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Delineation of wellhead protection areas in Crete, Greece using an analytic element model

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Abstract

Groundwater is one of the main sources of drinking water in many regions and therefore investing in its protection is of paramount importance. A very important step in ensuring water of good quality is the delineation of well head protection areas (WHPAs), which is the focus of this research. The area of interest is the basin of the Keritis River, located near the city of Chania, Crete, Greece. The main contamination threats in the area are: i) olive oil industries ii) cemeteries and iii) urban waste from the towns located near or within the basin. The delineation of WHPAs in this work is performed using a more accurate method than a simple fixed radius around the well, which is currently common practice in Greece. A decision support modeling tool called Wellhead Analytical Element Model (WhAEM) was used for this purpose. WhAEM is a groundwater flow model designed to facilitate the delineation of capture zones and mapping well head protection, using the analytic element method. The unique hydrogeology of the modeled area (location of local heterogeneities, discontinuities, rivers, recharge, no-flow boundaries) is taken into account in order to prevent potentially harmful contaminants reaching the water supply. This process can be used as a management tool by water resources managers, stakeholders and public authorities in order to impose rational measures and potential restrictions in urban, agricultural and industrial activities developed in the area.

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Keywords: well head protection areas; analytic element models; groundwater modeling; contamination; environmental protection

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1. Introduction

As global awareness towards the significance of preserving groundwater quality rises, there have been changes in laws involving WHPA (Well Head Protection Zones) or SPZ's (Source Protection Zones) affecting the safe distance from a well where a potentially polluting activity can take place. There are three methods to determine this distance: a) the simplistic method of setting a radius around the well based on experience, which is a low cost but highly uncertain approach, b) analytic element methods, which are mathematical models used for the delineation of SPZ's mainly based on the aquifer characteristics (porosity, hydraulic gradient, transmissivity and saturated depth) and c) numerical methods, which are also based on a mathematical model, but have the ability to account for seasonal changes in temperature, precipitation etc. [1]. The basic idea of numerical methods is to divide the area of interest in a very large number of cubes (or other geometrical shapes) with unique geo-hydraulic properties and summarize them to delineate the SPZ's. This creates very low uncertainty results for the predicted zones but also has a high cost of application due to the large quantity of data required to calibrate the model as well as the need for an experienced user to produce reliable results [1]. With all the above in mind, the method used in this paper is the analytical method because it is easier to use than the numerical method and provides much more reliable results than the simplistic. The analytic element method estimates the minimum time it takes for a water particle to reach the well, otherwise known as travel-time, to create points in all directions from the well, which when unified as a polygon form the SPZ. The goal of this research is to produce zones, aiming towards the preservation of both the quality and quantity of groundwater, without over restricting areas like the simplistic method could result in. The more sophisticated the method used, the less uncertainty exists in the results of the zones shapes, leading to optimal zones which benefit the economic growth by allowing the operation of potentially polluting activities only if they are outside the protection zone (according to the level of danger that the activity poses to the aquifer).

The basic classification of SPZ's by the EPA Great Britain separates the main capture zone in three different zones. The most sensitive is the inner protection zone, which is meant to protect against pathogenic microorganisms, viruses and in general biodegradable substances by giving them the appropriate time to decay and not pose danger to the consumer. The outer protection zone has the role of providing a minimum travel-time for slow decaying pollutants, giving them time to attenuate and reach the source in a concentration that are acceptable. The third is referred as the source catchment protection zone which corresponds to the area needed to provide long term sustainability for the wells in the aquifer; this zone is rarely defined for individual wells and is a requirement mainly for aquifers with a ratio of licensed yield to recharge greater than 75% [2].

The work presented here focuses on the delineation of protection zones in the area known as Kampos Chanion, near the city of Chania, Crete. This area is divided by the Keritis river, which brings water from the Leyka Oroi mountain at a height of about 1900 m and ends in the sea after passing the region of Platanias, which together with the lake of Agia are NATURA (2000) protected areas. Nineteen communities are within the general area of Kampos Chanion. Most wells are used for agriculture purposes with three being used for drinking, two of which are very near the lake of Agia [3,4,5]. Threats or polluting activities in the area are waste from olive oil producing industries, cemeteries and urban waste water from the communities.

2. Methodology

The WhAEM model requires the following input parameters for the estimation of the SPZs: the general hydraulic gradient of the area, pumping rates of all currently operating wells, the basic elevation level of the aquifer as well as its thickness, porosity, precipitation, maximum and minimum contours of water levels and general hydraulic conductivity values. Additional model parameters include inhomogeneous regions within which the hydraulic conductivity can vary significantly. This is illustrated in Fig.1 which shows the geologic map of the area where the hydraulic conductivity varies with color as follows: green represents highly permeable formations with K=300 m/d, gray represents impermeable formations with very low hydraulic conductivity value (K=0.000086 m/d), light blue is relatively permeable with K=8.61 m/d and light green has medium permeability (K=51.86 m/d). Pumping wells in the area are represented by black circles while the pollutant sources of olive oil industries and cemeteries are shown by red and green circles, respectively (Fig. 1). There is no legally permitted area to dispose suburban waste in the area. Table 1 shows the pumping rates and other information of the 12 wells used in this study. Wells will be referred to by their number in the text.

From the 12 wells presented in Table 1, Wells 1, 2 and 10 are of greater interest as they are active year-round and provide large quantities of drinking water, while the rest are used for agriculture and are mostly active during the summer months. There are some less significant wells in the area that have been used in the model but they don't have WHPAs assigned to them due to their low pumping rates. For the purposes of showing a larger variety of results, WHPAs have also been assigned to some of the wells used for agriculture.

Other model input includes no-flow boundaries, line sink boundaries such as the Keritis River (represented by a blue line) rivers and Agia Lake (represented by a blue polygon) where a fixed water level and riverbed resistance were defined, based on the interaction between the surface water system (river-lake) and the groundwater system (aquifer). After all the above parameters were defined, the calibration process begun by changing the BCs for water inflow and comparing the available water head field measurements to the modeled ones. For the purpose of selecting the best model fit the root mean squared error (RMSE) was calculated for each test and the model that presented the minimum RMSE value was selected.

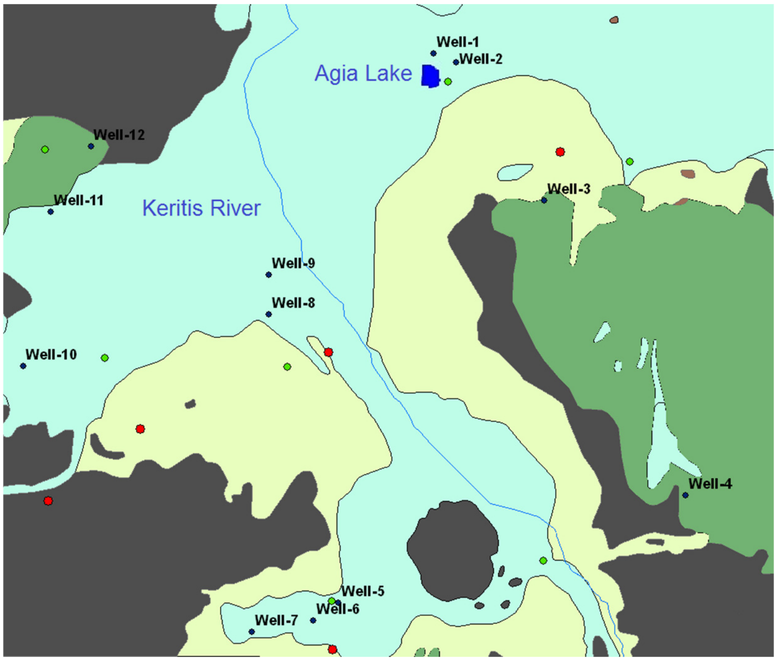

Fig. 1. Study area and geological map

Table 1. Wells and their pumping rates [3,4]

Well name, Location, Owner	Pumping Rate (m^3/d)	Well Name, Location (Owner)	Pumping Rate (m^3/d)
Well1, Agia, TOEB	2995	Well 7, Mesokefala, Private owner	960
Well 2, Agia, DEYAX	1618	Well 8, West of Keritis river	720
Well 3, Myloniana	12000	Well 9, Dregiades, TOEB	2640
Well 4, Skines, Community	2400	Well 10, Margarites, TOEB /OADYK	3720
Well 5, Skines, Community	3600	Well 11, Batolakos, TOEB	5760
Well 6, Skines, OADYK	3600	Well 12, Spilios, Community	1920

After the successful calibration of the model (RMSE and mean absolute difference between heads less than 1.5 m) the minimum time for water to reach the wells or the travel-time for each Source Protection Zone were defined. The shape of the zone is affected by numerous parameters as shown above, one of the most challenging being ambient flow as its quantity and direction depend on anomalies in the geology near the well and in the aquifer which are not easily defined with certainty.

For this reason, the model uses a reference time (T_0) in comparison with the desired travel-time (T) to create a dimensionless parameter ($\tilde{T}$) which determines the shape of the capture zone, according to the following equations:

$$\tilde{T} = \frac{T}{T_0} \quad (1)$$

$$T_0 = \frac{nHQ}{2\pi {Q_0}^2} \quad (2)$$

Where: n is the porosity, H is the aquifer thickness, $Q(\frac{m^3}{d})$ is the pumping rate of the well and Q_0 $(\frac{m^2}{d})$ is the water per meter of width $W(m)$ that will be pumped by the well. There are three equations on how to calculate the SPZ shape depending on the value of $\tilde{T}$. If $\tilde{T}$<0.1 the shape is a circle with the center being the well. If 0.1≤$\tilde{T}$≤1 it is still a circle but the center is not necessarily the well. When $\tilde{T}$>1 a boat shaped capture zone is formed. This is the most important condition since it represents SPZs in a more realistic way. The relevant equations are the following:

$$x = \frac{y}{tan(\frac{y}{L_S})} \quad (3)$$

$$L_S = \frac{Q}{2\pi Q_0} \quad (4)$$

$$Q_0 = \frac{Q}{W} = -k_i H \quad (5)$$

Where: $L_S(m)$ is the distance from the well to the stagnation point downgradient from the well, k $(\frac{m}{d})$ is the hydraulic conductivity, k_i is the hydraulic gradient (dimensionless) and $H(m)$ the saturated depth. The variable y is bounded as follows: $[-Q/(2Q_O)] < y < [Q/(2Q_0)]$.

Finally, $L_U(m)$ which is the length of the capture zone up-gradient is defined by [1]:

$$L_U = L_S[\tilde{T} + ln(e + \tilde{T})] \quad (6)$$

To determine the travel-times for each SPZ the Great Britain's EPA definitions of the three zones were used and extended. The inner protection zone or SPZ 1 restricts an area capable of providing the minimum time needed for attenuation of potentially harmful biodegradable microorganisms, allowing their concentrations to reach acceptable values according to EU restrictions. The travel-time for this zone is defined as 50 d or a minimum of 50 m. SPZ 2 is the outer protection zone that provides the minimum level of protection towards non-biodegradable substances providing adequate time to the authorities for mitigation if pollutants are detected. The travel-time in this case is set at 400 d or 250 m for wells with pumping rates less than 2000 m^3/d or 500 m if the rate is higher. The catchment protection zone or SPZ 3 is for the purpose of securing the protected yield for long term use, but is more relevant to aquifers than individual wells and has greater importance on highly exploited areas when the total water being pumped is equal or higher than 75% of the recharge. The travel-time in this case is suggested at 10 years or greater. Taking into consideration the recommended zones and extending them, 5 zones are defined in this work at travel times of 60 d, 180 d, 1 year, 5 years and 10 years for each well that is active during the period being modeled [2].

The final step is to estimate the uncertainty of the obtained results by performing a sensitivity analysis on the results. The main parameters used by the model were perturbed by 10% and 20 % and the difference in the mean absolute difference between the calibrated and the perturbed model heads was evaluated. The model parameters that were used in the sensitivity analysis are pumping well rates, hydraulic conductivity, water recharge, saturated depth, river or lake head levels.

3. Results

3.1. Summer period

First, a summer period simulation was performed where both seasonal and year-round pumping wells are active. The resulting SPZs are shown in Fig. 2. The blue line passing throw the map is Keritis River, while Lake Agia is located near the town of Agia. The difference between modeled and observed heads presented in Fig. 3 shows a reliable fit with an RMSE factor of 1.0 m and mean absolute difference of 0.925m, suggesting a successful calibration. The wells that are being highly threatened in Fig. 2 are 6 and 9 which have oil industries within their capture zones, for 1 and 10 years respectively. The authorities should take mitigation actions for both of them, with greater urgency for Well 6, 9 while Wells 1, 8 and 12 which have cemeteries within their capture zones and will require attention in the future.

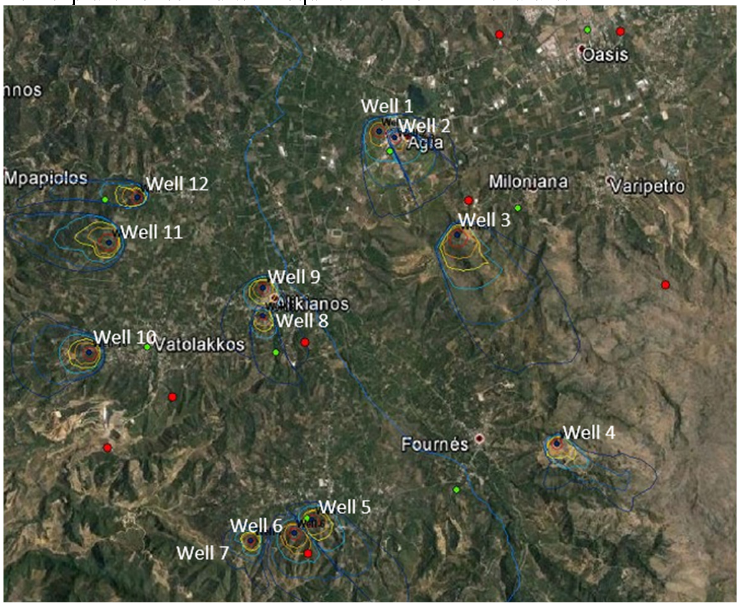

Fig. 2. SPZs for the summer period

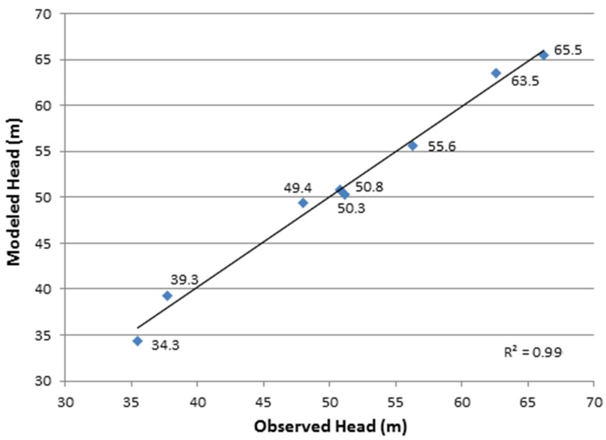

Fig. 3. Measured versus simulated hydraulic heads in m (summer period)

3.2. Winter period

In Fig. 4 the SPZs for the winter period are represented for the three wells (Wells 1, 2 and 10) that are active throughout the year. Well 2 is potentially threatened by the oil industry in its ten year SPZ, while Well 1 is at low risk due to the cemetery located nearby. The RMSE for this scenario is 2.6 m and the mean absolute difference is 2.0m. The difference of modeled and observed heads is shown in Fig. 5. This fit is not as good as for the summer period but is still considered acceptable given its lower significance (only three active wells during this period).

Fig. 4. SPZs for the winter period

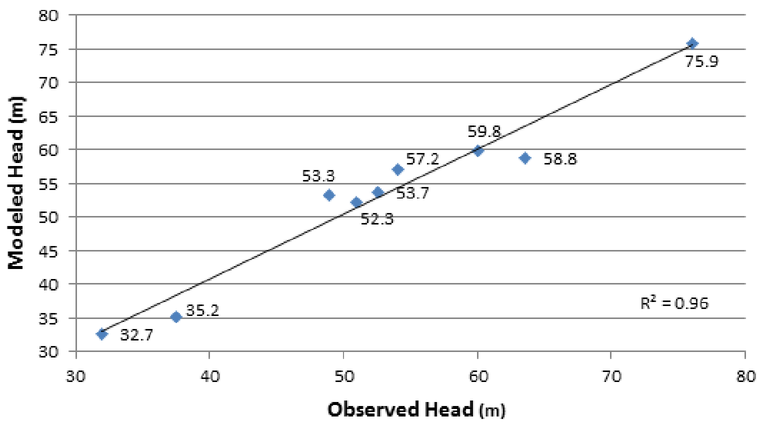

Fig. 5. Measured versus simulated hydraulic heads in m (winter period)

3.3. Sensitivity analysis

A sensitivity analysis was performed using the calibrated summer period model to identify which input parameters have the greatest effect on model results. The parameters that were selected are: a) river and b) lake head levels b) pumping well rates c) hydraulic conductivity d) water recharge and e) saturated depth and they were perturbed by ±10 %

and ±20 % (the lake and river heads were perturbed only by ±20% due to the very small effect on the MAD). The factor assessing their impact is the absolute difference of the calibrated and perturbed MADs for each sensitivity analysis scenario tested (Fig. 6). From the results it is concluded that the parameters affecting the calibration the most are the pumping rates and boundary conditions, followed by the saturated depth of the aquifer and hydraulic conductivity, while the river and lake heads have insignificant impact.

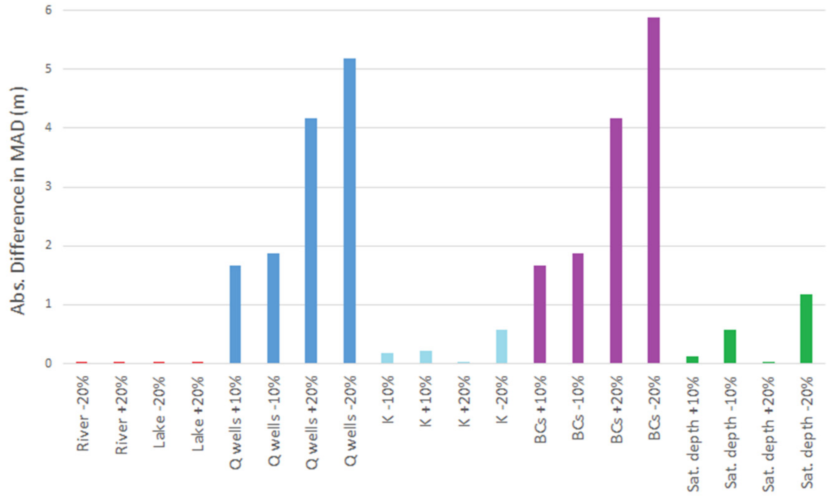

Fig. 6. Sensitivity analysis results

4. Conclusions

In this work, the delineation of protection zones in the area known as Kampos Chanion, near the city of Chania, Crete was performed. The major contamination threats in the area are olive oil producing industries cemeteries. Five SPZs were defined for each pumping well that correspond to travel times of 60 d, 180 d, 1 year, 5 and 10 years. A sensitivity analysis was also performed to assess the impact of input parameters to the model. It was concluded that the parameters affecting the results the most are the pumping rates and boundary conditions, followed by the saturated depth of the aquifer and then the hydraulic conductivity, while the river and lake heads have insignificant impact.

Based on the model results, during the summer period when the aquifer of interest is heavily exploited, wells that are potentially threatened by pollution activities are Well 6 (located in the southern part of the study area) and Well 9 (located in the center of the study area, near Alkianos). The most urgent threat exists for Well 6, since an olive oil industry is located inside the SPZ with travel-time of 2 years. A lesser threat is generated by the cemeteries affecting Wells 1, 8 and 12 therefore test are advised within the next 2 years for Wells 1 and 12, while for Well 8 within the next 5 years. During the winter period, when only three wells are active, Well 2 is potentially threatened by the oil industry in its 10 year SPZ, while Well 1 is at low risk due to the cemetery located nearby. Thus, in general precaution measures are advised such as water quality tests at least within the next year and inspection of the industries waste management procedures to ensure they pose no risk to the water quality of the aquifer. Also, the use of restriction or fine policies depending on the potential threats of the aquifer, as evidenced from water quality tests, should be considered. Finally, when considering locations for new potentially polluting activities it is highly important to keep the safety distances as suggested in the methodology presented here.

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