Pumping regime influence on groundwater quality in the proximity of a polluted lake

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Abstract

Our work analyzes the impact of the pumping regime in a series of wells on groundwater quality in an aquifer bounded by a polluted lake. The natural river Olt was modified for energetic purposes and turned into a lake in the proximity of the Romanian town of Slatina. Drinking water for Slatina is obtained by a pumping system of 160 wells disposed in lines along the lake margins. A total discharge of 460 l/s is pumped from two groundwater layers: a confined one and an unconfined (phreatic) layer, separated by an aquitard. We integrate the equations describing the three dimensional water flow and pollutant dispersion in the phreatic aquifer using the Visual MODFLOW-PRO program. We use boundary conditions from measured levels in the wells and local geomorphological data to calibrate the model. Model results agree well with observed equipotential lines for the phreatic aquifer. A big chemical plant situated upstream pollutes the lake and in turn the local groundwater. The chosen level of pumping in the wells is shown to strongly influence the flow direction in the phreatic and the resulting level of pollution in the pumped water. We show that decreasing the well pumping rates increases the water travel time such that the pollutant concentration in drinking water can be decreased under admissible limits. We calculate how pollutant concentration in the drinking wells depends on the value chosen for the dispersivity coefficient.
Keywords: groundwater pollution, pumping system, pumping rate, phreatic aquifer, pollutant concentration.

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1 Introduction

Groundwater constitutes an important component of many water resource systems. Due to good purification properties of the soil, groundwater is generally a very good source of drinking water. Drinking water for the Romanian town of Slatina is pumped from groundwater: 34 wells pump water from the phreatic aquifer and 83 wells pump from a deeper confined aquifer. The wells, functional since 1975, are disposed in lines on the banks of the river Olt, the fourth largest river in Romania by length and drainage area. Geo-morphologically, the pumping area is characterized by the presence of meadows and terraces of the river Olt.

The hydropower planning of the area downstream of the river Olt has resulted in the formation of the Strajesti, Arcesti, and Slatina lakes (the latter two shown in fig. 1). The presence of these lakes has altered the natural groundwater flow. The supply with water of the phreatic aquifer is mainly achieved by rainfall and by the discharge from the hydrographic net components whose free surfaces are situated at levels higher than the water table of the aquifer.

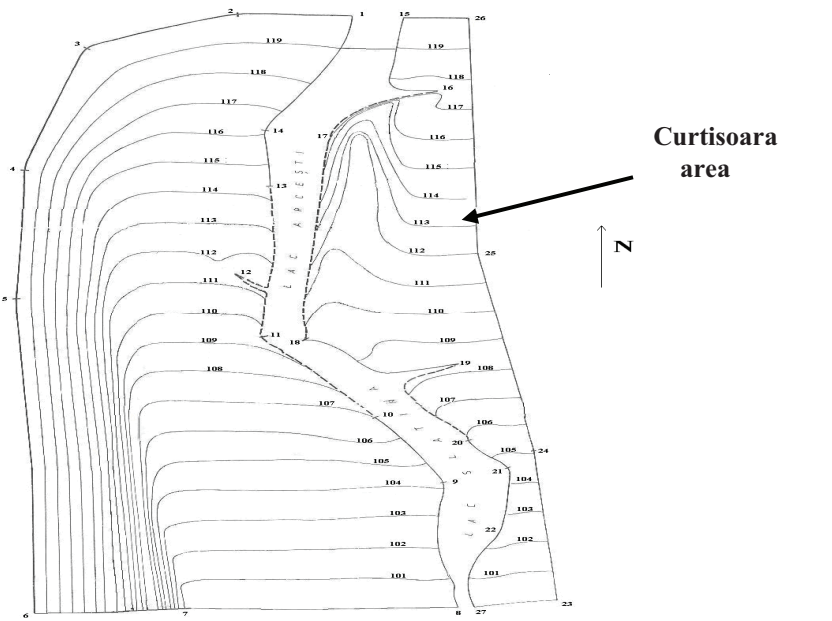

Figure 1: Measured equipotential (constant head) lines for the phreatic aquifer in the Slatina town area. River flow direction is from North to South.

Impervious spaces in the channel walls allow water to flow from the lake to the groundwater and vice versa. The aquifer's water quality can thus be influenced by the pollutant concentration of the river Olt. The river and local lakes are polluted by a large chemical plant situated upstream.

Groundwater is pumped from two groundwater layers: an unconfined phreatic layer and a deeper confined layer, as previously described in [1]. In the Curtisoara region there are 34 small depth (10-15m) wells in the phreatic aquifer with a total discharge of 118 l/s and 18 average depth (50-120 m) wells in the confined aquifer with a total discharge of 74 l/s, located N-E of the Slatina watershed and east of lake Arcesti (fig 1). Equipotential lines for the phreatic aquifer in our study region are shown in fig. 1. A cross section through the two aquifers is presented in fig. 2. The first 5-12m layer of the phreatic aquifer composed of alluvial materials such as coarse sand and gravel is directly connected to the river water in the Curtisoara area, as indicated by dashed lines along the river banks in fig. 1 (16-17-18). In the phreatic layer has observed transmissivity values between 50 and 1000 m^2/day and a hydraulic conductivity K=35m/day.

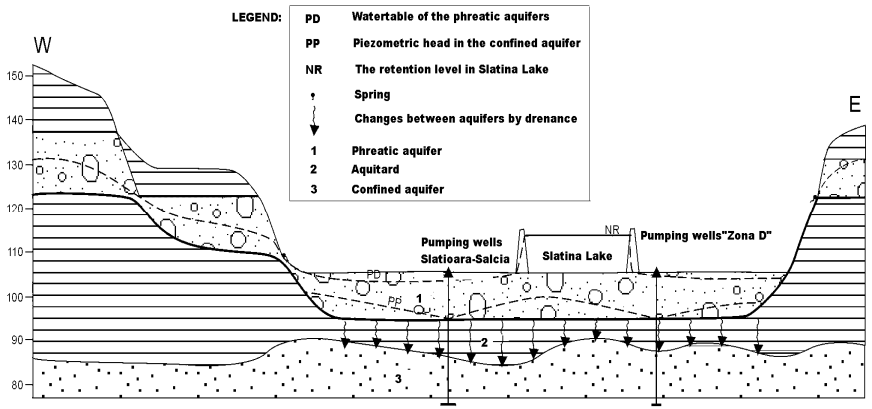

Figure 2: Hydrogeological section showing the local groundwater flow system in the Slatina lake region.

The confined aquifer stores water under pressure (fig. 2) in the Candesti layers (15-160m). Between the phreatic and the confined aquifer there is an aquitard with variable thickness (2-25m) and low hydraulic vertical conductivity K=2.5-3.0 10^{-4} m/day with some local values of 5 10^{-2} m/day. If M is the aquitard depth, the aquitard drainage parameter is K/M=1.5 - 3.0 10^{-5} day $^{-1}$.

The objectives of the present study are to understand the effect of pumping via a set of wells located along the river banks on the hydrologic flow regime and on groundwater vulnerability to pollution. In particular, we will assess the effects of both increased and decreased pumping rates in time, taking into account the changing water quality in the wells.

2 Mathematical formulation of the pollution model

Here we build a groundwater flow model to simulate the physical and chemical behavior of a pollutant in the Curtisoara phreatic aquifer. Our concrete aims are:

1. Investigate and explain the flow patterns in the phreatic aquifer.

2. Analyze how the phreatic aquifer flow pattern and pollutant concentration depend on the pumping rates in a set of wells located along the river bank.
3. Analyze the sensitivity of the calculated pollutant concentration to the choice of the dispersivity coefficient.

2.1 Mathematical modeling of groundwater flow

The groundwater flow can be described by introducing the velocity given by Darcy's law into the continuity equation [2]. The resulting diffusivity equation is

$$\mathrm{div}(\overline{\overline{T}}\ \mathrm{grad}h) = S\frac{\partial h}{\partial t} + q \tag{1}$$

where $\overline{\overline{T}}$ [L^2T^{-1}] is the transmissivity tensor; $\overline{\overline{T}} = \int_a^b \overline{\overline{K}}\,\mathrm{d}z$ (2)

$$T_{xx} = \int_a^b K_{xx}\,\mathrm{d}z, \qquad T_{yy} = \int_a^b K_{yy}\,\mathrm{d}z, \qquad T_{zz} = \int_a^b K_{zz}\,\mathrm{d}z \tag{3}$$

a, b [L] are the layer limits in the z direction; K_{xx}, K_{yy}, K_{zz} [LT^{-1}] are the hydraulic conductivities in the x, y and z direction. h [L] is the hydraulic or piezometric head, $h = p/(\rho \cdot g) + z$; q [LT^{-1}] is the incoming discharge into an elementary volume on the unit surface. S [L^3/L^3] is the storage coefficient or storativity, equal to the effective porosity for the phreatic aquifer:

$$S = \int_a^b S_s\,\mathrm{d}z \tag{4}$$

where S_s [1/L] is specific storage of a saturated aquifer (the volume of water that a unit volume of aquifer releases from storage for a unit decline in head).

For phreatic aquifers storage of water is primarily done by filling up and draining of pores. Therefore the storage coefficient is equivalent to the storage effective porosity n_c and the diffusivity equation becomes:

$$\frac{\partial}{\partial x}(K(h-h_s)\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K(h-h_s)\frac{\partial h}{\partial y}) = n_c\frac{\partial h}{\partial t} + q \tag{5}$$

where $h(x,y,t)$ [L] is the level of the groundwater surface, $h_s(x,y)$ [L] is the level of the aquitard, $K(x,y)$ [LT^{-1}] is the hydraulic conductivity assumed constant in the z direction, $n_c(x,y)$ is the drainage porosity and $q(x,y,t)$ is the source term, which in our study is the well discharge per unit area. Equation (5) together with specification of flow and/or head conditions at the boundaries and initial head conditions constitutes a mathematical representation of a groundwater flow in a phreatic system.

For the Curtisoara phreatic aquifer we integrate equation (5) with the MODFLOW-2000 program, using groundwater surface levels from a set of observation wells as boundary conditions. MODFLOW-2000 [3] is a computer

program widely used by hydrogeologists that simulates one, two or three-dimensional groundwater flow using a finite difference solution of the differential equation (1). MODFLOW-2000 can simulate steady and non-steady flow in an irregularly shaped system (confined, unconfined aquifers or a combination of them), externally driven flows (e.g., flows to wells and drains), areal recharge, evapotranspiration, flow through river beds and flow through heterogeneous porous media. In the present study we access MODFLOW-2000 from within Visual MODFLOW, a pre- and post-processor for the MODFLOW and MODPATH models, which allows us to solve the flow model and to perform particle tracking and velocity vector analysis.

2.2 Solute transport modelling

The three-dimensional pollutant transport equation for advection-dispersion, including the effects of retardation of solute transportation through adsorption, chemical reactions, biological transformations or radioactive decay can be expressed as:

$$\frac{\partial(n_e C)}{\partial t}+\frac{\partial(\rho_b C_a)}{\partial t}=\sum\frac{\partial}{\partial x_i}\left(n_e D_{ij}\frac{\partial C}{\partial x_j}\right)-\sum\frac{\partial}{\partial x_i}(n_e C v_i)+\sum C'w-\lambda(n_e C+\rho_b C_a) \tag{6}$$

where: C is volumetric concentration (mass of solute per unit volume of fluid [ML^{-3}]); n_e is the effective porosity (dimensionless); ρ_b is the bulk density of the aquifer material (mass of solids per unit volume of aquifer [ML^{-3}]); C_a is the mass concentration of solute adsorbed on or contained within the solid aquifer material (mass of solute per unit mass of aquifer material [MM^{-1}]); v_i is a vector of interstitial fluid velocity components [LT^{-1}]; w is a volumetric fluid sink (w<0) or fluid source (w>0) rate per unit volume of aquifer [T^{-1}]; C' is the volumetric concentration in the sink/source fluid [ML^{-3}]; λ is the decay rate [T^{-1}]; t is time [T]; x_i, x_j are any of the three Cartesian coordinates [L]. For a dispersivity coefficient α [L] and a diffusion coefficient D_0 [L^2T^{-1}], the second-rank tensor of dispersion coefficients D [L^2T^{-1}] can be written as $D = D_0 + \alpha|v|$.

The solute transport equation (6) needs to be integrated in three dimensions using initial and boundary conditions, and given source concentrations. Visual MODFLOW Pro can solve this equation using different numerical methods (MOC, MOC3D, MMOC, HMOC, Upstream Finite Difference, TVD). Here we use MOC3D, a subroutine developed by the U.S. Geological Survey [4] for simulation of three-dimensional solute transport in groundwater. The subroutine uses the method of characteristics to solve the transport equation (6) on the basis of the hydraulic gradients computed for a given time step following the integration of equation (5).

The hydrodynamic input data are: a constant aquifer thickness of 15m, aquifer length and width of 17000 m and 4000 m, an effective porosity of the material n_e = 0.2, total porosity, n=0.3 and hydraulic conductivities $K_x = K_y = K_z$ =35 m/day. The boundary conditions for the groundwater flow are illustrated in

fig. 3: ABCDEF is the river boundary with linear variation of the free surface level between h=120 m at A and h=100 m at F; section AM has constant head h=120 m; section FG has constant head h=100 m. Finally, we assume no discharge through the wall MG. The initial head in the aquifer is chosen as 115m. The coordinates for wells W1 through W7 are known (fig. 3). Water in the wells is pumped throughout the entire depth of the aquifer.

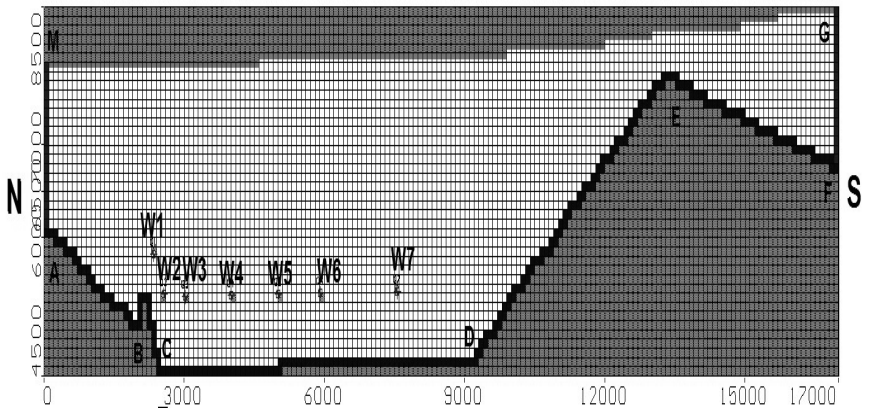

Figure 3: Boundary conditions for the phreatic aquifer. Domain dimensions shown in meters. Grid size is dx=100m, dy=100m. A line of wells going from north (to the left of the figure) to south is indicated by W1-W7. River flow is from N to S, river boundary is indicated by the ABCDEF contour.

The transport input data are: dispersivities $\alpha_x = \alpha_y = 100$ m, $\alpha_z = 10$ m and a diffusion coefficient $D_0 = 0$ m^2/day, such that our tensor of dispersion coefficients becomes $D_i = \alpha_i|v_i|$. The recharge flux and evapotranspiration are neglected. We assume the concentration of source (lake) pollutant does not change in time and impose this concentration $C(x, y, z) = C_0 = 100$ mg/l as the boundary condition for the dispersion equation (5) along the lake boundary ABCDEF. Initial pollutant concentration in the entire aquifer is $C_i(x, y, z) = 0$.

To simplify our analysis and graphical interpretation, the 34 Curtisoara-region wells are grouped into 7 groups, each group acting as a large well located in the centre of the group with a total discharge equal to the sum of discharges from the respective group; the locations of the large wells W1-W7 are shown in fig. 3.

We calibrate the flow model using a certain set of pumping discharges in order to obtain the water level contours given in fig. 1. This contour map of equipotential (constant head) lines for the phreatic aquifer has been drawn using measured levels in observation wells. We will call that set of discharges the "real pumping case"

Table 1 gives the coordinates of pumping wells, and the pumping data for the "real pumping case". For each of the 7 wells we show here the water discharge pumped (m^3/day) and the pollutant concentration C (mg/l) in the pumped water

after 5000 days computed with Visual MODFLOW PRO program, for dispersivity values α_L=20m and α_L=100m.

Table 1: Pumping data for wells and water concentration after 5000 days.

Well	Well coordinates		Q_{real} m^3/day	C(t=5000days) α_L=20m	C(t=5000days) α_L=100m
	X(m)	Y(m)			
W1	2349.25	5817.74	2000	91.234	85.476
W2	2570.19	5376.84	3000	99.864	98.764
W3	3025.91	5361.51	3000	87.748	89.199
W4	4021.15	5373.15	3000	82.000	82.415
W5	5013.00	5385.62	3000	84.220	83.912
W6	5911.80	5390.68	2000	89.648	89.290
W7	7507.00	5410.93	1500	83.462	82.305

3 Results and discussion

We analyze 3 different pumping scenarios: (1) no pumping from any of the wells (Q=0 m^3/day), (2) a case with Q=1000 m^3/day at all wells, (3) the above "real pumping case" at each well (with values from 1500 to 3000 m^3/day, at each well (with values from 1500 to 3000 m^3/day, see details in Table 1).

Table 2: Pollutant concentration in wells for three pumping schedules, after T days. Case α_L=100m.

T (day)	Q(m^3/d)	W1	W2	W3	W4	W5	W6	W7
500	real	27.72	86.92	27.85	17.86	22.44	18.00	18.01
	0	0.45	20.33	0.51	0.003	0.008	0.012	0.013
	1000	10.67	66.89	4.84	1.04	2.26	2.95	2.95
1000	real	46.20	92.71	61.84	47.58	52.15	47.54	47.54
	0	2.07	39.05	3.06	0.030	0.066	0.104	0.104
	1000	24.37	83.40	22.13	7.41	11.70	14.57	14.57
2000	real	65.85	97.91	80.51	72.40	74.56	74.26	74.26
	0	8.67	58.43	14.33	0.34	0.509	0.831	0.831
	1000	44.14	92.74	55.85	28.47	35.91	41.52	41.52
3000	real	76.50	97.57	85.69	79.15	81.07	83.51	83.51
	0	18.19	67.88	27.42	1.43	1.44	2.34	2.34
	1000	58.18	95.45	72.67	46.33	53.18	58.69	58.69
5000	real	85.63	97.50	89.85	82.65	84.29	89.53	89.53
	0	38.85	78.42	47.35	7.64	4.22	6.40	6.40
	1000	74.22	97.45	84.69	66.85	70.31	74.21	74.21

In each scenario we run two sets of simulations using two different dispersivity coefficients α_L (20m and 100m), for a total of 6 simulations. Resulting concentrations in each of the wells for the three scenarios are shown in Table 2.

We start by analyzing the water level contours, flow lines, flow direction along pathlines, and equal pollutant concentration surfaces in the aquifer when there is no pumping in the wells (fig. 4) and with the "real pumping case" rates (Q_{real}) given in Table 1 (fig. 5).

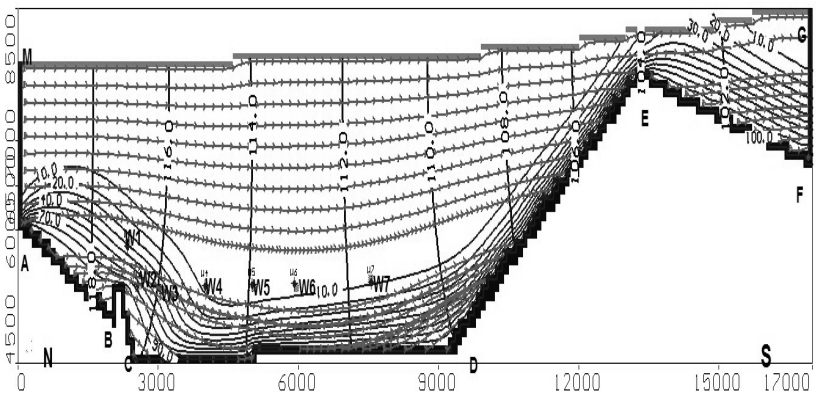

Figure 4: Equal hydraulic potential lines (in m), water flow lines (arrows) and equal pollutant concentration contours (from 10-100mg/l) in the phreatic aquifer, assuming no pumping in the wells. River boundary is ABCDEF. Distance between two arrow heads indicates the distance water covers in 1000 days. Water travels slowly from N to S (from left to right on our figure) at the eastern domain edge, and faster near the river.

In figures 4 and 5 arrows indicate the direction of flow in the aquifer and the distance between two consecutive arrow heads indicates the distance water covers in 1000 days. In the case in which there is no pumping, transversal dispersion ensures that the region east of the river becomes polluted after about 5000 days, but the overall level of pollution is much smaller than in the well region close to the lake (fig. 4). Water travels in the aquifer from N to S following the river flow, and flow rate decreases with distance from the river bed. Similarly, pollutant concentration contours are aligned with the lake boundary. Pollutant concentration decreases away from the lake, which is the pollution source in the problem.

Pumping water from the wells affects the flow and pollutant concentration at the well sites, with flow lines from the river going into the wells (fig. 5b). Wells (W1-W7) are supplied with water from both the polluted lake and from other, less polluted regions of the aquifer. The lake water needs at least 1000-2000 days to reach wells W3-W7. As the closest well to the lake, W2 is supplied from all directions with lake water and is thus most exposed to pollution (fig 5b).

Pollutant concentrations at W2 are larger than anywhere else in the aquifer, reaching 50 mg/l - half of the lake source concentration – after 137 days if α_L=100 m and after 147 days if α_L=20 m. W2 concentrations reach 90 mg/l after 700 days if α_L=100 m and after 600 days if α_L=20 m.

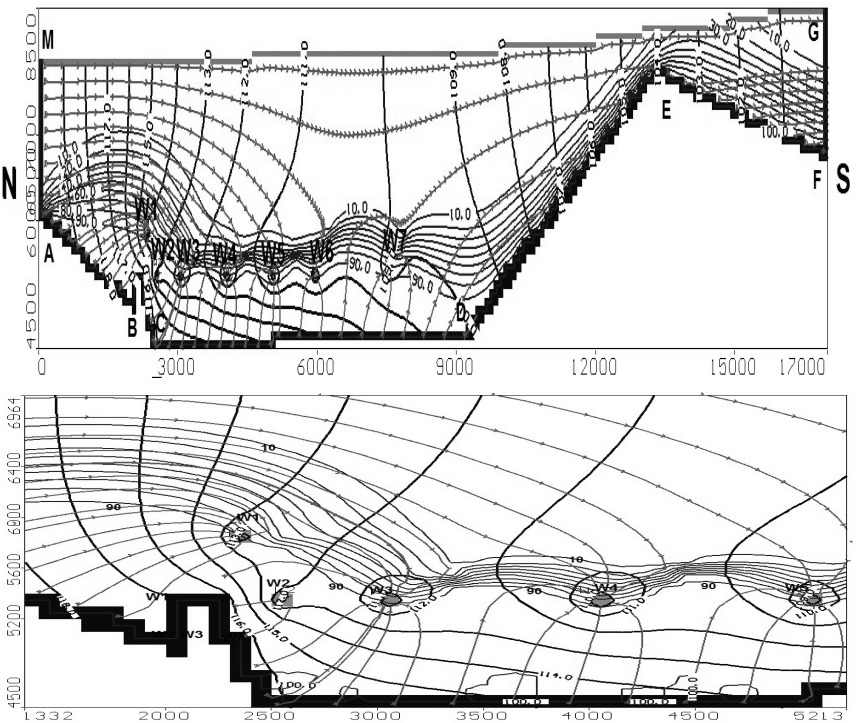

Figure 5: a (top): Flow lines (arrows) and equal pollutant concentration contours (from 10-100mg/l) in the phreatic aquifer, in the "real pumping case". River boundary is ABCDEF. Pumping results in flow towards the wells. b (bottom): Detail for fig 5a.

The concentration of pollutant in a given well depends on the closeness to the source (lake) and the time since the beginning of the pollution event (fig. 6). Pollutant concentration values increase in time, reaching the maximum value – equal to the source concentration of 100 mg/l faster if the well is closer to the pollution source (e.g., wells W2 and W3) and slower if the well is situated further from the source (e.g., well W6) (fig. 6).

Figure 7 shows the pollutant concentration in 7 wells after either 1000 days or 5000 days from the beginning of pollution, for the three discharge cases considered. After 1000 days (~3 years) of pumping the aquifer with the "real pumping case" rates (Q_{real}), the concentration of pollutant in the pumped water is about 50 mg/l in the wells. The only exception is well W2, where the pollutant

concentration is about 90 mg/l. After 5000 years of pumping, the pollutant concentration in the pumped water is above 70 mg/l. As expected, the larger the pumping rate at a given well, the larger the pollutant concentration in that well.

Finally, it is interesting to note that all wells are coupled to each other and need to be studied together as a system. Changing the discharge in a given well will impact the flow structure of the region and affect all other wells.

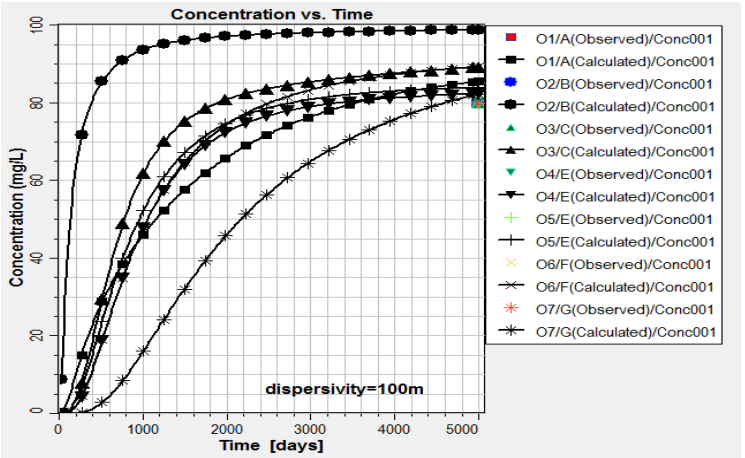

Figure 6: Variability of pollutant concentration in 7 wells over 5000 days, for dispersivity value. α_L =100 m. O1, O7 correspond to wells W1 through W7. Note the highest concentrations are in well 2.

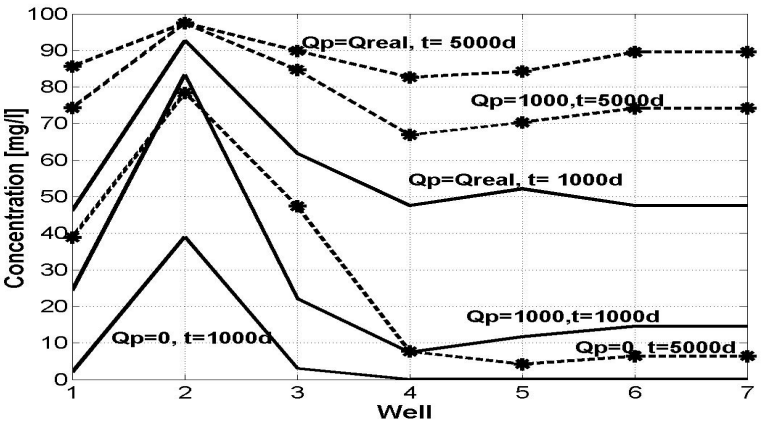

Figure 7: Pollutant concentration in 7 wells after 1000 and 5000 days from the beginning of the pollution, for three cases of discharge from the wells: "real pumping case", (Q_{real}), no discharge (Q=0), and the same Q=1000 m^3/day in all wells (α_L=100 m).

One of the largest uncertainties in our model is the choice of the hydrodynamic dispersivity coefficient α_i, an empirical factor which quantifies how much contaminants stray from the path of the groundwater which is carrying it. By averaging published data, researchers have suggested that the dispersivity coefficient should be taken as 1/10 of the length of flow path (e.g. [5] p. 382). Given that the distance between the wells and the river is about 900 m, a reasonable choice for dispersivity is α_L=100 m. To study the importance of this choice, we consider a set of simulations in which the "correct" α_L=100 m value is chosen and a set of simulations in which the "incorrect" value α_L=20 m is used.

The difference in pollutant concentrations between these two cases, C(α_L=20 m) - C(α_L=100 m), can be thought of as an absolute "error" due to a wrong guess for α_L. Figure 8 shows the resulting error for each of the wells over 5000 days for the case of no pumping in wells and realistic pumping. In the case with no well pumping, the error increases gradually in time in all wells with the exception of well W2.

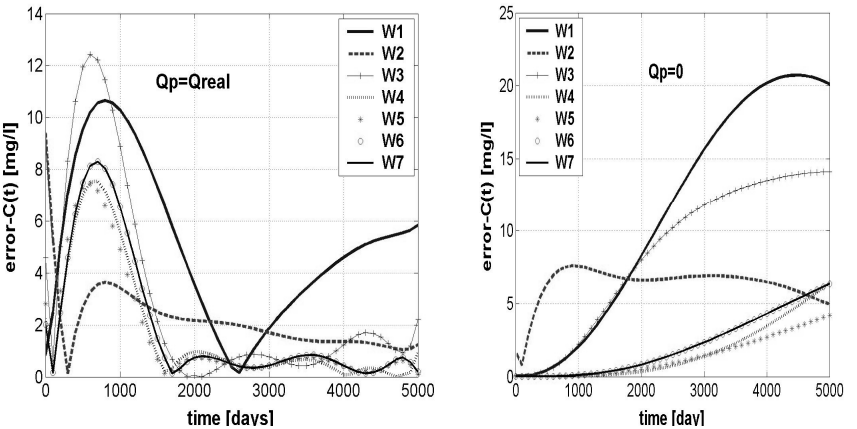

Figure 8: Error due to our choice of a dispersivity coefficient. Time varying differences between the pollutant concentrations in the cases α_L=20m and α_L=100m, for our set of 7 wells. Left subplot: "real pumping case", rate in the wells assumed. Right subplot: case Q=0, no pumping in the wells.

Assuming the present rates of pumping, pollutant concentration in well waters shows small variation with the choice in dispersivity. For "real pumping case", we can have most confidence in our results after about 2000 days: with the exception of well W1, the errors due to our choice of α_L decrease in time from a maximum of 12 mg/l and become negligible (1-5% of the total pollutant concentration) after about 2000 days.

Well W1 pollutant concentration responds most to changes in dispersivity (fig. 8). At W1 the local velocity has components in both the x and y direction such that both transversal and longitudinal dispersivity coefficients matter. Since

dispersion of fluid at W1 takes place at high flow speeds, a small change in α_L can result in a larger change in the dispersion tensor (with elements $D_i = \alpha_i|v_i|$) and a larger change in the pollutant concentration compared to other wells.

4 Conclusions

The water quality of the phreatic aquifer and hence the quality of the drinking water for the town of Slatina (Romania) is strongly determined by the quality of water in the river Olt. The river and local lakes are polluted by a large chemical plant situated upstream. We show here that pumping from a series of wells situated in a line along the river bank contributes to an accentuated pollution of the phreatic aquifer in the Curtisoara-Slatina region. The region to the east of the well line (further from the river) is most protected from pollution. By contrast, the well closest to the river (W2 in figures 3, 4, 5) was shown to be the most exposed to pollution. Assuming for example a constant nitrate river concentration of 100 mg/l, the European admissible upper limit of 50 mg nitrate/l will be reached in all drinking wells after 5000 days even if the discharge rate is only 1000 m^3/day.

In conclusion, we recommend the town of Slatina stops pumping from the phreatic aquifer in region W2 at the current levels. We recommend pumping water at W2 at a rate of at most 1000 m^3/day, or alternative measures such as building an impermeable river wall in the BC region (figures 3, 4) to prevent the polluted water from reaching well W2, pumping the water only from the deeper confined aquifer, or building a new set of wells further east from the lake boundary. We plan to analyze these alternative scenarios in future modelling work.

In the present work we have considered the flow of water and pollutant dispersion in the phreatic aquifer of the Curtisoara region. If the confined aquifer is strongly pumped via existing wells, the pressure in this aquifer decreases and water from the surface aquifer can penetrate the aquitard and enter the confined aquifer. In future work we plan to model the coupled phreatic aquifer - confined aquifer system, diagnose the vulnerability to pollution of the confined aquifer and discuss consequences for the quality of water pumped from the deep wells.

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