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Research paper

Groundwater modelling of the Tebessa-Morsott alluvial aquifer (northeastern Algeria): A geostatistical approach

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ABSTRACT

This paper studies aquifer's hydrodynamic behavior by combining a flow-simulation model with transmissivity optimization (cokriging) in order to provide an optimal management scheme for the groundwater aquifer. The use of a cokriging approach improves the transmissivity data which are insufficient for the database of the groundwater flow simulation model. The obtained results are then used to model the groundwater flow of the Tebessa-Morsott shallow aquifer, located in NE Algeria, under a steady and transient regime. The results of the model calibration for the steady-state (year 2010) show that the recharge by rainfall and leakage rate are similar compared to those calculated by the analytical approach, (84,354 m^3/day for the recharge and 36,986 m^3/day for pumped water flow rate). The results of the transient regime show the alluvial aquifer affected by large drawdowns reaching 40 m over 20 years (year 2030 scenario) due to increase in water exploitation from pumping wells to answer water needs of the Tebessa region.

1. Introduction

The degradation of the natural environment, including groundwater resources, has gradually become a global concern. Groundwater is the most important natural resource used for drinking by many people around the world, especially in arid and semi-arid areas (Shawgar et al., 2018; Hamed, 2015). The water resource cannot be optimally used and sustained unless the quantity of groundwater is assessed (Kevin, 2006; Shawgar et al., 2018). For this reason, it is of great importance to develop suitable simulation and optimization models for determining the optimal operation of pumping wells to ensure the maximum coverage of the water demands (Cornaton, 2004; Antoniou et al., 2019).

Deterministic numerical models simulating the behavior of groundwater are useful tools in evaluating, planning and managing this resource (Mary, 2002; Hill, 2006; Yangxiao and Wenpeng, 2011). More sophisticated and elaborate models are continuously being proposed under two to three dimensional consideration, and are usually solved by finite difference or finite element methods after imposing different boundary conditions for various aquifer configurations (Trescott, 1975). However, the information is usually limited by, and subject to, large sampling and interpretative errors. This restricts the development of more complex models applicable to this type of study. To overcome these difficulties, it is necessary to include the probabilistic approach (geostatistics) into these models in order to have a better quality, quantity and spatial distribution of hydraulic heads and hydraulic conductivities data used in the model.

In semi-arid areas of Algeria, the main source of water supply is groundwater because of its relatively easy exploitation (aquifers are shallow) (Chiles, 2004; Hamed et al., 2018). The population growth and agricultural modernization are causing a high demand for the groundwater potentials, already in limited quantity. For such reason, it is suitable to study the prediction of the groundwater aquifer state at short and long term.

The groundwater resources present an important source for water in this part of Algeria. Because of the lack of permanent surface water and reservoirs, owing to the arid climatic conditions, the groundwater resources constitute the most widely available source for fresh water (Rouabhia et al., 2010). In this region, groundwater is used for domestic, agricultural and industrial purposes (Drias, 2013; Fehdi et al., 2016).

The Tebessa-Morsott basin contains an alluvial aquifer which is under exploitation. As a result, groundwater levels and spring discharges are steadily decreasing threatening the short-term viability of resources

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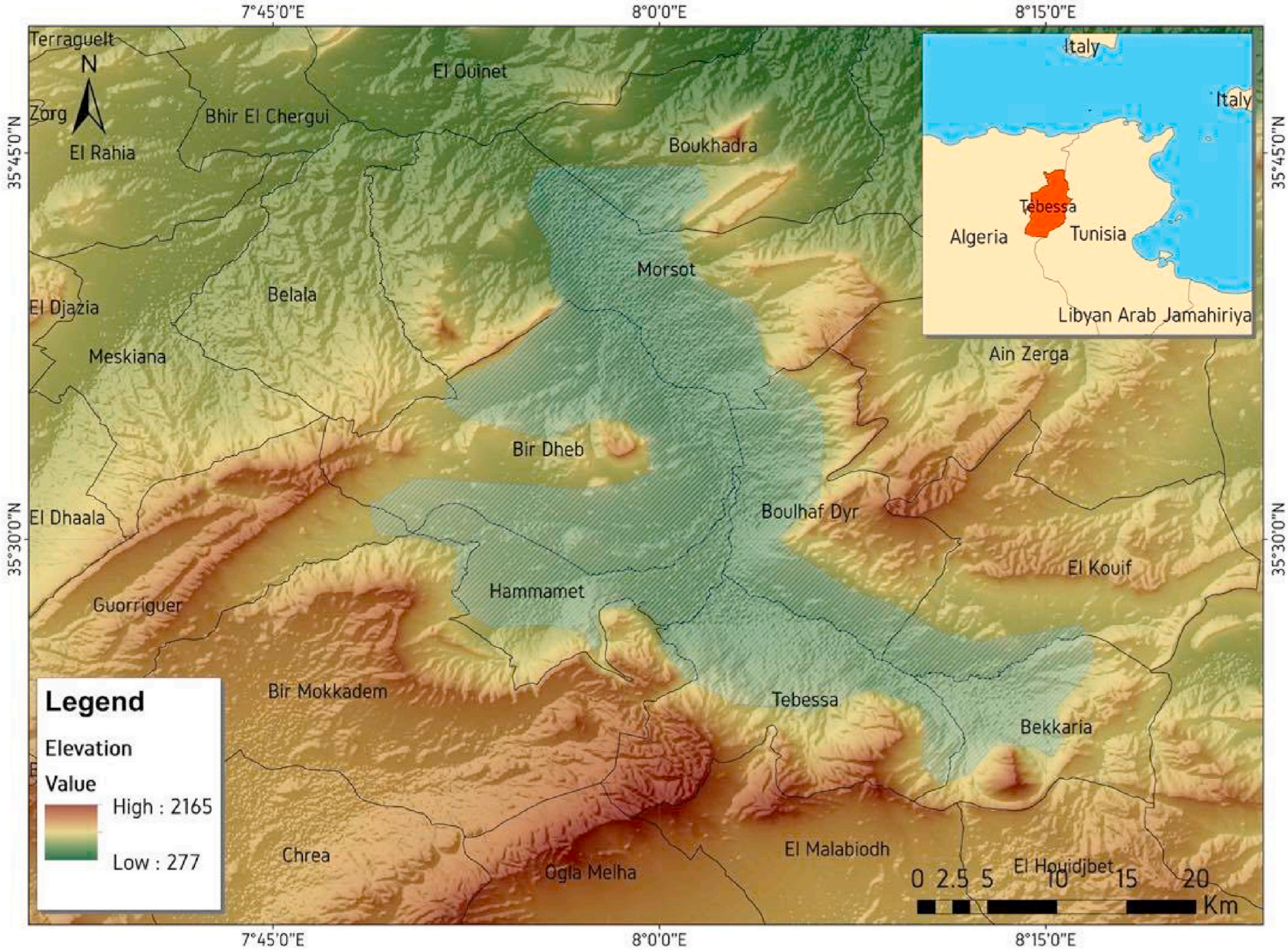

Fig. 1. Geographic location of the study area in northeastern Algeria.

(Drias, 2013). For the sustainability of the water resources, we propose to establish a diagnostic model of the hydrodynamic behavior of the aquifer. Such a diagnostic model will allow us to propose additions in order to ensure the rational management of the resource in the future. Hydrodynamic parameters are initially determined by a wide variety of analytical methods, such as Thies, Jacob and Chow (Theis, 1935; Jacob, 1940; Chow, 1952), which consider the aquifer heterogeneity. The hydrodynamic parameters (hydraulic heads, hydraulic conductivity and transmissivity) were then studied jointly by both the probabilistic method of the cokriging (Delhomme, 1978; Bohling, 2005; Shakeel, 1987) and the deterministic method using a groundwater simulation model by Modflow software (Version 3.0) (Harbaugh et al., 2000). The objectives of this study are: (1) enhance the aquifer hydrodynamic parameters (i.e. transmissivity, permeability and water head), which can be used later in the groundwater flow simulation by using geostatistical techniques (kriging and cokriging) and (2) study the actual and future effect of water extraction on the groundwater aquifer (under different scenarios) for better water resources management.

2. Material and methods

2.1. Study area

The city of Tebessa is located in the northeastern part of Algeria, at the gateway to the Algerian desert, about 650 km south-east of Algiers, the capital city (Fig. 1). The Tebessa-Morsott plain is part of the Medjerda watershed and the K'sob wadi sub-basin. The average elevation of the plain is about 900 m above sea level. The study area extends along the NW-SE direction and corresponds to a large closed depression (Kowalski et al., 1997) with an area of about 600 km$^{2.}$ It is bounded on the north by Zitouna Mountain, in the south by Bouroumane, Doukkane, Anoual, and Ozmour mountains, in the west by Matlougue Mountain, and by Djebissa Mountain to the east. These mountains are the main source of lateral water recharge of the shallow aquifer of Tebessa-Morsott. The piezometric levels vary between 710 m and 885 m above sea level with a hydraulic gradient (0.02–0.03) in the eastern and southern parts of study area (Drias, 2013). The climate is semi-arid, where the annual average rainfall is about 350 mm and evaporation rate is about 650 mm/year and the annual average temperature is 23 °C (Drias, 2013).

2.2. Geological and hydrogeological context

The geological structures are constituted by Cretaceous formations, forming a series of anticlines and synclines (Vila, 1980). The stratigraphic sequence is presented in the form of alternating carbonate formations of limestone, marly-limestones and argillaceous marls (Kowalski et al., 1997). Plio-Quaternary and Quaternary formations occupy the central part of the Tebessa-Morsott plain and are composed of alluvial deposits, conglomerates, gravels and sandstones, and contain the shallow groundwater aquifer (Drias, 2013). The Tebessa-Morsott shallow groundwater aquifer is mainly recharged by direct

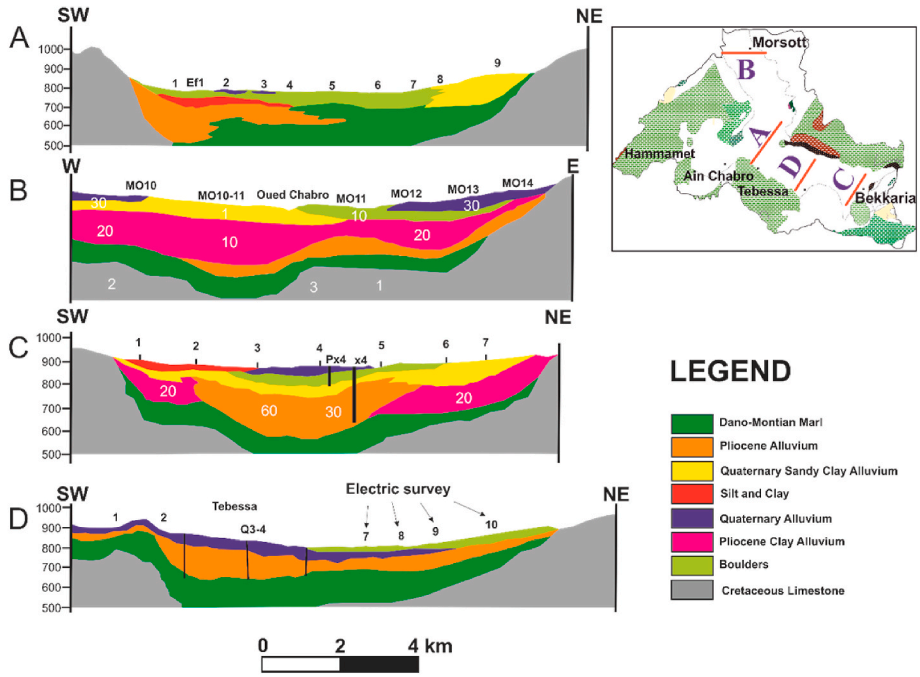

Fig. 2. Geo-electrical cross sections (modified from CGG, 1975). The Tebessa-Morsott groundwater aquifer is mainly located in Pliocene and Quaternary alluvium layers.

precipitation and from the leakage from a deep aquifer (cretaceous formation) through faults (Drias, 2013) (Fig. 2).

The thickness of the shallow aquifer is variable, reaching 300 m in the Ain Chabro area (southern part) thus constituting an area favorable for drilling. Transmissivities of the shallow aquifer were estimated from pumping tests of several water wells using analytical methods of Thies, Jacob and Chow (Theis, 1935; Jacob, 1940; Chow, 1952; Drias and Toubal, 2010) and probabilistics (cokriging) (Drias, 2013). The transmissivity values vary from 10^{-3} to 5×10^{-2} m^2/s, which allowed us to calculate the hydraulic conductivity of 3×10^{-4} m/s. The measured water discharge in 2010 from 22 water wells at Ain Chabro is 4700 m^3/day, which is the highest value in the study area.

2.3. Geostatistical approach

In hydrogeological studies, it is important to estimate hydrodynamic parameters from geoelectrical data. A number of authors give some linear regression models between hydrodynamic parameters (transmissivity, hydraulic conductivity) and electrical parameters (electric transverse resistance) (Pardo and Dowd, 2005). Multivariate geostatistical methods can also be used to find correlations between hydrodynamic and geoelectrical data (Shakeel, 1987). There is an advantage of using multivariate geostatistical method compared to the regression method, one being that the regression technique does not consider the spatial variability of the phenomenon; it simply neglects the spatial coordinates of the data. However geostatistics are based on the spatial variability and covariability of the different variables. Cokriging is a geostatistical technique, which improves the hydrogeological models. Cokriging calculates estimates for a poorly sampled variable with help of a well-sampled variable (Delhomme, 1978; Bohling, 2005). This is important in the case of the transmissivity (T) of an aquifer which is highly correlated with specific capacity and electric transverse resistivity (Shakeel, 1987). Also, T values are easy to measure in the field. The level of cross-spatial-correlation between two variables is given by the cross-variogram (Journel and Huijbregts, 1978; Vauclin et al., 1983).

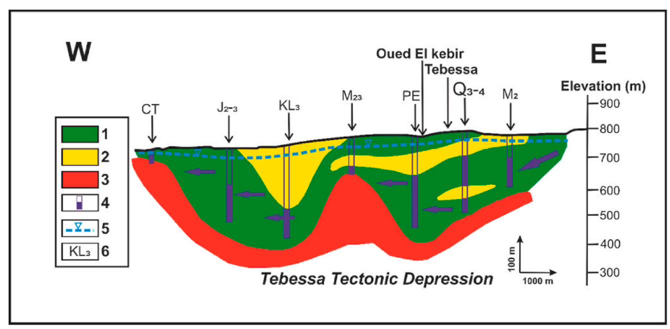

Fig. 3. Hydrogeological cross-section through the Tebessa-Morsott plain. **1** = Permeable zone (marly-limestones, alluvial fans, silts, calcareous crust, conglomerates, and gravels). **2** = Impermeable zone (clay and marl). **3** = Marly bedrock. **4** = Screened interval. **5** = Piezometric head. **6** = Well name. Elevations are above sea level. (modified from Drias and Toubal, 2010 and Rouabhia et al., 2010).

2.4. The Tebessa-Morsott aquifer numerical model development

The hydrodynamics and regional groundwater mass balance of the Tebessa-Morsott aquifer are still not well understood.

Developing the first numerical flow model of the study area will help to integrate all existing information and data on the Tebessa-Morsott aquifer for a better understanding of its groundwater flow hydrodynamics and provide a basis for a better groundwater management policies.

2.4.1. Aquifer geometry

Information from previous studies, (Rouabhia et al. (2010) and Drias (2013) combined with recent borehole lithostratigraphic logs and geoelectric pseudo-sections obtained from CGG (1975) helped in delineation of the main aquifer formations and morphology of the basement rocks (Fig. 3).

The piezometric map of 2010 (Drias and Toubal, 2010) was obtained from the steady state head of around thirty water wells exploiting the

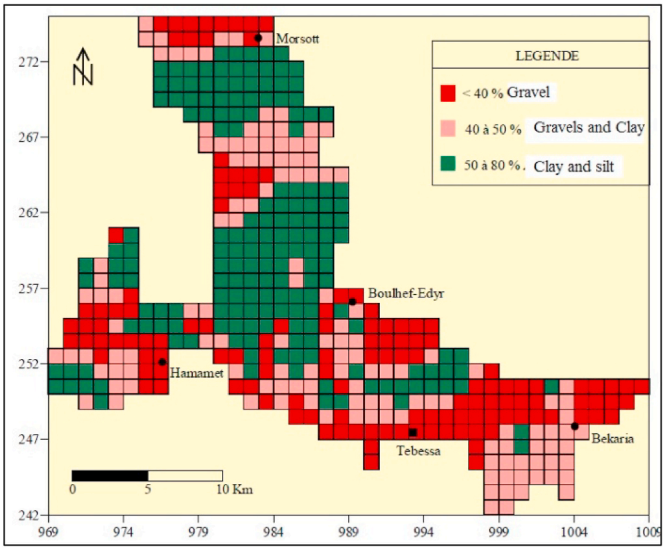

Fig. 4. Map of the total porosity (in %) of the Tebessa-Morsott alluvial aquifer (Kachi, 2007).

shallow aquifer (we note here that most of the wells were in the pumping shutdown state in 2010). This 2010 piezometric map was used as a top layer of the numerical model and for the calibration of the steady-state regime. Both the basement rock and the steady-state head maps allowed us to compute the saturated aquifer thickness map and develop the aquifer geometry model.

2.4.2. *Flow and mass transport*

Transmissivity values from 22 (short-term) pumping tests were provided by the local water management authority. These transmissivity data were estimated from conventional interpretation methods (i.e. assuming a homogenous medium) of drawdown data (Peaudecerf, 1970; Kerrou et al., 2010). First, in order to have a better transmissivity map for the whole area, we applied the cokriging method to the available transmissivity data. Next, the transmissivity map is transformed to hydraulic conductivities by using the total saturated thickness of the aquifer and length of water well screens for full penetrating water wells. After that, 22 permeabilities were calculated.

The mean hydraulic conductivity and the variance of the natural logarithm of hydraulic conductivities are 8.9 × 10−5 m/s and 0.67 respectively. These estimates are used as initial information for the calibration of the flow simulation model. With regard to transport parameters, there are no tracer test data to allow for the estimation of local dispersivity (Kerrou et al., 2010). However, the electrical resistivity value (ER) was used to estimate the porosity of the Plio-Quaternary formation of the shallow aquifer (Konikow and Reilly, 1998; Kachi, 2007). Fig. 4 shows the total porosity distribution at the Tebessa-Morsott aquifer (Kachi, 2007).

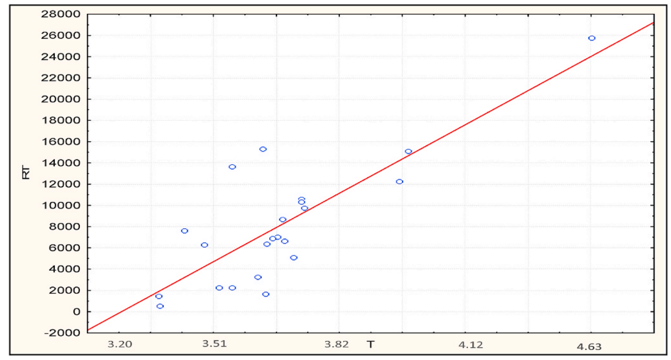

Fig. 5. Linear regression of Log (T) versus Log (RT).

2.4.3. *Water recharge zone*

Evaluation of effective recharge is a challenging task in arid and semi-arid regions (Scanlon and Goldsmith, 1997; Kerrou et al., 2010). Using Thorntwhaite's method, the effective recharge rate ranges between 5% and 8% of the regional average annual rainfall (Drias, 2013). These percentages are used in the numerical model according to the type of soil (the most permeable soils with 10% and the least permeable soils with 5%).

3. Results and discussions

3.1. *Geostatistical approach*

3.1.1. *Hydrodynamic and geoelectric data*

Transmissivity (T) data, mostly from short duration pumping tests, are available at 22 wells not well distributed in the study area (Drias, 2013). Data on electric transverse resistance (TR) exists at 127 points in the study area (GCG, 1975).

Kachi (2007) calculated the electric transverse resistance based on the apparent resistivity and saturated thickness, measured through Vertical Electrical Sounding (VES). The electric transverse resistance was corrected for the variations in the water resistivity measured directly in sampled water from wells. T and TR corrected values (Table 1) were used in the geostatistical approach (cross-variogram and cokriging).

Previous studies (Shakeel, 1987; Pardo and Dowd, 2005) showed that transmissivity and transverse resistance have a lognormal distribution and hence they were transformed to logarithmic distribution and their logarithms taken. The linear regression of Log (T) versus Log (TR) shows a good correlation coefficient of 0.715 (Fig. 5, Table 2) thus justifies the data transformation (see Fig. 6).

The experimental histograms suggest that a single adjustment by a log-normal distribution would be valid. However, the X^2 test rejects this hypothesis at the threshold of 0.05, for the Log (T) variables. Under these conditions, the adoption of the log-normal distribution for the two variables (T and RT) must be considered as a suitable reference model,

Table 1
Transmissivity (T) and Electric Transverse Resistivity (TR) input data used in cokriging calculation.

Well ID	T x10^{-3} (m^2/s)	TR corrected (Ω.m^2)	TR raw data (Ω.m^2)	Well ID	T x10^{-3} (m^2/s)	TR corrected (Ω.m^2)	TR raw data (Ω.m^2)
D12	0.08	3238	1865	Ac1 bis	1.71	6264	5350
X4	2.61	2245	6450	F3	1.73	8677	4850
W2 bis	3.2	10566	5880	N°69	0.80	2271	28000
X2	2.65	7031	4400	M1	3.57	15308	6503
J2-3	2.59	13616	10000	YS4-5	14.01	25721	19950
M2-3	0.29	554	4000	QR5	0.28	1438	1500
V4	3.71	6319	1850	E2-3	3.66	1663	1569
F2-3	2.3	9747	5300	FA2	1.69	6900	4300
Q3-4	4.8	10351	18000	EF1	4.25	6598	5811
FG1	4.55	5102	6000	KL3	1.10	7634	10075
Q5	2.47	15070	6300	M2bis	1.82	12240	6000

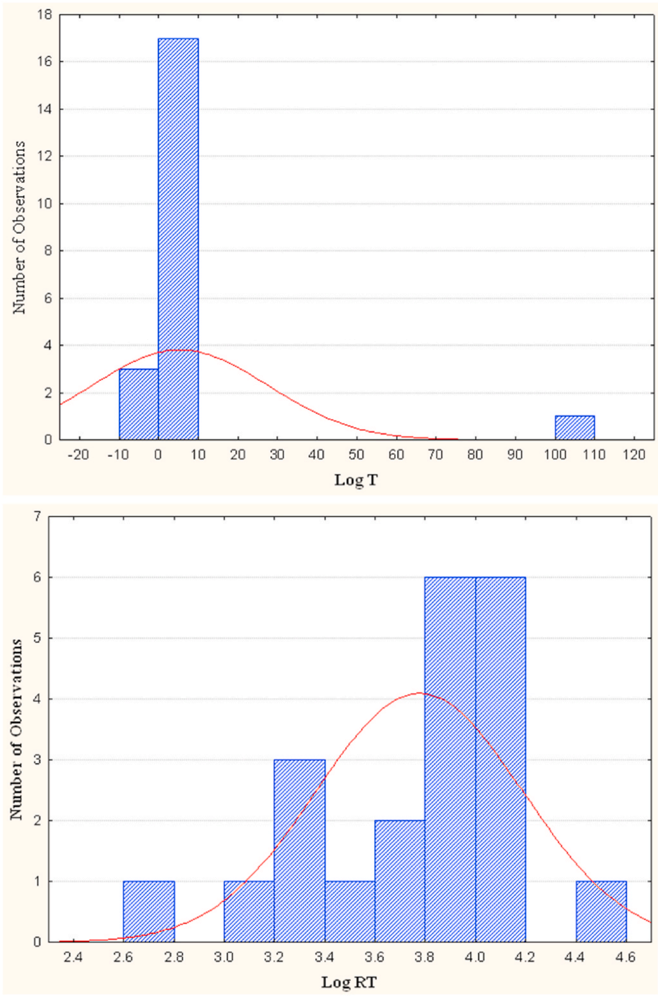

Fig. 6. Experimental histograms of Log (T) and Log (RT).

allowing simple and sufficiently precise calculations.

The histograms have a unimodal appearance; the distribution tail on the low value side (for TR) is due to the heterogeneous materials.

3.1.1.1. Experimental variogram. After data normalization, the experimental variograms were plotted by GS + software (Deutsch, 1998). Then, the best theoretical model was fitted to each variogram based on the minimum RSS (residual sums of squares). A cross validation method was used to determine the accuracy of the estimated data. The nugget effect for transmissivities can be attributed to measurement errors and micro-regionalization. These effects are however less important for transverse resistance (TR) which benefits from a measurement network, compatible with the scale of work. Fig. 7 shows the theoretical models (spherical) adjusted to experimental models considered consistent with the data.

3.1.1.2. Cross variogram. After data normalization, the experimental variograms were prepared. The results including cross-variograms are presented in Table 3 and Fig. 8.

Cross-validation tests confirm the validity of the variograms. The calculated transmissivity values using a cokriging system are then carried out on square mesh of uniform sizes (500 m × 500 m). The results are presented in Fig. 9 (a,b,c). The residual transmissivities (Fig. 9a) show that the deviations are minimal and justify the choice of the spherical model which fits well with the logarithmic variables while the obtained transmissivities map is much better and reflects the lithology of the aquifer well.

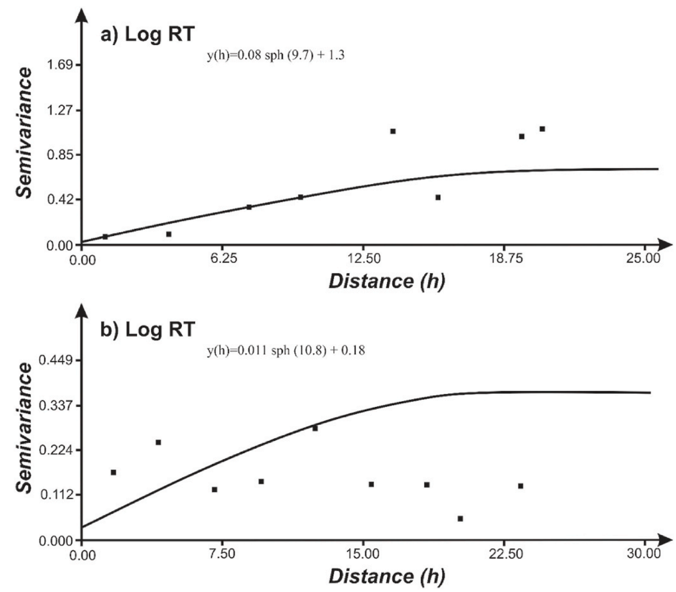

Fig. 7. Experimental semi variograms of: a) Transmissivities, b) Electric transverse resistance.

Table 3
Cross variograms and validation results [Log (T), Log (TR)].

Theoretical model				Cross validate		
Equation	Nugget effect	Rang	Scale	md	msqe	mrd
$y^{zx} = 0.089$ Sph (14.48) + 0.38	0.089	0.38	14.48	0.007	0.994	0.0106

md: mean deviation; msqe: mean squared error; mrd: mean reduced deviations.

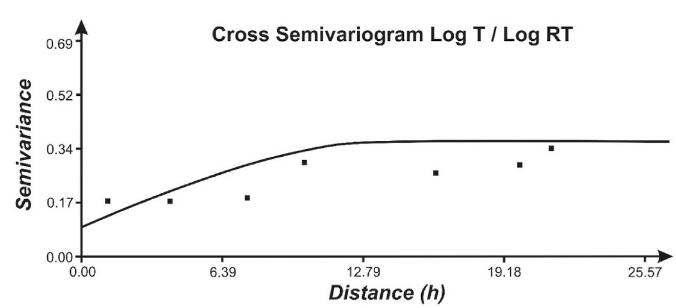

Fig. 8. Cross variogram (log T, log RT).

Table 2
Results of linear regression.

Variable	Number of Obs.	Std error of estimation	R multiple	R^2	R^2 Adjusted	di	p	F
T	22	2.028	0.715	0.512	0.488	1.20	0.00017	21.02

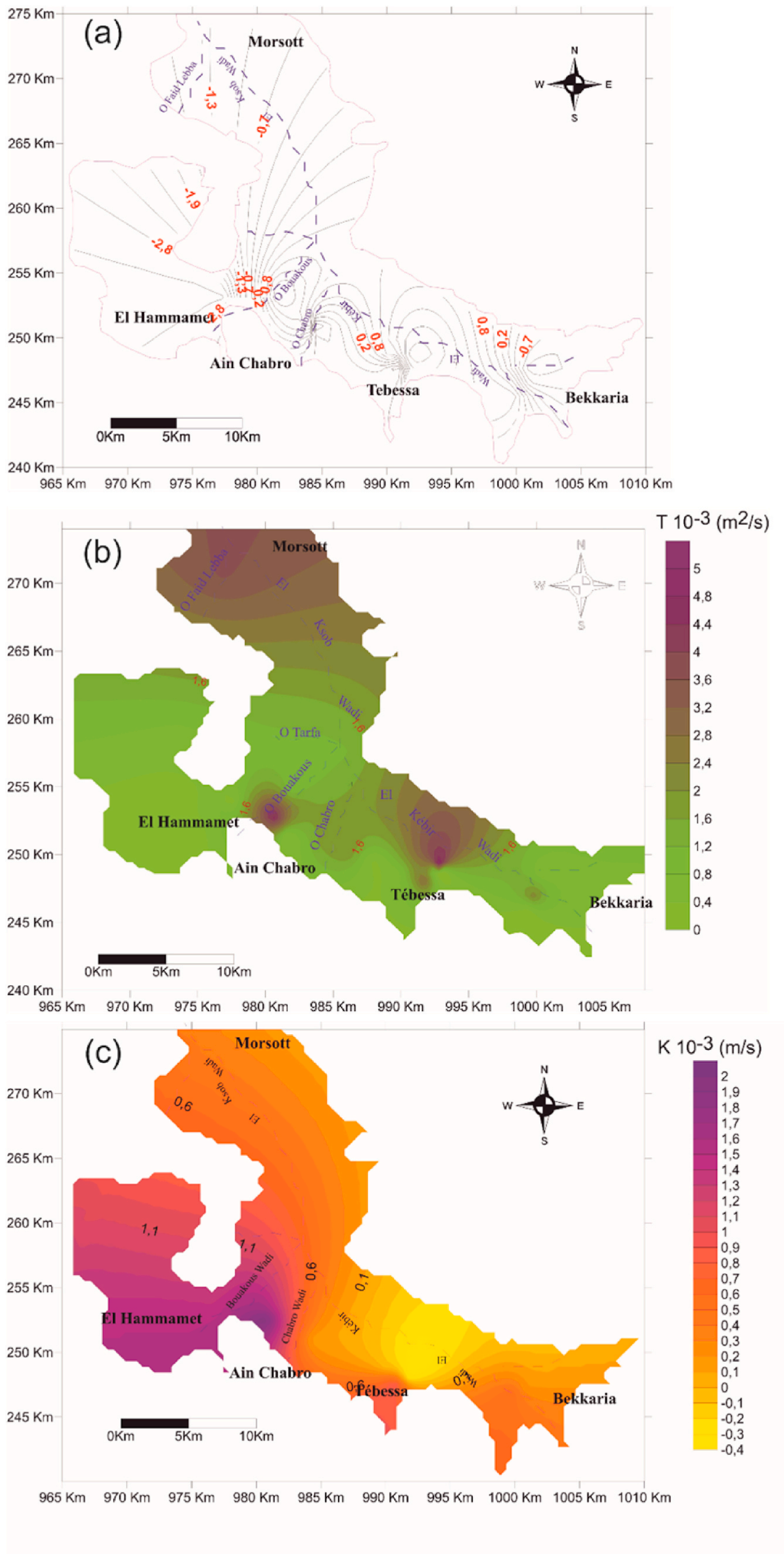

Fig. 9. (a) Map of residual values of transmissivity, (b) Kriged map of transmissivity (10-3 m^2/s), (c) Kriged map of hydraulic conductivities (10-5 m/s).

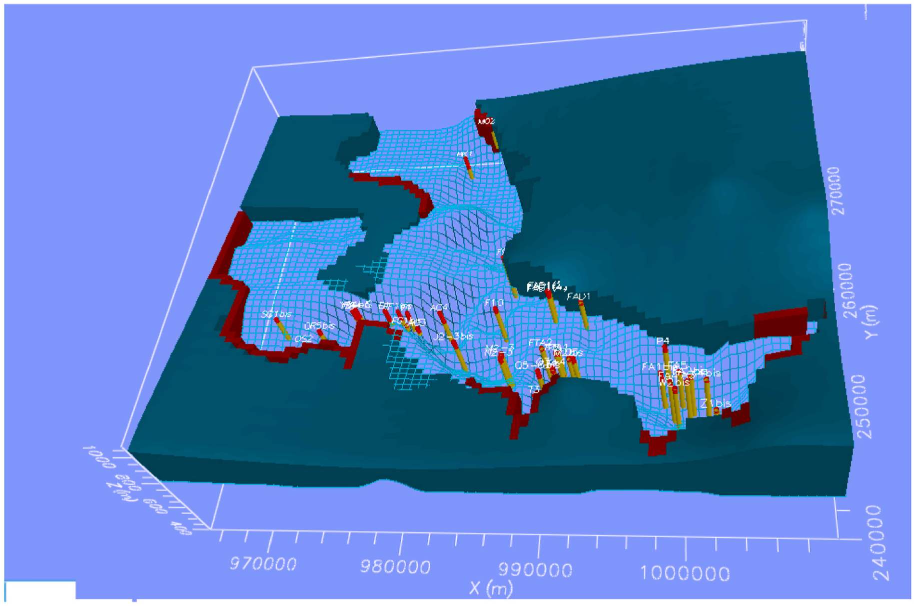

Fig. 10. Model grid and boundary conditions of the Tebessa-Morsott aquifer. Brown blocks show the boundaries open to lateral water flow.

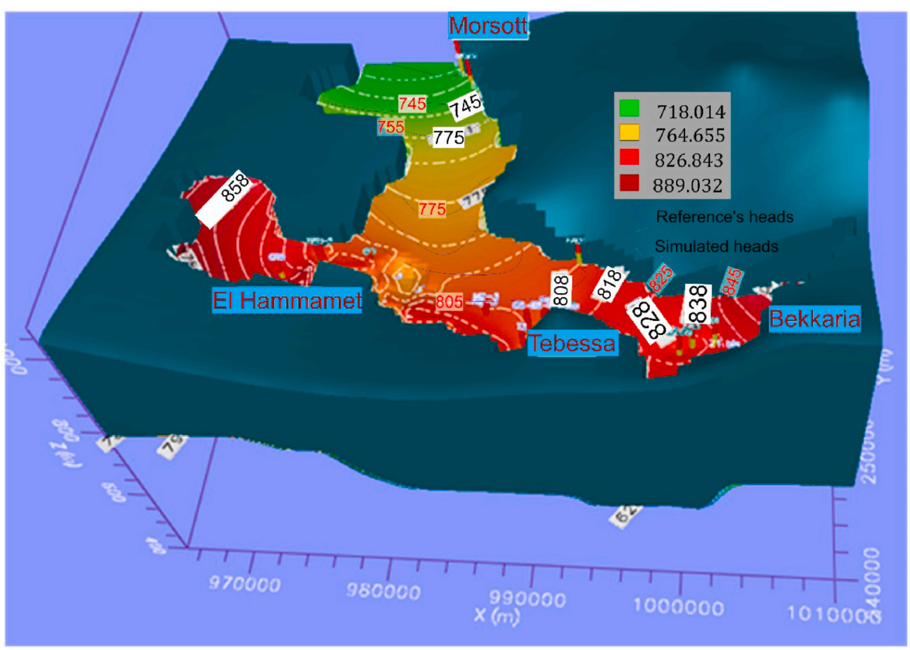

Fig. 11. Simulated heads in steady-state regime.

3.2. Groundwater flow model of a shallow aquifer in Tebessa-Morsott

The groundwater flow model was developed using MODFLOW Software (Harbaugh et al., 2000; Waterloo, 2011). The finite difference model consists of 70 rows, 82 columns and 1 layer. The study area (600 km^2) is covered by 1200 cells and each cell has a dimension of 500 m × 500 m (Fig. 10).

A three-dimensional (3D) digital hydrogeological framework model (HFM) was developed which defines the physical geometry and materials of hydrogeological units and the hydrogeological structures (Hill, 2006). The hydrogeological framework model was discretized into numerical flow model input arrays using Hydro-geological Unit Flow package of MODFLOW-2000 (Harbaugh et al., 2000). The permeability distribution map of the top layer of the aquifer is used by Modflow software. In some lateral boundaries of the Tebessa-Morsott alluvial aquifer, the boundaries are closed and do not permit lateral flow. These closed boundaries are first detected from the piezometric map. Some boundaries were simulated as open flow boundaries where hydraulic gradients permit flow across these boundaries through fractures or high permeability zones.

3.2.1. Flow simulation model

3.2.1.1. Steady state regime. The simulation is divided into a steady state regime and a transient regime. The steady state regime is before 2010 with no pumping. The transient regime was then developed for the period 2010 and 2030 and was divided into annual stress periods for which pumping rates were defined. The constructed numerical model

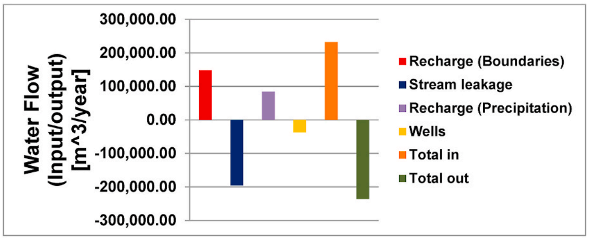

Fig. 12. Aquifer budget in the steady-state regime.

was calibrated using a nonlinear regression method. The final calibrated model was evaluated by comparing measured and computed groundwater heads and discharges (pumping wells). Good fit with observed groundwater heads are observed in areas of flat hydraulic gradients. Mean fit with the observed groundwater heads is visible in areas with steep hydraulic gradient (Fig. 11).

The results from the hydrogeological assessment of calibration in the steady-state regime are the followings (Fig. 12):

- Outflow from Tebessa-Morsott aquifer: 195,320.6 m^3/year.
- Contribution by the boundary limits (Maestrichtian and Turonian limestones): 147,953.4 m^3/year.

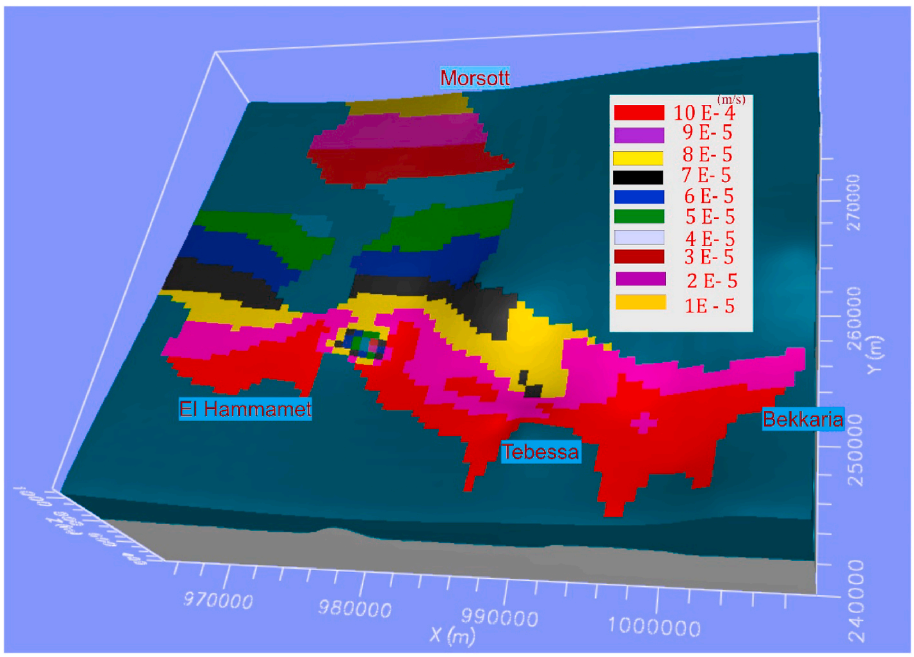

Fig. 13. Hydraulic conductivity map generated by model in the steady-state regime. Units are in m/s.

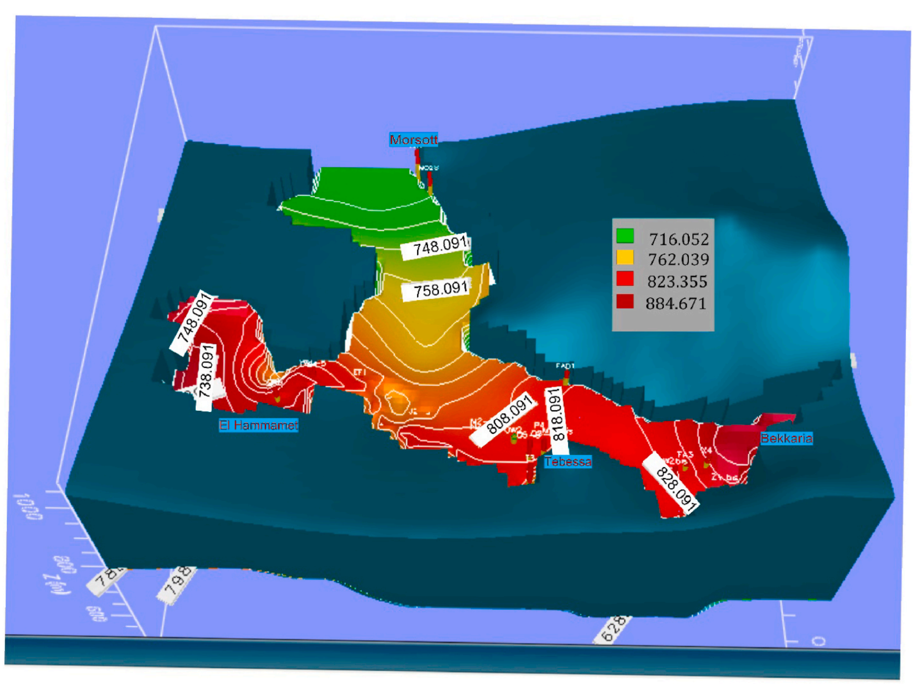

Fig. 14. Simulated heads for transient regime in the case of the first scenario.

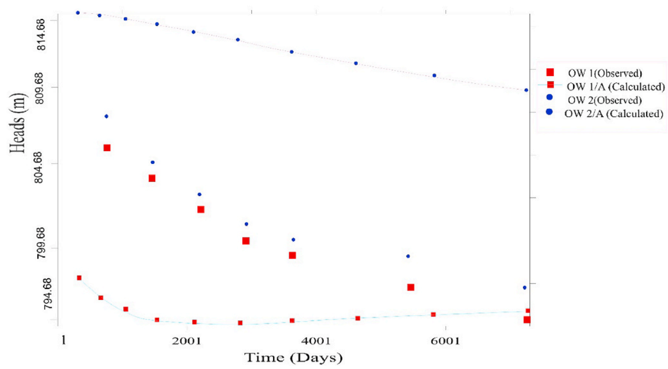

Fig. 15. Average of simulated groundwater level in well GR5 (El Hammamet zone) in the case of the second scenario (transient regime).

- Contribution by precipitation (recharge): 84,354.33 m^3/year.
- Pumped water rate: 36,986.0 m^3/year.

The results obtained by the model, especially recharge by rainfall and inputs by border limits, are similar to those calculated by the empirical approach.

The various tests of the model made it possible to adjust the hydraulic conductivity ranges from 10^{-5} to 10^{-4} m/s (Fig. 13). The most permeable areas are found in the south part of the plain (Ain Chabro), while in the center part the hydraulic conductivity values remain low. Overall, this distribution resulting from calibration is the same as that obtained from block kriging. However, a slight increase in values is obtained in the south part of the plain (Ain Chabro) (10×10^{-4} m/s), while in the center of the plain the hydraulic conductivity decreases to 10^{-5} m/s.

3.2.1.2. Transient regime. The simulation in the transient regime represents a continuation of the steady-state regime under external conditions. The main objective of this simulation step is to represent the future conditions of the hydraulic heads of the Tebessa-Morsott aquifer. Two scenarios were developed during this transient regime modeling: (1) first, with same existing recharge and discharge conditions of the steady-state regime and a simulation for 20 years, and (2) second, with increasing discharge from the productive water wells.

The hydraulic heads map generated with the first scenario shows similarities with flow directions as calculated in the steady state, with: $h_{min} = 716.05$ m (Morsott zone) and $h_{max} = 884.67$ m (Bekkaria and Tebessa zones) (Fig. 14). In the second scenario, we increased the discharge rate from the most productive wells located in four different sectors of the study area namely: El Hammamet (GR5), Ain Chabro (J2-3bis), Tebessa (T3) and Bekkaria (W2bis). The hydraulic heads map generated in the second scenario (Fig. 15) shows considerable drawdowns in the aforementioned wells of up to 40 m in the south part of steady area (El Hammamet zone).

4. Conclusions

In this paper, an approach for hydrodynamic data preparation for the numerical hydrogeological model is presented for the combined use of a flow-simulation model with optimized transmissivity values using a cokriging method aiming at the rational and optimal management of groundwater aquifer. The use of the cokriging method helps in improving the transmissivity data, which are originally insufficient for the database of the flow simulation model. This made it possible to optimize the permeability fields in steady-state, whose values range from 10 to 4 to 10-2 m/s. The results of the transient regime for the Tebessa-Morsott aquifer hydrodynamic model reveal large drawdowns reaching 40 m for the year 2030 scenario. For future recommendations, we propose an artificial recharge of the Tebessa-Morsott shallow aquifer by the flood waters of Bouakous River while setting up levees at the borders of the river to reduce the velocity of flowing waters and increase the effective infiltration (recharge) to the shallow aquifer.

Declaration of competing interest

We declare that there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2020.100444.

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