Regional Groundwater Flow Modeling of the Chalk Aquifer of Beauvais, Paris Basin, North of France

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Abstract: In this paper, a regional model to assess groundwater resources of the shallow groundwater system of Beauvais in the North of France has been satisfactorily completed using geophysical surveys and numerical modeling using MODFLOW-2000. A three-dimensional flow model has been developed for this aquifer using a large amount of available geological and hydrological data. The numerical flow model was calibrated and validated with datasets during 1998–2010. The calibration was done both by the automated parameter PEST and by the trial and error process. The main objective is to quantify the components of the groundwater mass balance, to estimate the hydraulic conductivity distribution and to characterize the hydrologic system. Furthermore, MODFLOW model was used to estimate the recharge, discharge, base flow and water Table fluctuation. Numerical simulations indicate that the Canada lake, located in the Thérain valley, acts as a most discharge area for regional groundwater flow. Groundwater inflow from the recharge from Beauvais plateau which is mainly due to precipitation supplies the aquifer with most of its water. Following the calibration process, a sensitivity analysis was carried out. The results show that the aquifer exhibits the highest sensibility to the recharge parameters changes and hydraulic conductivity. The impact of the changes for both these hydraulic parameters appears to differ from large decrease to large increase in total groundwater discharge. The delicate shifts in the groundwater systems, which cause the changes in the recharge and discharge, clearly show the need for hydrological modeling.

Keywords: Beauvais, chalk aquifer, modflow-2000, groundwater flow model, sensitivity analysis, recharge.

1. INTRODUCTION

Numeric models defining groundwater flow systems are commonly based on a governing equation that combines Darcy's law and water mass balance. Such models require both geologic and hydrologic data to properly define initial conditions, boundary conditions, hydraulic properties, and possible stresses to the system [1,2]. Actually, numerous models for porous media flow have been successfully developed in the last few decades [3-5]. MODFLOW-2000 code [6], employed within the framework of the Groundwater Modeling System (GMS 6.5) is capable of simulating groundwater flow in steady/transient, three dimensional, anisotropic and heterogeneous systems. Due to its capability, MODFLOW is widely used to simulate different types of groundwater problems in different geographical regions, such as the arid, semi-arid and humid areas [7,8]. In addition, it has become an invaluable tool for proper management of the water resources, especially for assessing and preventing the impact of future activities on groundwater resources [9-11]. The Beauvais city, a rapidly developing region in Oise department, is experiencing increased surface and groundwater use disputes.

In addition, there is a clear need to define water budget components more accurately and to identify controls on water redistribution in order to improve our understanding groundwater's hydrodynamic flow within the chalk aquifer [12-14]. To solve these problems and to investigate the impact of the hydraulics parameters on aquifer water levels, a methodological approach of coupling Geographic Information System and the numerical model with the finite-difference code is proposed and then applied. Data processing steps undertaken in this study are briefly described, and a critical assessment of data availability and requirements for successful monitoring and modeling is given. First, we try to determinate the hydrodynamic behaviour of the chalk, to identify the main factors affecting underground flow and to describe groundwater systems and their dynamics. After that, we seek to understand the functioning of the hydrogeological system by components quantification of the groundwater mass balance and the hydraulic conductivity's spatial distribution. A sensitivity analysis was also performed on the major model parameters. Finally, a preliminary application of the model to the Beauvais aquifer's will contribute to adequate land and

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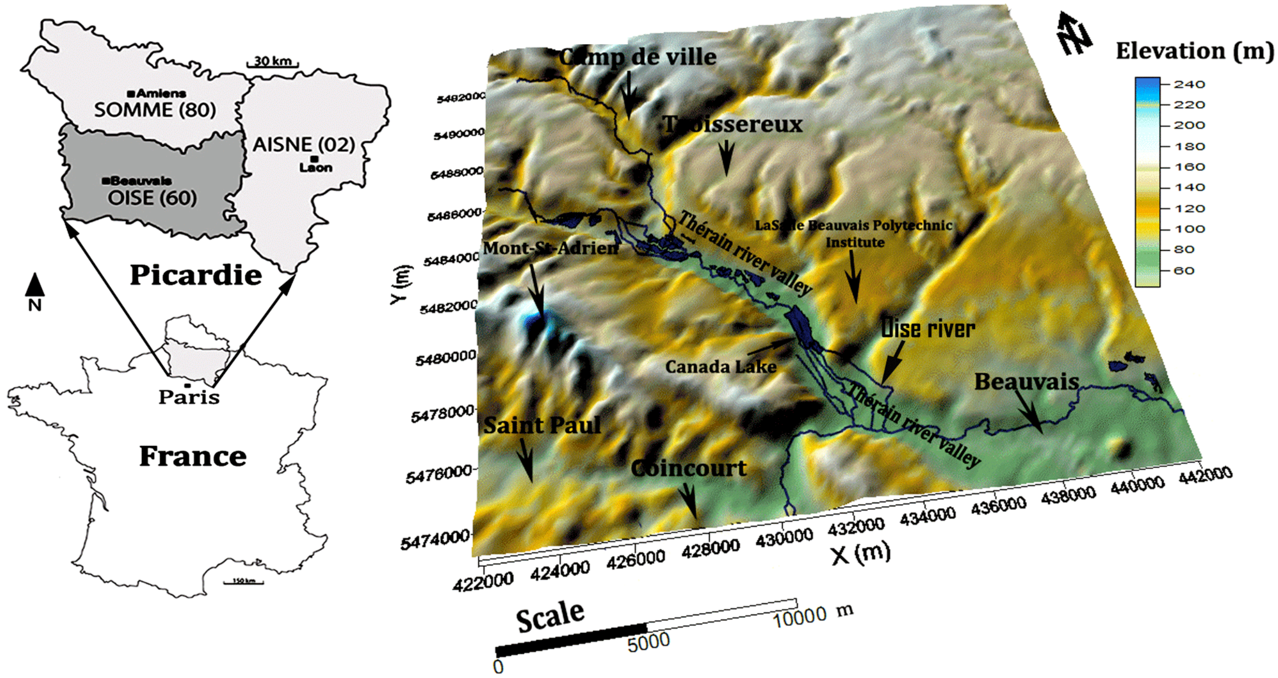

Figure 1: Location map of the study area and topographic framework showing the main physiographic features of Beauvais.

water planning strategies, as well as to preventing quantitative and qualitative alteration of the environmental conditions.

2. MATERIALS AND METHODS

2.1. Study Area

The study area is located in the city of Beauvais, the french department of Oise, about 80 km North of Paris (Figure **1**). It covers 33.31 km^2 and bounded by the Saint-Adrien anticline and the cities of Troissereux, Fouquenies, Goncourt, Therdonne and Tillé. The area is drained by several rivers taking place in the Thérain valley, the most important one being the Oise river [15]. The water is used to provide drinking water for the city of Beauvais and its suburbs mainly Troissereux and Fouquenies (about 60000 m^3/day), for irrigation in valleys and for industry purposes. The morphology of the study area varies between 57 m and 170 m with an average elevation of 100 m above-sea-level. The region receives an annual precipitation ranging between 600 mm/year and 800 mm/year and an annual average temperature ranging between 8°C and 15°C.

Runoff is taking place by rivers with permanent flow and a general flow is observed to the south, more locally to the Thérain valley, the main drainage valley [16]. The superficial formations are composed by a thin layer of clay, silt and marl that is derived from the chalk's dissolution and quaternary deposits. The majority of these soil's types are localized in the Thérain valley and the topographic depressions, which represents a small part of the Beauvais watershed area.

2.2. Hydrogeology and Transport Parameters

The groundwater level of the chalk aquifer is observed by many piezometric compains carried out using several piezometers and wells. From Figure **2**, the water table is near land surface in valleys especially in the Thérain valley ranging between 60 m and 90 m but as much as 110 m below land surface beneath hills.

The range of seasonal fluctuation of the water Table is as little as 2 m in valleys, but may exceed 10 m beneath hills. In addition, the hydraulic gradient appears to be more than 7% and generally reflects the raid surface topography. There are many destinations where groundwater discharges as seepage into streams, lakes, or other surface water bodies, and also as evapotranspiration in the whole areas. In the study area, the Thérain valley is the main drainage valley. With regard to hydrodynamic parameters, there are No tracer test data to allow the estimation of local dispersivities. In addition, the high resolution of ERT was used to estimate some hydraulic parameters like the chalk's porosity formation. The relationship between bulk resistivity of a fully saturated porous medium (ρ_b (Ohm.m)), its porosity ($\varnothing$ (-)) and the

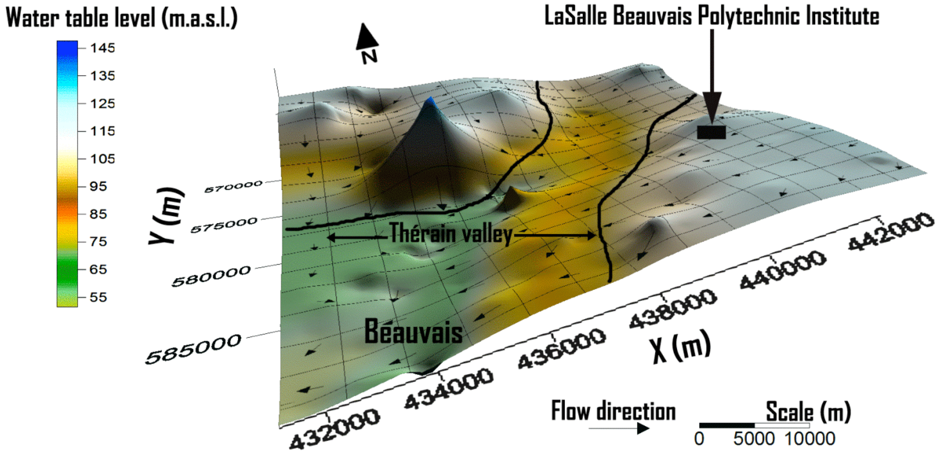

Figure 2: Groundwater level and flow direction of the chalk aquifer of Beauvais.

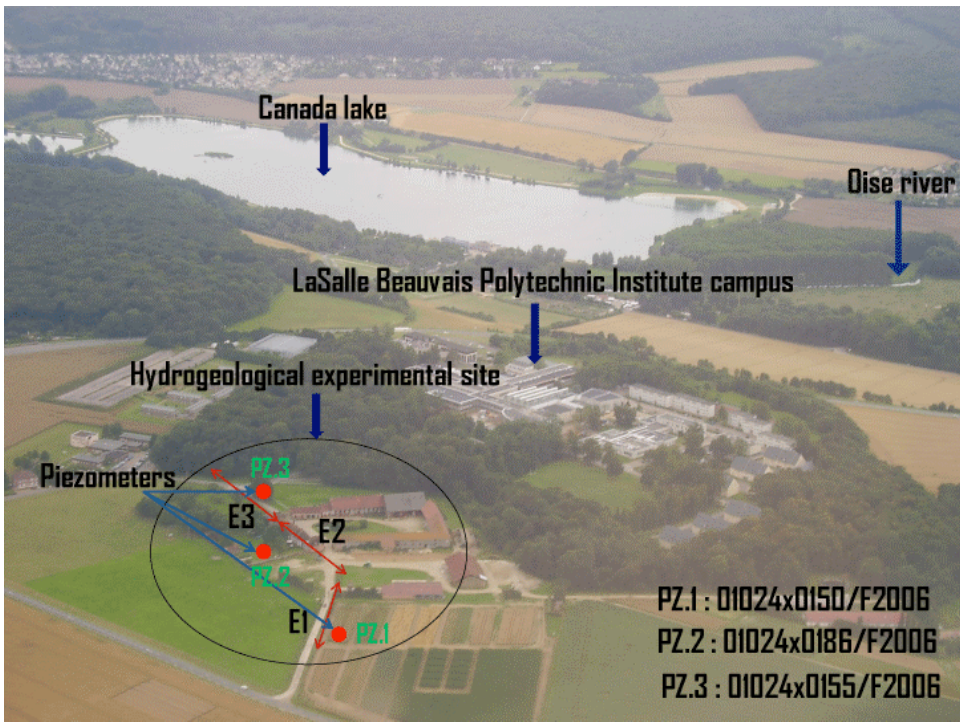

Figure 3: Location of ERT profiles (E1, E2 and E3) and the piezometers used in the research site of the LaSalle Beauvais Polytechnic Institute (from Google Earth).

resistivity of the fluid within the pores (ρ_f (Ohm.m)) is expressed by Archie's law [17]:

$$\varphi_b = a\varphi_f \phi^{-m} = F\varphi_f \quad (1)$$

where *m* and *a* are dimensionless material dependent empirical factors; *m* is known as the cementation index; and *F* is the Humble formula [18].

Three Electrical Resistivity Tomography (ERT) profiles (E1, E2 and E3) with their corresponding piezometers, were conducted in the research site of the Polytechnic Institute of Beauvais (Figure **3**) along a profile line of length 315 meter, using 64 electrodes deployed at an inter-electrode spacing of 5 meter.

The ERT survey was carried out using a multi-electrode system (ABEM Terrameter SAS 4000) and the data recorded using Gradient array (a type of Schlumberger array). Figure **4** shows an example of an ERT profile with the corresponding piezometer lithology and resistivity profiles used for porosity estimation.

ERT profile (SW–NE oriented) was performed perpendicular to the Oise river on the right site of the Polytechnic Institute of Beauvais. The models reach a

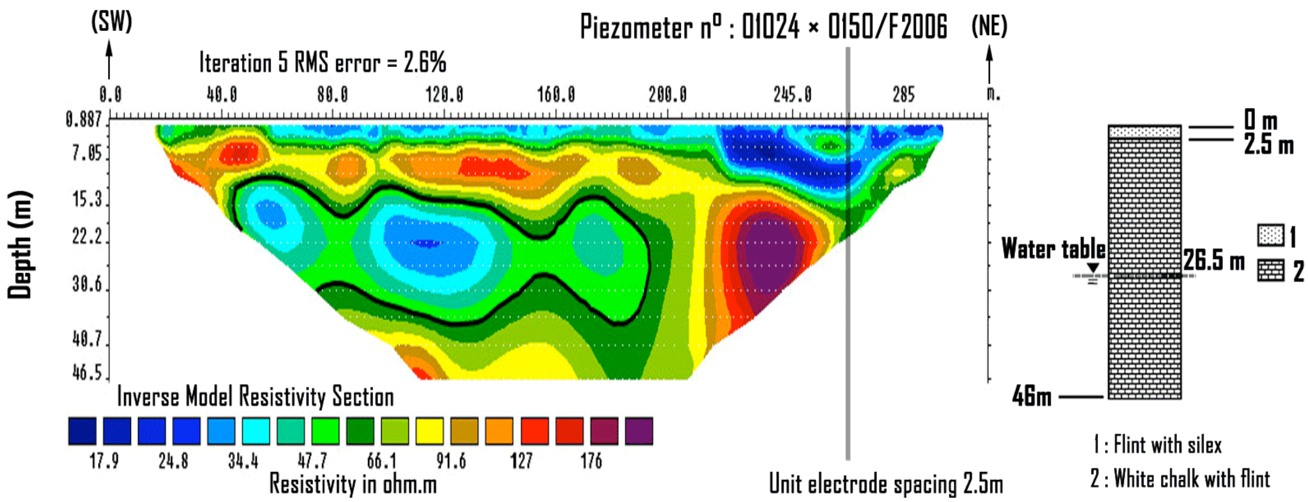

Figure 4: Obtained ERT profile showing the local lithologies of the sub-surface. The water table level is included.

Table 1: Measured Resistivities and Porosity Values Estimated by Archie's law

Well number	UTM Coordinates		Depth (m)	Z.Value (m)	Fractures or Bulk-Media Resistivity (Ohm.m)	Porosity (%) for a=0.81, m=2
	X (m)	Y (m)				
01024X0150/F2006	580618.69	2496411.10	80	118	66.1	11.2
01024X0186/F2006	580839.00	2496371.10	60	118	74	10.4
01024X0155/F2006	580768.90	2496150.79	102	115	80	10

maximum study depth of 46 m with obtained RMS of 2.6%. The ERT shows a vertical and horizontal heterogeneous distribution of the electrical resistivity values. These variations reveal the presence of two layers. The first layer composed by alluvions represents a small part of soil constituted by silt, clay and flint with a small thickness ranging between 1 m and 2.5 m. The second one is formed by a soft Campanian chalk based on the hard Santonian chalk and covered by a superficial layer of clay and some tableland of silt. Considering Archie's law, it is known that the low resistivity of pore fluid in the rock with porosity has an active role in decreasing the bulk resistivity (i.e. total resistivity) of the rock. The application results of Equation 1 assuming Humble formula [18,19] for unconsolidated formations: $F = 0.81\phi^{-2}$ are displayed in Table **1**. The ratio $\frac{\varphi_b}{\varphi_f}$ is the formation factor (F). Table **1** shows that the chalk's porosity formation ranges between 10 and 11.2%.

2.3. Hydraulic Parameters

The hydraulic parameters of the chalk aquifer were based on the number of aquifer tests and geophysical investigations performed at the study area. The results and the interpretations of the available 10 pumping tests (see Figure **6**) are shown in Table **2**.

The hydraulic transmissivity ranges between 10^{-3} and 10^{-2} m^2/s. Furthermore, the specific storage varies between 0.01 and 0.63 l/s and the hydraulic conductivity ranges between 5×10^{-4} and 5×10^{-5}m/s. A hydraulic conductivity value was assigned to each model cell to represent the heterogeneous nature of the materials in the model layer. Within each model cell, the horizontal hydraulic conductivity (K_x) was assumed homogeneous. The vertical hydraulic conductivity values (K_z) were established by a variable anisotropy ratio K_x/K_z ranging between 3 and 13.

2.4. Estimation of Recharge

Aquifer recharge was estimated using water balance technique:

$$P = Excess + RET + \Delta W = R + Q + RET + \Delta W \tag{2}$$

where *R* is recharge (mm), *P* is precipitation (mm), *Q* is net runoff (mm), *RET* is real evapotranspiration (mm) and ΔW is change in soil moisture storage (mm).

Table 2: Hydrodynamic Characteristics of the Chalk Aquifer (Deduced from Drilling Well Reports of BRGM (Bureau De Recherches Géologiques et Minières))

Well n°	Hydraulic Transmissivity (10^{-2} m^2/s)	Hydraulic Conductivity (10^{-4} m/s)	Specific Storage (l/s)
1	1.10	3.20	0.53
2	1.90	5.00	0.17
3	0.10	0.50	0.27
4	0.12	0.70	0.20
5	0.90	1.20	0.63
6	0.22	0.60	0.50
7	0.87	1.80	0.10
8	0.90	2.20	0.33
9	1.00	3.00	0.34
10	0.56	1.40	0.22

Table 3: Thornthwaite Water Budget: Monthly Data at the Research Site of the Lasalle Beauvais Polytechnic Institute (France) (*P*, Monthly Rainfall; *Pet*, Thornthwaite Monthly Potential Evapotranspiration; *Ret*, Monthly Actual Evapotranspiration; *D*, Deficit; Exc, Excess; *Q*, Net Runoff and *R*, Recharge)

	September	October	November	December	January	February	March	April	May	June	Juliet	August	Yearly
T (°C)	12.80	10.60	7.20	2.60	6.30	5.10	6.80	9.10	15.60	15.60	17.30	17.00	10.50
P (mm)	34.50	68.50	67.90	67.90	49.80	32.80	88.70	52.50	94.00	30.50	61.00	80.60	728.70
PET (mm)	62.27	44.56	23.51	6.94	19.95	16.55	29.58	45.96	97.91	101.56	112.57	101.37	662.73
P - PET (mm)	-27.77	23.94	44.39	60.96	29.85	16.25	59.12	6.54	-3.91	-71.06	-51.57	-20.77	65.97
RFU (mm)	0.00	23.94	68.33	120.00	120.00	120.00	120.00	120.00	0.00	0.00	0.00	0.00	692.27
RET (mm)	34.50	44.56	23.51	6.94	19.95	16.55	29.58	45.97	94.00	30.50	61.00	80.60	487.66
D (mm)	27.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.91	71.06	51.57	20.77	175.08
Exc (mm)	0.00	23.94	44.39	60.96	29.85	16.25	59.12	6.54	0.00	0.00	0.00	0.00	241.05
Q (mm)	0.00	17.96	33.29	45.72	22.39	12.19	44.34	4.89	0.00	0.00	0.00	0.00	180.77
R (mm)	0.00	5.99	11.10	15.24	7.46	4.06	14.78	1.62	0.00	0.00	0.00	0.00	60.25

In order to estimate the potential evapotranspiration (*PET*), several methods were applied, in particular the Thornthwaite method [20] :

$$PET = 16\left(\frac{10t}{I}\right)^{a} \tag{3}$$

where *PET* is potential evapotranspiration (mm), *t* is mean temperature (°C), *i* is monthly heat indices, *I* is the annual or seasonal heat index and represent the summation of 12 values of monthly heat indices.

$$I = \sum_{i=1}^{12} i = \sum_{i=1}^{12} \left(\frac{t_i}{5}\right)^{1.514} \tag{4}$$

where t_i is temperature in °C of *i* th month and *a* (empirical exponent) = $0.675 \times 10^{-6} I^3 - 0.771 \times 10^{-4} I^2 + 0.1792 \times 10^{-1} I + 0.49239$.

After calculating PET, the Thornthwaite formula was applied consequently to estimate RET. The Thornthwaite and Mather water budget [21] is an applicable tool to estimate surpluses of water, which are not stored in the soil profile [22]. It is one of the most suitable methods for monthly and annual water budgets computation. Based on the infiltration coefficient around 25% of the effective precipitation, the computation of water balance is based on the difference between precipitation (P) and potential evapotranspiration (PET).

- When P ≥ PET, RET is equal to PET and the surplus (P – RET) represents the superficial or groundwater flow.
- When P < PET, this indicates the amount by which the climatic demand for water cannot be met by precipitation; rather, it is pumped from the soil reserves. In addition, the soil-water storage (RFU, in mm) is equal to (RET – P).
- When the stock is null, the evaporation will be equal to the rainfall.

Table **3** summarizes the calculation of the balance sheet. The calculation starts at the end of low water (September), beginning of the water year where the RFU is considered as zero. Groundwater and surface water are down to the minimum. The rainfall in November, December and March reconstitutes the main part of the reserve. Calculated RET is estimated to 487.66 mm/year. The total recharge from P to the aquifer is also estimated to 241.05 mm. The general procedure for estimating recharge values was to multiply the value of excess rains quantity in each month by infiltration coefficient (25%).

The value of infiltration coefficient was estimated according to the soil type, land use and evapotranspiration rate. The amount of recharge from precipitation is around 60.25 mm. The highest values of recharge occur from October to April, the period of high precipitation.

3. NUMERICAL GROUNDWATER MODELING

3.1. Numerical Methods and Model Selection

The groundwater component of the flow model was represented using the transient 3-D groundwater flow equation (Eq. (5)) [6]:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_S\frac{\partial h}{\partial t} \quad (5)$$

where K_{xx}, K_{yy}, and K_{zz} = the hydraulic conductivity along the x, y and z axis that are assumed to be parallel to major axis of the hydraulic conductivity (L/T), h = the potentiometric head (L), W = volumetric flux per unit value representing sources and/or sinks of water (W < 0.0 for outflow of the groundwater system, W > 0.0 for inflow (T^{-1}), S_S = specific storage of porous material (L^{-1}), and T = time).

This equation is based on a mathematical approximation of a basic groundwater flow equation which takes into account variables like hydraulic head,

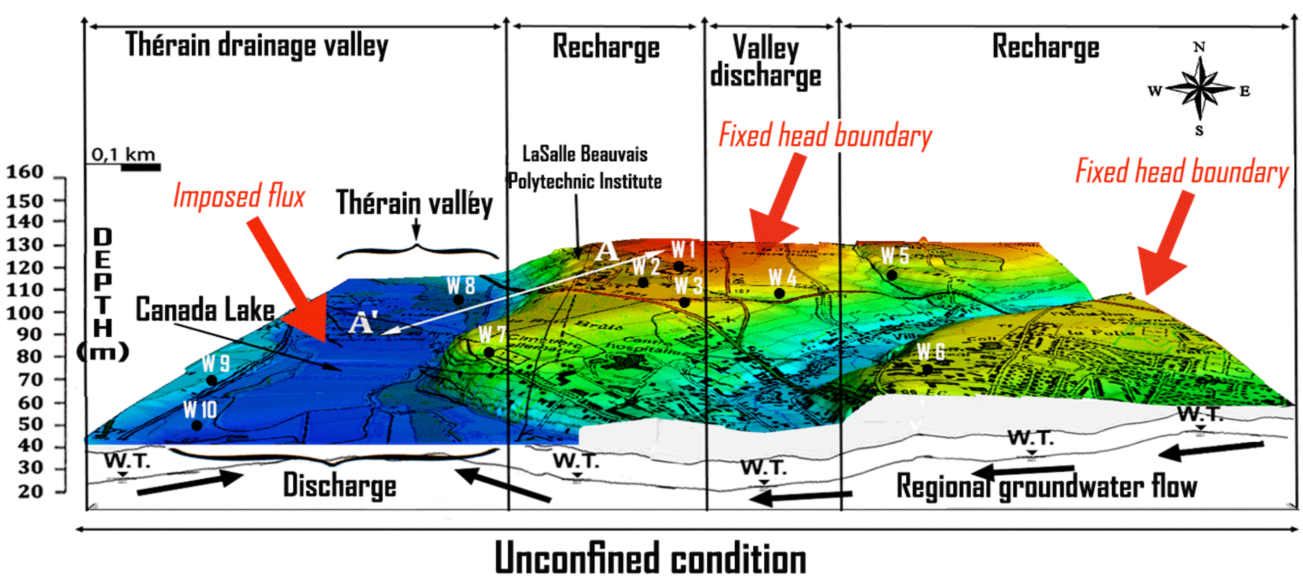

Figure 6: Conceptual 3-D model showing the principal components of the groundwater system and the monitoring wells (W1,...,W10) used in calibration process at the Beauvais regional scale.

aquifer transmissibility, aquifer storage coefficient and time. Groundwater flow in the chalk aquifer was simulated using the modular groundwater flow model MODFLOW-2000 [23]. MODFLOW-2000 solves the finite difference equations simultaneously, using one of several numerical-solver algorithms. It accounts for groundwater flow between cells and external sources or sinks of water, such as stream aquifer hydraulic interaction, aquifer recharge, or groundwater withdrawal by wells [22].

3.2. Model Discretisation

The numerical model of the chalk aquifer contains 88 rows × 70 columns and one layer with a total of 6160 cells (Figure **5a**).

The modeled domain covers an area of 3000000 m^2 with an average thickness of 50 m. A medium refinement was specified along the Oise river. After construction of finite difference model grid, it was rotated so that the y-axis would roughly be parallel to the Oise river direction (Figure **5b**). The purpose for rotating the grid is to align model rows with the principal direction of groundwater flow, which is primarily toward the Oise river. A single hydrogeological unit is represented as a single model layer with layer top and bottom elevations following the natural surfaces. Thus, the top elevation is spatially variable and corresponds with surface elevation, based on a compiled topographic Beauvais contour map.

3.3. Boundary Conditions

Before the construction of numerical model, it is necessary to identify the different boundary conditions of the chalk aquifer system.

Steady state boundary conditions are a prescribed constant lateral inflow at most of the length of the northern and the eastern boundary of the aquifer. These boundaries are modeled as a fixed-head condition. The hydrologic and climatic processes, including recharge groundwater, flow to rivers and evaporation from the water Table are assigned to a specified head. It is applied on the top of the modeled domain. The movement and the interaction of groundwater to and from rivers are another important boundary conditions. The flux of water between the groundwater system and the rivers is, in part, dependent on the hydraulic head in the groundwater system and is simulated as the head dependent flux boundary. This type of flow boundary involves specifying the hydraulic head of the surface water and a transfer coefficient. Finally, Canada lake constitutes the main outputs of the system and provides a constant head boundary (as specified head boundary, with a zero assigned value) [22]. The specified head is assigned as a known hydraulic head value using the groundwater levels measured at a number of monitoring wells in aquifer (Figure **6**).

A summary of model parameters is given in Table **4**.

4. RESULTS AND DISCUSSION

4.1. Model Calibration

In order to adjust the simulated heads and to reduce the error between the measured and calculated values, model calibration is needed. The model fit can be evaluated by comparing the root mean square errors (RMSE) of hydraulic heads between simulations. The RMSE is usually considered to be the best measure of error if errors are normally distributed [24]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(h_{obs} - h_{sim}\right)^2}{n}} \tag{6}$$

where h_{obs} is the observed head value, h_{sim} is the simulated head value and n is the number of simulation's days.

However, several parameter estimation codes existed at the time of calibration [25,23,26]. The parameter estimation program PEST [27], coupled to MODFLOW-2000, was initially selected because of its ability to limit parameter value ranges and parallel process utilities. The chalk model of Beauvais was calibrated in two steps: (1) steady-state calibration with average conditions during 1998 and (2) calibration with transient condition from 1998 to 2010.

4.2. Modeling Results

4.2.1. Steady State Flow Model and Initial Conditions

With selected boundary conditions and model parameters, the model was adjusted to achieve the best agreement between the hydraulic heads that were observed in 1998 and the simulated hydraulic heads computed by MODFLOW-2000. The input data in the model were recorded hydraulic heads, recharge rates and hydrodynamic parameters values from the drilling and pumping tests (Figure **6**).

Table 4: Characteristics of the Developed Model for the Chalk Aquifer of Beauvais and Short Justification

Parameter	Value	Notes
Model dimensions	70 columns × 88 rows	Model orientated at west of grid north so that the Oise river axis is parallel to the long axis of the simulation
Layer(s)	Single layer	Unconfined system
External boundary conditions	No flows	
Internal boundary conditions	Active cells for groundwater; lake and river cells	
Hydraulic conductivity (m/s)	5×10^{-5} - 5×10^{-4}	
Anisotropy ratio	3 – 13	
River bed conductance (m/s)	0.03	Parameter based upon a river, 5 m wide, with river-bed sediments, 0.2 m deep, and a hydraulic conductivity of the river-bed sediments of 1.24 10^{-4} m/s
Specific storage (l/s)	0.01 - 0.63	
Recharge	Modified weekly	Recharge from rainfall, surpluses of water, which are not stored in the soil profile and computation of monthly and annual water budgets are estimated by Thornthwaite and Mather formula.
Starting Head levels	Potentiometric data of 1998	
Stress period; and time step length	1 month; with 2 week time step	
Calibration period	1998 – 2010	Limited by the extent of input/calibration datasets.
MODFLOW solver package	The calibration of the numerical model to fit field observations was calculated in a time dependent, iterative and semi-automatic fashion using PEST	PEST is a robust algorithm and his basic idea is the minimization of an objective function defined by the squared-weighted sum of residuals

The model was calibrated by optimizing the hydraulic conductivity for the saturated zone. Then, the values of hydraulic conductivity obtained were interpolated by geostatistical methods to characterize the heterogeneity of the aquifer [28]. The calibration results are shown in Figure **7**.

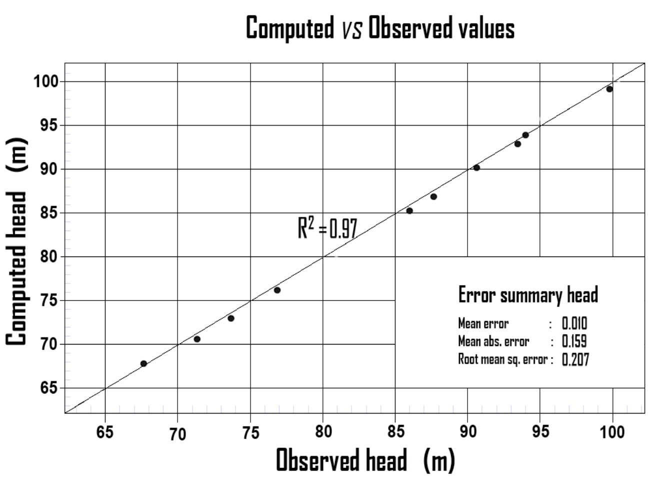

Figure 7: Scatter plot of observed and computed hydraulic heads for the steady state conditions.

This plot displayed a correlation coefficient of 0.97, indicating a good overall fit. The root mean square error is 0.207 m and the mean absolute error is 0.159 m for heads (50 < Hobs < 100 m) confirming the good correlation between computed and observed hydraulic heads.

4.2.1.1. Hydraulic Conductivity Distribution

The steady state flow model is used to estimate hydraulic conductivities, and get suitable initial conditions (heads) for the transient model. Using the calibrated flow model, it is clear that the aquifer system is insensitive to changes in hydraulic conductivity in the modeled domain. Thus, the steady-state modeling showed that the numerical model divides the chalk aquifer into two major domains (Figure **8**): the first one is characterized by medium hydraulic conductivity (less than 10^{-4} m/s) which occur 60 % of the of superficies of study area; and the second domain is characterized by exposed chalk in the valleys [29] where hydraulic conductivity value is higher and usually exceed 2×10^{-4} m/s. However, within the Oise river and arround the lakes, the hydraulic conductivity is much higher, greater

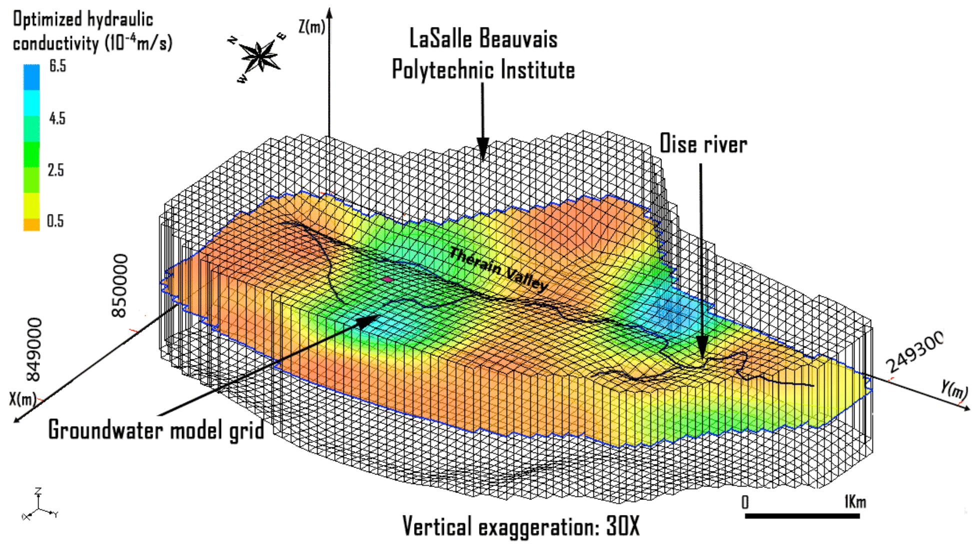

Figure 8: Estimated hydraulic conductivity of the chalk aquifer (obtained from PEST optimization method).

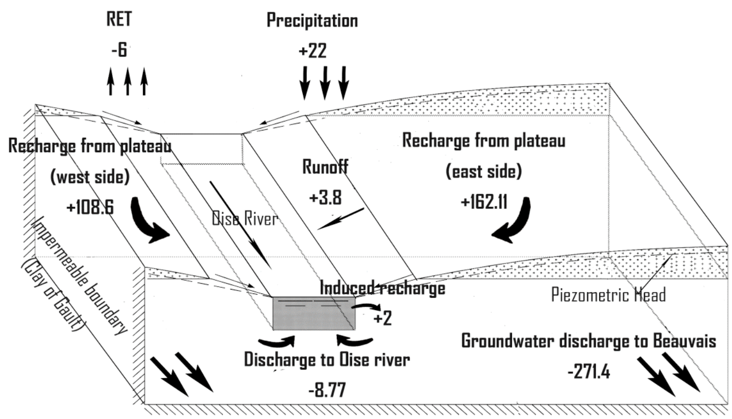

Figure 9: Regional water balance (l/s) of the chalk aquifer of Beauvais.

than 3 × 10^{-4} m/s and can sometimes exceed 5 × 10^{-4} m/s. These higher hydraulic conductivity values are due to the development of solution-enhanced fractures in the chalk [30].

4.2.1.2. Steady Water Balance

A summary of all inflows and outflows of the regional model is called a water budget or volumetric budget. Budget terms are expressed in (l/s) and are positive when entering and negative when leaving the groundwater system [8,22].

Figure **9** shows a schematic 3-D cross-section of the regional water balance derived from the steady state simulation.

Precipitation and actual evapotranspiration represents respectively 22 l/s and 6 l/s. A flow of 8.77 l/s is drained and discharged intermediately to the Oise river.

Furthermore, a total of 271.4 l/s of flow water is discharged directly on the southern part of the modeled domain. However, the river creates an upstream lake that causes an infiltration of surface waters into the aquifer. This induced recharge from the Oise river accounts for 2 l/s. Aquifer recharge from plateau (east and west) accounts respectively for 162.11 l/s and 108.8 l/s. The total water budget shows an imbalance between inflows and outflows. The difference between total inflow and outflow should equal to the total change in water storage. Thus, the average annual inflow to the groundwater system from precipitation, recharge from plateau and runoff is estimated at 298.51 l/s. However, the total groundwater discharge during the period of simulation is quantified at 286.17 l/s. In addition, a volume of approximately 12.34 l/s represents the total water storage change to groundwater through intermediate the Oise river, wetlands (plateau) and runoff.

4.2.2. The Transit State Flow Model

4.2.2.1. Model Calibration and Validation

The same model was converted to a transient state through the addition of the storage parameters (hydraulic transmissivity, specific yield and specific storage) in the same zone of hydraulic conductivity, calibrated and then validated by assessing the ability of the model to simulate the annual variation of the hydraulic heads [29]. Therefore, calibrating these parameters is crucial for transient simulations and for allowing a detailed calculation of the water budget [31]. The transient state model was calibrated using the available hydraulic heads level data from the period of 1998-2008. Transient model calibration was obtained with a root mean square error of 0.951 m and a mean absolute error of 0.499 m, which shows that the model is performing well. Three examples of the achieved calibration degree are presented in Figure **10**.

Afterward, the model validation is an extension of the calibration process. Its purpose is to test and assure that the calibrated model properly assesses all the variables and conditions which can affect model results. One of the most effective procedures for model validation is to use only a portion of the available

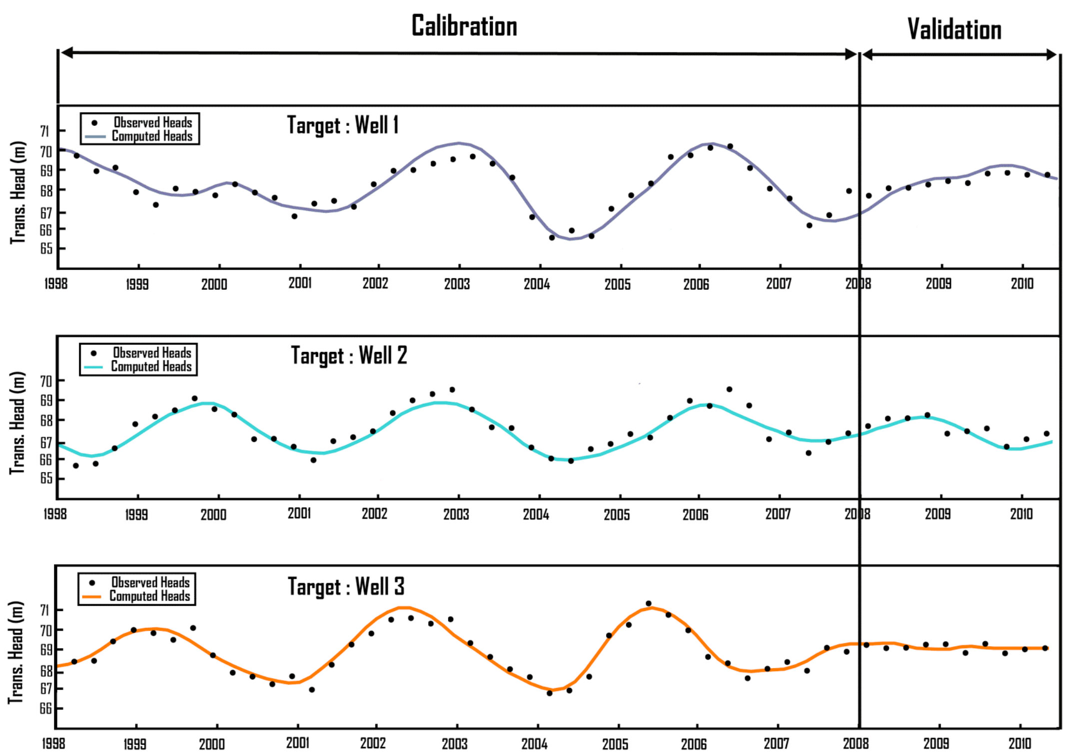

Figure 10: Fitted observed and computed hydraulic heads time series at three monitoring wells as result of model calibration.

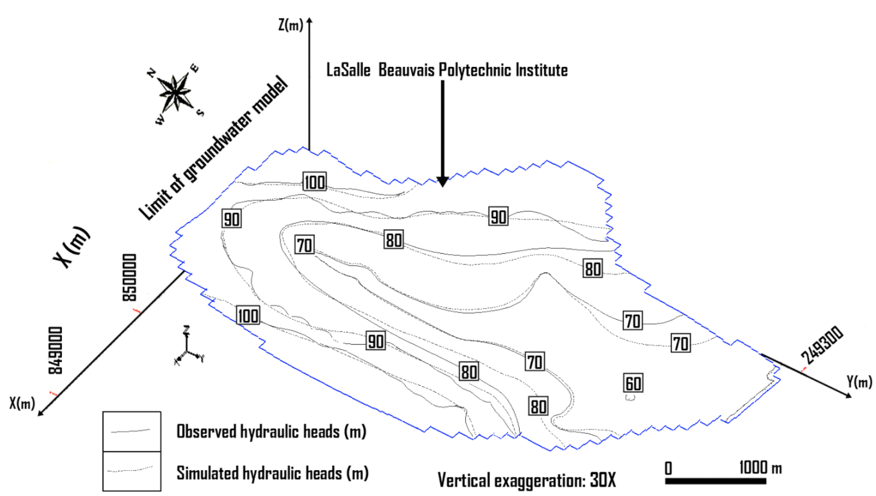

Figure 11: Simulated and observed hydraulic heads for the chalk aquifer as result of model validation (year 2010).

records of observed values for calibration [22]. Thus, the remaining data from 2008 to 2010 was used for the validation processes (Figure **10**). Moreover, Figure **11** shows a good agreement between observed and simulated hydraulic heads for 2010. The values of the hydraulic parameters estimated, as well as calibrated, are given in Table **5**.

The optimized hydraulic transmissivity varies between 0.007 and 0.05 m^2/s. The calibrated values of the specific storage range between 0.04 and 0.78 l/s. Finally, the specific yield deduced by the model range between 0.001 and 0.015. Following the calibration/validation processes, a sensitivity analysis was carried out in order to verify the importance of the different input parameters on the simulation results.

4.2.2.2. The Transit Water Budget

After obtaining the calibrated hydraulic parameters, the model was run to calibrate the groundwater balance for the year 2010 (Table **6**).

Like the steady state stage, the transit water budget over the regional aquifer shows an imbalance between inflows and outflows. Groundwater inflow from the recharge from plateau (east and west) supplies the aquifer with most of its water. This amounts to more than 300.16 l/s, or about 71.94% of the total input to the chalk aquifer. Recharge represents the second important source of groundwater inflow, which is mainly due to precipitation. The recharge amounts to 65.81 l/s, which represents 15.77% of the total inflow of water in the aquifer. Other inflow to the groundwater system is obtained from the constant heads and rivers. The amount of the constant heads is about 32.06 l/s, or about 7.68% of the total input. Also, the inputs of water from the rivers are about 10.17 l/s. The main outputs of water from the aquifer are drainage to Canada lake, to evapotranspiration and to Oise river. The drainage averages 148.33 l/s, which represents about 95.5 % of the total outflow. This drainage is mainly directed to the Canada lake, with 79.58% of the total outflows. Groundwater drainage to the Oise river is 8.72 l/s, or about 5.62% of the total outflows. Evapotranspiration is about 16 l/s, or 10.30% of the total outflows. From Table **5**, the overall inflow exceeds the overall outflow, indicating a surplus of about 151.90 l/s. This water excess is compensated by water from the aquifer's storage.

4.2.2.3. Sensitivity Analysis

In order to test the stability of the obtained numeric solution, the calibrated model was submitted to sensitivity analyses. The sensitivity analysis consisted on changing only one input parameter at a time while keeping all others fixed. The objective was to evaluate the groundwater system response to changes in various hydraulic parameters and to investigate how combined hydraulic head constraints can improve the calibration process in the groundwater flow system [22]. The values of the hydraulic parameters with respect to the best estimates were perturbed and the response of simulated hydraulic heads was observed [32,22].

Table 5: Optimized Hydraulic Parameter Values

Parameter	Estimated value	Calibrated value
Hydraulic transmissivity T_h (m^2/s)	0.001 – 0.01	0.007 – 0.05
Specific storage S_s (l/s)	0.01 – 0.63	0.04 – 0.78
Specific yield S_y (dimensionless)	0.001 – 0.004	0.001 – 0.015

Table 6: Transient State Calibration in the Aquifer System: Water Budget (2010)

	Input (l/s)	0utput (l/s)	Input (%)	Output (%)
Storage	9.02	-2.32	2.17	1.50
Constant heads	32.06	-123.61	7.68	79.58
General heads	300.16	-4.67	71.94	3.00
Rivers	10.17	-8.72	2.44	5.62
Recharge	65.81	0.00	15.77	0.00
Evapotranspiration	0.00	-16.00	0.00	10.30
Total	417.22	-155.32	100.00	100.00

Table 7: The Hydraulic Head Variations in the Three Monitoring Wells, Owing to Changing Hydraulic Parameters and Recharge

Parameters	Hydraulic Head (m)			
		Well 1	Well 2	Well 10
1.0 × K 1.0 × S 1.0 × R	Min. Max. Mean	64.85 86.65 70.45	60.34 80.74 67.79	50.2 65.9 59.02
3.0 × K 1. 0 × S 1.0 × R	Min. Max. Mean	59.30 79.44 64.06	55.89 76.70 63.23	48.65 60.08 51.03
0.5 × K 1. 0 × S 1.0 × R	Min. Max. Mean	70.53 92.9 77.87	67.87 87.90 80.02	59.90 74.30 62.92
1.0 × K 3. 0 × S 1.0 × R	Min. Max. Mean	65.90 89.34 72.56	59.09 78.90 65.87	49.56 63.87 55.43
1.0 × K 0.5 × S 1.0 × R	Min. Max. Mean	64.98 87.67 71.23	65.76 84.45 70.56	54.98 70.02 60.70
1.0 × K 1. 0 × S 3.0 × R	Min. Max. Mean	72.98 94.09 80.56	69.98 89.90 86.89	56.98 69.99 65.89
1.0 × K 1.0 × S 0.5 × R	Min. Max. Mean	60.02 80.98 68.89	55.87 76.67 60.54	50.56 60.89 56.67

In this study, the model's sensitivity to changes of hydraulic conductivity (K), specific storage (S) and recharge (R) that represent the most significant parameters in the process of calibration was checked by conducting simulation trials for each parameter.

For the sensitivity analysis, values for K, S and R were multiplied by a factor of 1 (model standard), 0.5 and 3 in separate simulations. We looked at how the hydraulic heads in the model changed under the calibrated model conditions and with incremental changes in the assumed model parameters. Table **7** shows the variation in the hydraulic heads at three selected wells (W1; W2 and W10) from the model calibration based on variation of hydraulic parameter inputs. The selected sensitivity analyses show that the variation of hydraulic heads is highly dependent on variation of recharge parameters more than the hydraulic parameters.

Thus, increasing the recharge values by 3 produced an increase over a 20% in inflow water volume, whereas, reducing recharge by 0.5 diminished outflow water volumes, reducing the water Table levels by 3.5m of the model aquifer. Furthermore, the model is sensitive to hydraulic conductivities and (slightly) to specific storage. Notably, increasing the hydraulic conductivity to 3 caused over 10% decrease in the water Table level, while, reducing conductivity by 0.5 diminished inflow water volumes, increase the water Table levels by 7.5m.

5. CONCLUSIONS

An integrated methodology of groundwater flow model was developed to validate the groundwater data deduced from the geophysical, hydrodynamic studies of the chalk aquifer of Beauvais.

In the first step, a large amount of available geological and hydrological data was integrated to construct a 3-D groundwater flow model. Then, a sophisticated MODFLOW-2000 was applied to simulate 3-D groundwater flow. The model was calibrated and validated with datasets of 1998–2010 period. Calibration efforts were oriented to hydraulic parameters, whereas the spatially distributed recharge was fixed since it is considered representative of the actual condition. The horizontal hydraulic conductivity obtained ranges between 2 × 10^{-4} m/s 5 × 10^{-4} m/s and the calibrated specific storage values vary between 0.04 and 0.78 l/s. In order to test the stability of the obtained numeric solution, the calibrated model was submitted to sensitivity analyses. The model aquifer is more sensitive to recharge than to hydraulic conductivities and specific storage. Finally, the hydrogeological investigations and numerical modeling seem to be a useful tool to better understand the groundwater unconfined aquifer of Beauvais. All information can be considered as a reference and represents a base for future hydrogeological work of groundwater which contributes to major management problems of chalk aquifer of Beauvais. Moreover, this groundwater flow model can be used as the basis for further development of a contaminant transport model.

REFERENCES

[1] Carroll RWH, Pohll GM, Earman S, Hershey RL. A comparison of groundwater fluxes computed with MODFLOW and a mixing model using deuterium: Application to the eastern Nevada Test Site and vicinity. J of Hydrology 2008; 361: 371- 385. http://dx.doi.org/10.1016/j.jhydrol.2008.08.005

[2] San Juan C, Kolm KE. Conceptualization characterization and numerical modeling of the Jackson Hole alluvial aquifer using ARC/INFO and MODFLOW. Engineering Geology 1996; 42: 119-137. http://dx.doi.org/10.1016/0013-7952(95)00073-9

[3] Gelhar LW. Stochastic Subsurface Hydrology. Prentice Hall. Englewood Cliffs 1993.

[4] Regli C, Rauber M, Huggenberger P. Analysis of aquifer heterogeneity within a well capture zone, comparison of model data with field experiments: a case study from the river Wiese. Switzerland. Aquat Sci 2003; 65: 111-128.

[5] Chenini I, Ben Mammou A. Groundwater recharge study in arid region: An approach using GIS techniques and numerical modeling, Computers and Geosciences 2010; 36: 801-817. http://dx.doi.org/10.1016/j.cageo.2009.06.014

[6] McDonald MC, Harbaugh AW. A modular three-dimensional finite-difference ground-water flow model. Techniques of Water-Resources Investigations of the USGS 1988; 6: 400.

[7] Reeve AS, Warzocha J, Glaser PH, Siegel DI. Regional ground-water flow modeling of the Glacial Lake Agassiz Peatlands, Minnesota. J of Hydrology 2001; 243: 91-100. http://dx.doi.org/10.1016/S0022-1694(00)00402-9

[8] Zghibi A, Zouhri L, Tarhouni J. Groundwater modelling and marine intrusion in the semi-arid systems (Cap-Bon, Tunisia). Hydrol Process 2011; 25: 1822-1836. http://dx.doi.org/10.1002/hyp.7948

[9] Chen X, Huang Y, Ling M, Hu Q, Liu B. Numerical modeling groundwater recharge and its implication in water cycles of two interdunal valleys in the Sand Hills of Nebraska. Physics and Chemistry of the Earth 2012; 53-54: 10-18. http://dx.doi.org/10.1016/j.pce.2011.08.022

[10] Batelaan O, De Smedt F, Triest L. Regional groundwater discharge: phreatophyte mapping, groundwater modelling and impact analysis of land-use change. J of Hydrology 2003; 275: 86-108. http://dx.doi.org/10.1016/S0022-1694(03)00018-0

[11] Price M, Low RG, McCann C. Mechanisms of water storage and flow in the unsaturated zone of the Chalk aquifer. J Hydrol 2000; 233: 54-71. http://dx.doi.org/10.1016/S0022-1694(00)00222-5

[12] Belhanafi L, Roussel P, Vilmus T. La plaine de canada « Beauvais (Oise) » : Projet d'aménagement d'une base de loisirs; Modélisation hydrodynamique en vue de la protection du champ captant. Bureau de recherches géologiques et minières. Service géologique national. N° Rapport 1993 ; R36656 Paris 4S/93.

[13] Crampon N, Roux JC, Bracq P. Hydrogéologie de la craie en France. Hydrogéologie 1993; 2: 81-123.

[14] Korkmaz S, Ledoux E, Önder H. Application of the coupled model to the Somme river basin. J Hydrol 2009; 366: 21-34. http://dx.doi.org/10.1016/j.jhydrol.2008.12.008

[15] Mahler BJ, Valdes D, Musgrove M, Massei N. Nutrient dynamics as indicators of karst processes: Comparison of the Chalk aquifer (Normandy, France) and the Edwards aquifer (Texas, U.S.A.). J Contam Hydrol 2008; 98: 36-49. http://dx.doi.org/10.1016/j.jconhyd.2008.02.006

[16] Zouhri L, Lutz P. A comparison of peak and plate electrodes in electrical resistivity tomography: application to the chalky groundwater of the Beauvais aquifer (northern part of the Paris basin, France). Hydrol Process 2010; 24: 3040-3052. http://dx.doi.org/10.1002/hyp.7719

[17] Archie GE. The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. AIME 1942; 146: 54-67. http://dx.doi.org/10.2118/942054-G

[18] Winsauer WO, Shearin HM, Masson PH, Williams M. Resistivity of brine-saturated sands in relation to pore geometry. AAPG Bull 1952; 36: 253-277.

[19] Kerrou J, Renard P, Tarhouni J. Status of the Korba groundwater resources (Tunisia): observations and three-dimensional modelling of seawater intrusion. Hydrogeol J 2010; 18(5): 1173-1190. http://dx.doi.org/10.1007/s10040-010-0573-5

[20] Thornthwaite CW. An approach toward a rational classification of climate. Geographic Review 1948; 38: 55-94. http://dx.doi.org/10.2307/210739

[21] Thornthwaite CW, Mather JR. Instructions and tables for computing the potential evapotraspiration and the water balance. In: Publications Climatology. Laboratory of Climatology, Drexel Institute of Technology, Centerton, New Jersey. USA 1957; 10: 183-311.

[22] El Yaouti F, El Mandour A, Khattach D, Kaufmann O. Modelling groundwater flow and advective contaminant transport in the Bou-Areg unconfined aquifer (NE Morocco). J of Hydro-environment Research 2008; 2: 192-209. http://dx.doi.org/10.1016/j.jher.2008.08.003

[23] Harbaugh AW, Banta ER, Hill MC, McDonald MG. MODFLOW- 2000. The U.S. Geological Survey Modular Ground-Water Model e User Guide to Modularization Concepts and the Groundwater Flow Process. U.S. Geological Survey, Water-Resources Investigations Report 2000; 92: 121.

[24] Anderson MP, Woessner WW. Applied Groundwater Modeling: Simulation of Flow and Advective Transport Academic Press In San Diego California 1992.

[25] Poeter EP, Hill MC. Documentation of UCODE, a computer code for universal inverse modeling. US. Geological Survey Water-Resources Investigations Report 1998; 98-4080: 116.

[26] Hill MC, Banta ER, Harbaugh AW, Anderman ER. MODFLOW- 2000. The US. Geological Survey Modular Ground-Water Model e User Guide to the Observation, Sensitivity, and Parameter-estimation Processes and Three Post-processing Programs. US Geological Survey. Water-Resources Investigations Report 2000; 00-184: 210.

[27] Doherty JL. PEST: Model Independent Parameter Estimation. User Manual. 4th edn Watermark Numerical Computing Brisbane Australia 2000.

[28] Zimmerman DA, Marsily GD, Gotway CA, Marietta MG, Axness CL, Beauheim RL, Bras RL, Carrera J, Dagan G, Davies PB, Gallegos DP, Galli A, Gomez-Hernandez J, Grindrod P, Gutjahr AL, Kitanidis PK, Lavenue AM, McLaughlin D, Neuman SP, Rama-Rao BS, Ravenne C, Rubin Y. A comparison of seven geostatistically based inverse approaches to estimate transmissivities for modeling advective transport by groundwater flow. Water Resources Research 1998; 34(6): 1373-1413. http://dx.doi.org/10.1029/98WR00003

[29] Grapes TR, Bradley C, Petts GE. Hydrodynamics of floodplain wetlands in a chalk catchment: The River Lambourn. UK. J Hydrol 2006; 320: 324-341. http://dx.doi.org/10.1016/j.jhydrol.2005.07.028

[30] Mansour MM, Hughes AG. Application of Numerical Modelling to Investigate Recharge to the Chalk Aquifer Beneath Thick Till Deposits in East Anglia. Groundwater systems and water quality programme internal report IR/04/127. Keyworth Nottingham British Geological Survey 2004.

[31] Barth C, Krause P, Boyle DP, Markstrom S. Hydrological modeling of a groundwater dominated watershed using a loosely coupled modeling approach. International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand Inc 2007; 601-607.

[32] Yu Z, Schwartz FW. Automated calibration applied to watershedscale flow simulations. Hydrol Process 1999; 13: 191-209. http://dx.doi.org/10.1002/(SICI)1099-1085(19990215)13:2<191::AID-HYP706>3.0.CO;2-N

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