USE OF SIMULATION MODELS IN THE PROTECTION OF GROUNDWATER AQUIFER SYSTEMS. APPLICATION AT THE UPPER ANTHEMOUNTAS BASIN IN CHALKIDIKI, GREECE.

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ABSTRACT

The importance of the development and application of groundwater simulation mathematical models in the protection of aquifer systems is nowadays recognised as an undisputable fact. In this paper a mathematical model that was developed in order to simulate the function of the Upper Anthemountas aquifer in Chalkidiki, Greece, is presented. The case study application investigated concerned the possible malfunction of the Waste Water Treatment Plant located within the study area. According to this scenario a possible malfunction of the treatment plant could pollute the underlying aquifer. A network of observation wells located downstream of the plant could detect the pollution and predict the time needed to reach the productive wells surrounding the area. This allows the local water resources managers to formulate a priori action-plans including, the alteration of the pumping schedule in order to prevent polluted water to be abstracted from the nearby wells and at the same time protect the public health, along with necessary measures concerning the prevention of further pollution and the restoration of the groundwater aquifer system.
1. INTRODUCTION

The protection and prevention of further pollution of groundwater aquifer systems is one of the main targets of the European Union Water Framework Directive 2000/60. This can only be accomplished in well investigated and accurately simulated aquifers. In order to impose the principles of the directive one needs to develop and apply mathematical simulation models calibrated over the specific characteristics of the aquifer under investigation. The degree of approach between the simulation model and the aquifer system based on both the available data and the assumptions made during the simulation, determines the accuracy of the model and thus the ability to investigate the application of management policies.

One of the most interesting features of the EU directive is the development, organisation and distribution of observation networks. These networks aim both at the enrichment of the available data and at the constant observation of the status of the aquifer system and mainly the quality of groundwater. In order though to accomplish these targets in the less cost expensive way the observation networks must be well organised in both their spatial distribution and the schedule of measurements [1].

In this paper a mathematical model that was developed through the application of the well known Visual ModFlow software [2] in order to simulate the function of the Upper Anthemountas aquifer in Chalkidiki in northern Greece, is presented. For the development of the three dimensional simulation model all the available data were used including borehole geological sections descriptions, pumping tests results, water uses and rainfall data.

One of the numerous applications of simulation models is the protection of groundwater quality and the prevention of its further pollution. The case study application investigated, concerned the Waste Water Treatment Plant located within the study area. According to this scenario a possible malfunction of the treatment plant could pollute the underlying aquifer. A network of observation wells located downstream of the plant could detect the pollution and predict the time needed to reach the productive wells surrounding the area. This allows the local water resources managers to take measures including, the alteration of the pumping schedule in order to prevent polluted water to be abstracted from the nearby wells and at the same time protect the public health, along with necessary measures concerning the prevention of further pollution and the restoration of the groundwater aquifer system.

2. USES AND APPLICATIONS OF GROUNDWATER SIMULATION MODELS

Once a mathematical groundwater simulation model has been created and properly calibrated it can be used in several applications concerning quantity and quality management time depended problems. As far as quantity management is concerned such applications could include the prediction of the development of the aquifer according to possible management scenarios (forward in time) and the investigation of previously applied water resources related activities (backward in time). Respectively quality management applications could include the investigation of the transport of pollutants both forward and backward in time. The investigation of forward in time transport of pollutants is used to determine the vulnerability of the aquifer due to possible pollution incidents as well as the response of the aquifer to rehabilitation actions. On the other hand the investigation of backward in time transport of pollutants can result in the determination of the pollutant source and the application of the “polluter-pays” principle [3] as imposed by the water framework directive 60/2000/EC and the 2004/35/EC directive for the environmental liability [4].
3. DESCRIPTION OF THE STUDY AREA

The aquifer of the Upper Anthemountas basin in the Chalkidiki peninsula in northern Greece was used as a case study application. The Upper Anthemountas basin, with an area of 90 km$^2$, represents the eastern part of the Anthemountas river basin (Figure 1). The river stretches in a length of 30 km from west to the east and its basin’s total area is about 430 km$^2$. The surface flow of the river is very limited due to both low precipitation and the fact that the upper geological layers consist mainly of permeable and semi-permeable soils. As a result, the river appears to have surface outflows only for a short time after intense rainfall.

The data used in this paper are derived from a research project developed by the Division of Hydraulics and Environmental Engineering of the Aristotle University of Thessaloniki aiming at a more rational water resources management scheme for implementation in the area [5].

Figure 1. The study area of the upper Anthemountas in Chalkidiki in northern Greece
Based on the available data, that included borehole descriptions, geological sections, water level measurements, water uses, pumping tests, rainfall data, field measurements and other relevant data, a mathematical model was formulated [6] using Visual ModFlow [2] as simulation software. This three dimensional simulation model is applied over the study area in order to demonstrate one of its possible uses, that of protecting the groundwater quality.

4. THE GROUNDWATER POLLUTION SCENARIO

The developed groundwater simulation model for the upper Anthemountas aquifer [5, 6] was used in order to investigate the effectiveness of an observation network deployed downstream of the waste water treatment plant located in the area, to identify a pollution incident caused by a malfunction of the plant and provide immediate information concerning the measures that should be taken in order firstly to control the pollution plume and secondly to rehabilitate the aquifer.

The observation network consists of two existing pumping wells located downstream of the treatment plant and upstream of a productive water supply well, as shown in figure 2. It was decided to use two of the numerous existing pumping wells in order to minimize the total cost of the proposed procedure. The first observation well aims at the, as early as possible, detection of the pollution, while the second assists in the determination of the actual direction of movement and the dimensions of the formulated plume, elements that can help the decision makers to take the necessary measures for the protection of the water supply well specifically and the groundwater quality generally.

An existing well located about 200m downstream the WWTP and on the main direction of flow, was chosen as observation well 1. The distance from the plant was chosen in order to be certain that the possible pollution will be detected regardless of the actual position of the specific component of the treatment plant that caused the pollution incident.

Figure 2. The waste water treatment plant, the observation wells and the water supply well.
According to a hypothetical scenario a malfunction at the WWTP resulted in a leak of a concentration of 500 mg/l to the aquifer. The pollutant is considered to be conservative in order to be able to focus on the formulation of the plume and its detection by the observation network rather than deal with chemical reactions of a certain pollutant.

Through the application of the simulation model a number of different scenarios were investigated according to the frequency of observations. The worst case scenario is produced when considering that the pollution arrives at the observation well just after the last sampling. In this way the total time between the start of the leakage at the plant and the detection of the pollution equals to the sum of the time of travel and the time interval between two consecutive samplings. According to the simulation model the time of travel between the WWTP and the first observation well is two months.

As previously mentioned a second observation well is introduced in order to determine the actual direction of movement and the dimensions of the formulated plume. This enables the water resources managers to determine additional information that will assist them to take the proper measures for the protection of the aquifer. This information includes a more accurate estimation of the permeability coefficient and the velocity field formulated at the period under investigation. The position of the second observation well was selected among the existing wells located in the middle of the distance between the first observation well and the water supply well. Figure 3 presents the concentration variation versus time at the first observation well (left curve), the second observation well (center curve) and the under protection water supply well (right curve) under the do nothing scenario. It is obvious that the pollution detected at the observation well will result and pollute the groundwater abstracted by the water supply well.

![Concentration vs. Time](image)

Figure 3. Concentration versus time at the first observation well on the left, the second observation well in the middle and the water supply well on the right
A number of different scenarios were investigated according to the interval between successive samplings at the observation well thus determining the time of detection of the pollution. According to these scenarios when a concentration above normal is measured at the first observation well the waste water treatment plant immediately stops functioning in order to prevent further pollution of the aquifer. Seven different time intervals were investigated. According to the first one (indicated as 0 months) in table 1 and figure 4, the sampling coincides with the arrival of the pollution at the observation well. All the other scenarios refer to the time interval between successive samplings and thus between sampling and the time of arrival of pollutants. It is obvious that the sooner the detection of the pollution the better for the protection of the groundwater quality. In the third column of table 1 the maximum concentration of the pollution arriving at the water supply well is indicated, while at the fourth column the duration of a concentration of pollutants above a limit of 5 mg/l is presented. In the last column an index of the persistence of the pollution is introduced. The persistence of pollution is numerised as the product of the maximum concentration arriving at the water supply well and the number of days the quality of the water abstracted by the protected well is effected by the pollution incident.

Figure 4. Analysis of the effects of the frequency of measurements at observation well 1 at the quality of water abstracted at the water supply well
(a) Maximum concentration observed according to the measurement frequency
(b) Maximum duration of concentration over the limit of 5 mg/l
(c) The persistence of the measurement schedule
Table 1. Analysis of the effects of the frequency of measurements at observation well 1 at the quality of water abstracted at the water supply well

<table>
<thead>
<tr>
<th>Interval between samplings</th>
<th>Days from start of pollution</th>
<th>Maximum concentration</th>
<th>Duration of pollution</th>
<th>Persistence index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60</td>
<td>11</td>
<td>230</td>
<td>2530</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>14</td>
<td>270</td>
<td>3780</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>21</td>
<td>300</td>
<td>6300</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>30</td>
<td>380</td>
<td>11400</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
<td>60</td>
<td>420</td>
<td>25200</td>
</tr>
<tr>
<td>5</td>
<td>210</td>
<td>70</td>
<td>500</td>
<td>35000</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
<td>75</td>
<td>550</td>
<td>41250</td>
</tr>
</tbody>
</table>

It is obvious that the less the persistence index the better the solution. One can easily observe from figure 4 that a critical point in the selection of the time interval between samplings is formulated at the three months interval. A sampling interval that exceeds three months, increases significantly the persistence of pollution index and can result to a very serious and dangerous for the quality of the water abstracted from the water supply well, pollution incident.

Another interesting conclusion is derived by the difference between the concentrations measured simultaneously at the two observation wells. After a number of successive application of the simulation model for different values of the leakage from the waste water treatment plant, the values of the concentrations recorded at the same time at the two observation wells were calculated as well as the resulting maximum concentration arriving at the water supply well. Figure 5 was produced through the combination of all these parameters. It indicates the relation between the leakage from the pollution source, the maximum concentration expected to arrive at the water supply well and the difference between the observed concentrations at the two observation wells. The development of figure 5 allows the water resources managers when measuring the
concentrations at the two observation wells to estimate the characteristics of the pollution incident (leakage rate) and mainly to predict the magnitude of the problem at the water supply well (maximum concentration) and take the necessary measures.

5. CONCLUSIONS

In this paper an application of a mathematical groundwater simulation model for the organisation of an observation network aiming at the protection of the groundwater quality, was presented. The remarks introduced in this paper aim to emphasise the need to develop simulation models in order to protect groundwater aquifer systems.

Based on a hypothetical scenario that a malfunction of the waste water treatment plant caused a pollution incident to the underlying aquifer, the effectiveness of the observation network is investigated. The effectiveness of this network is based on the position of the observation wells relative to the waste water treatment plant, the water supply well and of course each other.

The conclusions derived from the presented analysis are considered to be very useful for water resources managers. The fact that one can investigate these scenarios a priori, at the development of the waste water treatment plant or whatever possible pollution activity, enables them to organise action-plans that can be immediately imposed upon the observation of a pollution incident thus preventing the development of a more serious situation that will be hard to deal with.

6. REFERENCES