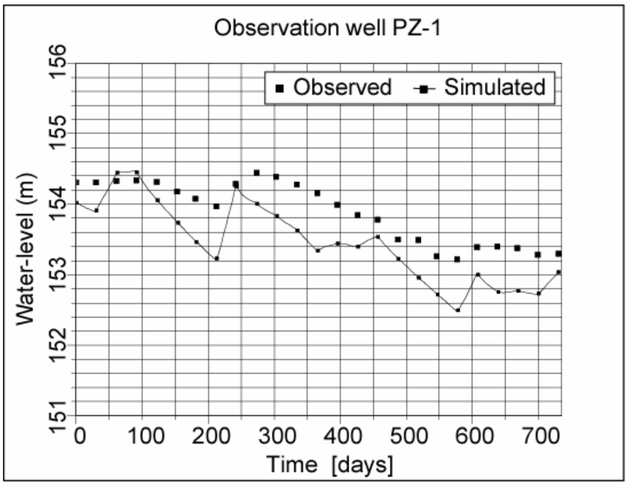

Figure 8. Hydrographs showing the simulated and the observed water level at piezometer PZ-1

6. DISCUSSION

Numerous hypothesis are implicitly or explicitly assumed in the various phases of this study, as in any hydrogeological investigation requiring the development of a model of an aquifer system. We discuss here a number of these assumptions and their effects on the interpretation of the results.

Overland flow is assumed to be very low; consequently the difference between precipitation (*P)* and actual evapotranspiration (*ET)* is considered as the recharge in this flat unconfined sandy aquifer. This assumption neglects particular events, such as a relatively rapid snow melt, that could result in significant overland flow.

The conceptual model of the portion of the aquifer that is considered in the water budget analysis assumes that no groundwater exchange is taking place through the crystalline bedrock underlying the sandy aquifer. The available data do not support any field estimate of the hydraulic properties of the bedrock units. However the presence of geological structures, such as a fault or a shear zone, could create an hydraulic connection between the sand aquifer and other aquifer systems, resulting in significant amount of inflow or outflow that would affect the water budget of the aquifer.

The numerical model of groundwater flow in the Saint-Honore aquifer is used to test selected hypothesis assumed in the water budget analysis, particularly concerning the aquifer boundaries, the recharge and the quantity of water circulating through the aquifer. Table 1 compares the values of the water budget components as estimated by the water budget analysis based on field data, and as computed by the transient simulation. The values of the aquifer discharge to streams obtained from the simulations, (404 and 283 mm) are comparable to the field estimated values (324 and 296 mm). The change in groundwater storage is significant, both in the simulated and in the field estimated water budget. The values of potential evapotranspiration (*ET*) obtained from the transient simulations are 429 et 388 mm for the first and second years respectively, as compared to 403 and 427 mm estimated from the water budget analysis. In both cases, these values of actual *ET* are lower than the 30-year average estimated value of potential *ET* (514 mm; EC, 2003), which is expected. The causes of these various discrepancies could be numerous, including inaccuracies in the conceptual model, in the boundary conditions, in hydraulic stress values and in the hydraulic properties of the aquifer and aquitard units.

7. CONCLUSION

The conceptual model of the Saint-Honore aquifer that is presented here is considered appropriate in spite of the numerous simplifying assumptions used for its development. A water budget exercice has been conducted for two consecutive 12-month periods; the annual values of actual evapotranspiration (*ET*) thus obtained are 403 and 427 mm, for total precipitation (*P*) values of 813 and 814 mm during the respective periods. These actual *ET* values are lower than the 30-year average value of 514 mm, as expected. The precipitation values are also significantly lower than the 30-year average value of 951 mm.

The numerical model of groundwater flow in the Saint-Honore aquifer has been calibrated both in steady-state and in transient flow regimes. Model calibration was carried out by varying the hydraulic conductivity values in the model within plausible ranges, in order to produce the best fit between simulated and observed hydraulic heads. Water level measurements in thirty-one observation wells were considered for calibration of the steady-state model, whereas seventeen piezometers with a two-years water level record were used for the calibration of the transient model.

The results of the transient flow simulation are in line with the water budget analysis based on field data, both carried out during the same two-year period (table 1). Also, simulated hydrographs for seventeen observation wells reproduce fairly well the two years records of water level measurements. This calibrated numerical model could be used as a predictive tool in order to analyse different scenarios of groundwater recharge and withdrawal

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