Establishing wellhead protection areas and managing point and non-point pollution sources to support groundwater protection in the aquifer of Upper Anthemountas, Greece

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Abstract: Nowadays, the protection of groundwater resources constitutes an issue of high importance and urgent necessity due to their increasing degradation caused by various human activities. The practice that is usually applied in order to achieve the aforementioned goal involves the protection of the wells used for the abstraction of groundwater, and is implemented through methods and techniques which result in the delineation of specific protection areas (wellhead protection zones) surrounding the wells. The main purpose of this task is the proper management of every potential pollution source located in the interior of these protection areas and posing a serious threat to freshwater physical status. Within this framework, the main objective of this study is the development of a well-designed protection plan in order to support groundwater protection in the aquifer of Upper Anthemountas. This plan includes the delineation of protection areas around specific wells applying three different methods, as well as the identification, detection, and recording of various potential point and non-point pollution sources existing in the study area. Moreover, it aims at the proper management of these sources, especially if they are located within the protection zones. Finally, in order to strengthen this plan and provide further protection to local groundwater resources, the determination of specific areas (“pollution” zones) around the potential pollution sources is performed. In the interior of these areas future water abstraction has to be avoided.

Key words: Groundwater protection, wellhead protection areas, groundwater modeling, pollution sources management, Greece

1. INTRODUCTION

Nowadays, the pollution of groundwater resources has evolved into a major environmental problem all over the world, since they constitute the final receivers of various hazardous substances, residues and derivatives of numerous human activities. This fact, in conjunction with their increasing utilization in order to meet various human needs, renders the protection of groundwater resources an issue of paramount importance and absolute necessity. Besides, groundwater protection is strictly imposed not only by the European Union Framework Directive 2000/60/EC, but also by all relevant European and national legislation (Paradis et al., 2007; Theodossiou and Latinopoulos, 2009; Siarkos and Latinopoulos, 2012; Siarkos et al., 2014; Staboultzidis et al., 2017).

A commonly applied practice adopted by the competent authorities in order to protect groundwater resources includes the determination of specific areas of protection surrounding abstraction wells (wellhead protection areas, WHPAs), as well as the detection of potential pollution sources located in the interior of these areas, aiming at the efficient control of these sources (U.S. EPA, 1987; Paradis et al., 2007; Exposito et al., 2010; Rajkumar and Xu, 2011; Siarkos and Latinopoulos, 2012; Siarkos et al., 2014; Staboultzidis et al., 2017). In order to determine these protection areas, a wide variety of methods have been developed and are currently implemented, ranging from simple and low-cost methods, such as the drawing of a circle of arbitrary radius centered at the well, to more complex and costly ones, such as the application of numerical modeling (U.S. EPA, 1987; Ceric and Haitjema, 2005; Theodossiou et al., 2006; Siarkos and Latinopoulos, 2012; Siarkos et al., 2017). According to Hasfurther et al. (1992), the selection of
these methods is based on user expertise, available resources, existing and field collected data, as well as the desired degree of confidence in meeting protection goals, while it is inextricably linked to the criterion used for the delineation, i.e., distance, time-of-travel, drawdown, flow-system boundaries (U.S. EPA, 1987; WHO, 2006; Rajkumar and Xu, 2011; Siarkos and Latinopoulos, 2012; Siarkos et al., 2014).

Within this framework, in the present study, a two-stage approach is implemented in order to support groundwater protection in the aquifer of Upper Anthemountas. The first stage consists of the establishment of protection areas around a number of specific wells (domestic, livestock and industrial wells) by applying three different delineation methods and using the time-of-travel (ToT) criterion. The second stage involves the detection of potential sources of pollution located in the study area in order to properly manage these sources, preventing the selected wells from being polluted. Furthermore, during the second stage, the determination of specific areas around the pollution sources is performed in order to provide further protection by defining those areas in the interior of which groundwater abstraction must be avoided in the future. What is worth mentioning is that the aforementioned pollution sources are both point and non-point sources located in the study area. Nevertheless, with regard to non-point pollution sources, only sources of limited extent were taken into consideration, thus excluding agricultural activities which constitute diffuse source of pollution, extending in a large area and depending on the spatial distribution of crops (Siarkos and Latinopoulos, 2012).

As mentioned above, three different delineation methods, i.e., the calculated fixed radius (CFR) method, the simplified variable shapes (SVS) method and, finally, numerical modeling were implemented. Of these methods, the calculated fixed radius and the simplified variable shapes are based on analytical equations and, therefore, are considered to be quite simplistic. In order to delineate the WHPAs by applying these two methods, the U.S. EPA Well-head Analytic Element Model, WhAEM (Haitjema et al., 1994; Kraemer et al., 2003; Kraemer et al., 2007) was used. At this point, it should be mentioned that the first of the aforementioned methods, i.e., the calculated fixed radius method, differs from the arbitrary fixed radius (AFR) method, a common technique applied at initial stages of a wellhead protection program by setting a fixed distance from a well circumscribing a zone of equal distance around the well (U.S. EPA, 1987; Exposito et al., 2010; Sevastas et al., 2015).

Finally, the third method includes the application of numerical modeling, and more specifically, the use of the MODPATH code (Pollock, 1994). In order to delineate the WHPAs by applying this method, the simulation of the groundwater flow of the aquifer under study is required. To this task, the widely applied code MODFLOW (Harbaugh et al., 2000; McDonald and Harbaugh, 1988) was used, while the model which was developed was based on the one formed in a previous study by Sevastas et al. (2014). Through the application of this method, a backward particle-tracking simulation was performed tracked from the selected abstraction wells. Moreover, MODPATH was used for the delineation of the areas surrounding the pollution sources, which will be henceforth called “pollution” zones, keeping the same conditions (i.e., groundwater velocity field) as in the previous case, while performing a forward particle-tracking simulation tracked from the whole group of pollution sources.

The main scope of the present study is the development of a well-designed groundwater protection plan for the study area which focuses on the protection of local groundwater resources against various point and non-point pollution sources. This is considered to be very important for the study area, since groundwater constitutes the sole source of water in meeting the various water needs. In order to accomplish the aforementioned goal, the following steps were applied: a) improvement of the existing steady-state groundwater flow model (Sevastas et al., 2014) through certain modifications regarding the aquifer’s conceptual model and the model calibration procedure, which is now performed by solving the inverse problem and, therefore, applying the PEST tool (Doherty, 2002); b) application of the aforementioned delineation methods using both the adjusted parameters (i.e., hydraulic conductivity, recharge) and the results (i.e., hydraulic head) of the improved model; c) detection, recording and depiction of potential pollution sources by using GIS
tools; and d) determination of the “pollution” zones surrounding the pollution sources by applying the MODPATH code.

2. STUDY AREA

The Upper Anthemountas sub-basin, being the eastern part of the entire Anthemountas basin, is situated in Chalkidiki Peninsula, Greece, south east of the city of Thessaloniki (Figure 1). The basin occupies an area of about 110 km$^2$, and is bordered to the west by the Lower Anthemountas basin and to the south by the Nea Moudania basin. Within the boundaries of the basin, two main settlements are located, Galatista and Galarinos (Figure 1). The study area is a typical rural area, where agriculture dominates in both the local economy and land use. Livestock activities contribute to the economic development of the region as well. Water demand in the region is confined mainly to drinking and irrigation, and is met respectively through few public supply wells and a large number of privately owned irrigation wells, the latter due to the lack of an organized irrigation system. Moreover, there are few wells for both livestock and industrial purposes, as shown in Figure 1 (Latinopoulos et al., 2000, 2001; Sevastas et al., 2014).

Figure 1. Boundaries of the Upper Anthemountas basin and the aquifer under study – Location of operating wells per water use

The Upper Anthemountas basin belongs geologically to the Circum Rhodope Belt, and includes a great variety of sediments combined with various hard igneous and metamorphic rocks. More specifically, the sediments that filled the basin consist of deposits of Neogene age and of Quaternary age (Pleistocene – Holocene). The Neogene deposits are made of clay and marl with intercalations of sands, conglomerates and sandstones. The Pleistocene deposits, of a thickness up to 100 m, dominate over the study area and consist mainly of hard-grained material, sands, pebbles and clay, in the shape of a terrace system (Latinopoulos, 2001, 2001; Fikos et al., 2005; Sevastas et al., 2014). These sediments compose the main aquifer system of the study area in the form of successive water-bearing layers without regular geometric growth, separated by lenses of semi-permeable or impermeable materials. The aforementioned aquifer system, which is considered to be a semi-confined aquifer, is exclusively used in order to meet the various water needs (Latinopoulos, 2001; Latinopoulos et al., 2001).
From a hydrological point of view, the catchment consists of a dense well-formed stream network. Moreover, the Anthemountas River crosses the basin flowing from east to west. However, the surface flow of the river is very limited due to both low precipitation and the fact that the upper geological layers comprise mainly permeable and semi-permeable soils. As a result, the river appears to have occasional outflows only for a short time after intense rainfall (Latinopoulos, 2001; Fikos et al., 2005; Sevastas et al., 2014).

In general, the study area is characterized by a net deficit in the aquifer water balance, since total water demand exceeds natural recharge. This happens mainly due to the increased water demand to serve irrigation needs (Latinopoulos, 2001; Fikos et al., 2005). On the contrary, various studies conducted in the area (e.g., Latinopoulos, 2001; Fikos et al., 2005) showed that local groundwater resources are of good quality with an exception of an area in the eastern portion of the aquifer where increased nitrate concentrations due to agricultural and livestock activities are observed (Kazakis, 2013). However, considering that pollution in the case of groundwater resources occurs after some time, as well as that remediation of polluted groundwater is characterized as a time-consuming and costly procedure, protection measures should be implemented (Latinopoulos, 2001). Establishment of protection zones and proper management of potential pollution sources constitute the first step towards this direction. According to this, an important step in order to successfully complete the wellhead protection process is the identification, detection and recording of such pollution sources. If these sources are located in the interior of the protection zones, they should be controlled and managed accordingly (Siarkos and Latinopoulos, 2012).

In the present study, point and non-point pollution sources related to industrial, urban and livestock activities were detected and recorded. Table 1 presents all the aforementioned pollution sources, which are listed and codified so as to be identified in subsequent parts of this text, while Figure 2 depicts the location of these sources along with the location of the wells selected for the delineation procedure. These wells are domestic, livestock and industrial wells situated in the interior of the Upper Anthemountas aquifer. At this point, it should be mentioned that two of the livestock wells located in the northern portion of the aquifer were excluded from the delineation procedure due to their direct proximity to each other which leads to inaccurate results during the application of MODPATH.

<table>
<thead>
<tr>
<th>a/a</th>
<th>Pollution Source</th>
<th>a/a</th>
<th>Pollution Source</th>
<th>a/a</th>
<th>Pollution Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>olive oil mill wastewater</td>
<td>12</td>
<td>trash-debris site</td>
<td>23</td>
<td>sheepfold</td>
</tr>
<tr>
<td>2</td>
<td>distillery</td>
<td>13</td>
<td>cemetery</td>
<td>24</td>
<td>sheepfold</td>
</tr>
<tr>
<td>3</td>
<td>furniture workshop</td>
<td>14</td>
<td>cattle farm</td>
<td>25</td>
<td>sheepfold</td>
</tr>
<tr>
<td>4</td>
<td>automobile junkyard</td>
<td>15</td>
<td>gas station</td>
<td>26</td>
<td>sheepfold</td>
</tr>
<tr>
<td>5</td>
<td>automobile junkyard</td>
<td>16</td>
<td>abattoir</td>
<td>27</td>
<td>sheepfold</td>
</tr>
<tr>
<td>6</td>
<td>marble quarry</td>
<td>17</td>
<td>poultry farm</td>
<td>28</td>
<td>sheepfold</td>
</tr>
<tr>
<td>7</td>
<td>marble quarry</td>
<td>18</td>
<td>poultry farm</td>
<td>29</td>
<td>auto repair shop</td>
</tr>
<tr>
<td>8</td>
<td>machine shop</td>
<td>19</td>
<td>sheepfold</td>
<td>30</td>
<td>abattoir</td>
</tr>
<tr>
<td>9</td>
<td>machine shop</td>
<td>20</td>
<td>sheepfold</td>
<td>31</td>
<td>window glass factory</td>
</tr>
<tr>
<td>10</td>
<td>wastewater treatment plant</td>
<td>21</td>
<td>sheepfold</td>
<td>32</td>
<td>cheese dairy</td>
</tr>
<tr>
<td>11</td>
<td>eel breeding facility</td>
<td>22</td>
<td>sheepfold</td>
<td>33</td>
<td>olive oil mill</td>
</tr>
</tbody>
</table>

By examining Figure 2, it can be concluded that the great majority of the pollution sources can be found in the north-eastern and eastern part of the study area near the settlement of Galatista, where the major part of the local population is observed. Moreover, as it is obvious from Table 1, livestock-related pollution sources (e.g., sheepfolds, poultry and cattle farms, abattoirs) are the most common in the study area. Some other potential pollution sources detected in the region include several auto-related pollution sources (e.g., automobile junkyards, machine shops, auto repair shop, gas station), as well as various product processing plants (e.g., furniture workshops, marble quarries, cheese dairy, olive oil mill). Finally, it is worth mentioning that both the cesspools existing in the settlement of Galarinos and the abandoned mines constitute considerable sources of groundwater pollution in the study area.
3. MODEL DEVELOPMENT PROCEDURE

3.1 Conceptual model development

The development of the conceptual model is considered to be the most important part of the modeling procedure, since the accuracy and reliability of mathematical model results (groundwater flow or/and mass transport models) significantly depend on how the conceptual model of the aquifer system under study is formed (Ahmed and Umar, 2009; Latinopoulos and Siarkos, 2014). An in-depth description of the conceptual model of the Upper Anthemountas aquifer is presented by Sevastas et al. (2014), where detailed information is provided regarding the geometry and the boundary conditions of the aquifer system, its hydraulic parameters (i.e., hydraulic conductivity), as well as its recharge and discharge conditions. In the present study, the conceptual model was kept almost intact, except for certain modifications that were made for the needs of this study. These modifications are related to the boundaries, the hydraulic parameters and the discharge of the aquifer system.

First of all, in Figure 1, the new boundaries of the aquifer under study are depicted, as they resulted after a more thorough investigation of the geology of the Upper Anthemountas basin in order to include the whole set of loose formations located in the region and, at the same time, exclude the rock formations surrounding the basin. In this way, a more realistic representation of the Upper Anthemountas aquifer is achieved.

Additionally, since in the present study the delineation of protection zones is attempted, the determination of the aquifer’s effective porosity is required for the implementation of the delineation methods mentioned in the “Introduction” section. Due to no data availability regarding this specific parameter, its quantification was based on literature, while taking into consideration the values of hydraulic conductivity in the study area (0.29 – 2.51 m/d) (Latinopoulos, 2001). So, for hydraulic conductivity values in the range of $10^{-1}$-$10^{0}$ m/d, effective porosity receives values between 0.07 and 0.15 (WHO, 2006). Nevertheless, the accurate estimation of effective porosity was accomplished after the final determination of hydraulic conductivity during the calibration process of the steady-state model (see “Steady-state model development” section).

Finally, with regard to the aquifer discharge and, more specifically, the definition of the pumping rates of the abstraction wells, recalculation of the equivalent pumping rate per water use (i.e.,
domestic, agricultural, livestock and industrial) was performed, based on a more detailed recording of these wells and, therefore, a more realistic representation of their spatial distribution (referring to the year 2000) (Figure 1). In order to calculate the equivalent pumping rate, the total annual water consumption and the total number of operating wells per water use were taken into consideration. The results of the aforementioned procedure are presented in Table 2. In the parentheses, the number of the wells located in the interior of the aquifer system is listed.

### Table 2. Equivalent pumping rate of operating wells per water use

<table>
<thead>
<tr>
<th>Water Use</th>
<th>Number of wells</th>
<th>Total water consumption (m$^3$/y)</th>
<th>Equivalent pumping rate (m$^3$/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic (Galarinos)</td>
<td>2 (2)</td>
<td>14,289</td>
<td>19.57</td>
</tr>
<tr>
<td>Domestic (Galatista)</td>
<td>5 (5)</td>
<td>148,427</td>
<td>81.33</td>
</tr>
<tr>
<td>Agricultural</td>
<td>160 (125)</td>
<td>3,930,728</td>
<td>67.31</td>
</tr>
<tr>
<td>Livestock</td>
<td>5 (4)</td>
<td>156,922</td>
<td>85.98</td>
</tr>
<tr>
<td>Industrial</td>
<td>2 (2)</td>
<td>44,800</td>
<td>61.37</td>
</tr>
</tbody>
</table>

#### 3.2 Steady-state model development

The groundwater flow simulation procedure involved the development of an improved steady-state model in order to form a generic image about the behavior of the Upper Anthemountas aquifer, as well as to properly adjust specific aquifer parameters (i.e., hydraulic conductivity, recharge and discharge components) through the model calibration procedure. The values of the adjusted parameters were then used for the implementation of the various delineation methods mentioned in the “Introduction” section and described analytically in the “Delineation of protection and pollution zones” section.

In the aforementioned improved model, spatial discretization was kept identical to the previous model developed by Sevastas et al. (2014), thus resulting in a grid consisting of 120 columns, 65 rows and 1 layer (two-dimensional areal model) and in cells with 100-m side. With regard to the model calibration, the automated inverse model calibration tool PEST was used instead of the trail-and-error methodology which was applied by Sevastas et al. (2014). In that way, better calibration of the steady-state model was performed and, therefore, better adjustment of the aquifer parameters was achieved. The calibration was made using 15 observation wells monitored during October 2000 (Latinopoulos, 2001) by properly adjusting aquifer hydraulic conductivity and recharge values. However, depending on the calculated values and on if they did not meet the predefined value range, the calibration procedure was repeated after modifying the pumping rate of irrigation wells. At this point, it should be mentioned that solving the inverse problem is a difficult and time-consuming procedure, which is even more hindered in the absence of sufficient data (Sevastas et al., 2015).

Through the aforementioned procedure, the aquifer hydraulic conductivity and recharge, as well as the pumping rate of irrigation wells were adjusted and determined. More specifically, hydraulic conductivity was found equal to 0.31 m/d, recharge equal to 0.263 mm/d and well pumping rate equal to 57.31 m$^3$/d. Based on the above-mentioned hydraulic conductivity value, effective porosity was assigned a value of 0.10, which was considered constant through the whole study area. With respect to the model calibration results, the accuracy of the simulation was tested by calculating the mean error (ME), the mean absolute error (MAE) and the root mean square error (RMSE). The ME was found equal to -0.147m, indicating that, on average, the simulated groundwater levels were slightly lower than the observed groundwater levels. The MAE and RMSE estimates were found equal to 1.609 m and 1.843 m, respectively, signifying a rather successful calibration and, therefore, a satisfactory simulation. Figure 3 shows the results of the steady-state model calibration in a scattergram of observed versus simulated groundwater levels.

The results of the simulation are expressed as water table contour maps and directions of groundwater movement together with mass water balances for the model domain. Figure 4a depicts the final isopiezometric contours produced by the model, making obvious the gradual decline of groundwater levels as moving from the eastern boundary to the western, where the contours appear
to be denser. This is totally attributed to the hydraulic head value assigned to the western aquifer boundary. Furthermore, the direction of groundwater is illustrated in Figure 4b, where its movement towards the aforementioned area becomes more apparent.

The flow budget of the aquifer system for the steady-state simulation is presented in Table 3. The first two columns give the exact volume of water (in m$^3$/d) referring to the various water balance terms, while the two last columns provide the different water balance terms as percentages of the total inputs or outputs. Groundwater inflow to the system occurs almost exclusively from recharge (99.1%), which is due to precipitation and irrigation return water, while the main source of groundwater outflow is groundwater abstraction (69.1%). Finally, what is worth mentioning is that the total water budget over the entire aquifer shows a perfect balance between inflows and outflows, which is consistent with the steady-state modeling conditions (Varni and Usunoff, 1999; Bradford and Acreman, 2003).

Figure 3. Scattergram of observed versus simulated groundwater levels for the steady-state simulation in monitoring wells.

Figure 4. (a) Simulated groundwater levels and (b) main flow direction vectors.
4. DELINEATION OF PROTECTION AND “POLLUTION” ZONES

4.1 Theoretical framework

In the present study, the delineation of wellhead protection zones was accomplished through the application of the following methods: a) the calculated fixed radius (CFR) method (1st method); b) the simplified variable shapes (SVS) method (2nd method); and c) the MODPATH code (3rd method). In order to apply the first two methods, the WhAEM computer program was used, while the third method was implemented within the framework of Groundwater Modelling System (GMS 8.1). MODPATH was also used for the delineation of the “pollution” zones.

With respect to the CFR and SVS methods, they are incorporated into the WhAEM computer program through the Simple WHPAs tool. The calculation of WHPA dimensions using this tool depends on several parameters, including the magnitude and direction of the ambient flow near the well or wellfield, which is challenging to characterize. The magnitude of the uniform flow (i.e., the total amount of water in the aquifer integrated over the saturated thickness, per unit width of the aquifer) is denoted by \( Q_o \) [L²/T], and can be estimated from the hydraulic gradient \( i \) [-] and the aquifer transmissivity \( kH \) (hydraulic conductivity, \( k \), times saturated aquifer thickness, \( H \)) [L²/T] (Kraemer et al., 2003; Kraemer et al., 2007). The magnitude of the uniform flow rate is calculated as:

\[
Q_o = kHi
\]

The shape and size of a simplified time-of-travel protection zone can be related to a dimensionless travel time parameter \( \tilde{T} \) (Figure 5) defined as:

\[
\tilde{T} = \frac{T}{T_o}
\]

where \( T \) is the time-of-travel [T] and \( T_o \) [T] is a reference time defined as:

\[
T_o = \frac{nHQ}{2\pi Q_o^2}
\]

where \( n \) is the aquifer porosity [-] and \( Q \) [L³/T] is the pumping rate of the well.

When \( \tilde{T} \leq 0.1 \), the calculated fixed radius (CFR) centered on the well, including a safety factor for a non-zero ambient flow field, is given by:

\[
R = 1.1543\sqrt{(QT)/(\pi Hn)}
\]

When \( 0.1 \leq \tilde{T} \leq 1 \), the CFR is given by:

\[
R = L_x[1.161 + \ln(0.39 + \tilde{T})]
\]
where \( L_s \) is the distance from the well to the stagnation point down gradient from the well given by:

\[
L_s = \frac{Q}{(2\pi Q_o)}
\]  

(6)

and where the eccentricity \( \delta \) (Figure 5) is given by:

\[
\delta = L_s [0.00278 + 0.652\tilde{T}]
\]  

(7)

When \( \tilde{T} > 1 \), a uniform flow envelope, the so-called boat-shaped protection zone, can be defined as:

\[
x = \frac{y}{\tan(y/L_s)}
\]  

(8)

where \( y \) is bounded by:

\[
-Q/2Q_o < y < +Q/2Q_o
\]  

(9)

and clipped at the up-gradient distance \( L_u \) given by:

\[
L_u = L_s [\tilde{T} + \ln(e + \tilde{T})]
\]  

(10)

More details about the aforementioned calculation sequence can be found in Ceric and Haitjema (2005) and Kraemer et al. (2007).

With regard to the 3rd method, MODPATH is a particle tracking post-processing package which was developed to compute three-dimensional flow paths using output from steady-state or transient groundwater flow simulations. MODPATH uses a semi-analytical particle tracking scheme that allows an analytical expression of the particle’s flow path to be obtained within each finite-difference grid cell. Particle paths are computed by tracking particles from one cell to the next until the particle reaches a boundary, an internal sink/source, or satisfies some other termination criterion. The particles can be tracked either forward (“pollution” zones) or backward (protection zones) in time assuming they are transported by advection only (Pollock, 1994; Rayne et al., 2001).
4.2 Wellhead protection zones

In order to apply the CFR and SVS methods the parameters values (i.e., hydraulic conductivity, pumping rates, effective porosity), properly adjusted through the calibration procedure of the steady-state model, were used. However, according to the analysis made in the “Theoretical framework” section, in the case of eccentric circular (Equations 5-7) and boat-shaped (Equations 8-10) protection zones, hydraulic gradient (i) has to be defined. For this task, the hydraulic head distribution (Figure 4a) resulting from the steady-state model was taken into consideration and, therefore, the hydraulic gradient determination was based on this distribution. The results of the whole procedure are depicted in Figure 6, in which the significantly increased hydraulic gradient in the western part of the aquifer, that is consistent with the sharp decline of the hydraulic head in that area (Figure 4a), is far from obvious. With regard to the 3rd method (MODPATH), its application was based on the results of the groundwater flow simulation procedure.

In all cases, 20 particles located in the centre of each well were used in order to best visualize the particle path lines (Rayne et al., 2001; El Yaouti et al., 2008; Siarkos et al., 2017), while the time-of-travel (ToT) criterion was applied as a delineation criterion. A wellhead protection area delineated applying the ToT criterion is the area surrounding a well that contributes groundwater flow to the well within a specified period of time. The size of this area is determined by the distance obtained by multiplying the specified value of ToT with the groundwater velocity (Badv and Deriszadeh, 2005; Mogheir and Tarazi, 2010; Siarkos and Latinopoulos, 2012). In all cases, ToT was assigned a value of 10 years (3,650 days) which is considered to be a satisfactory time period for the protection of abstraction wells regarding various forms of pollution (e.g., pathogens, toxic substances) (WHO, 2006; Siarkos and Latinopoulos, 2012; Staboultzidis et al., 2017). At this point, it should be mentioned that first the delineation of protection zones by applying the 3rd method (MODPATH) was performed, in order to obtain the direction of groundwater flow, and then, the 2nd method (SVS) was implemented setting the correct angle each time.

The wellhead protection areas resulting from the application of the three different delineation methods are illustrated in Figures 7 and 8. Figure 7 refers to the western part of the study area, while Figure 8 to the eastern part. Moreover, the extent of these areas resulting from each method is presented in Table 4. By studying these figures, in some cases, the differences in the results of the three delineation methods are far from obvious. Typical examples are the protection areas of the wells W6, W7 and W8 located in the western portion of the aquifer (Figure 7). In these wells, the implementation of the 2nd (SVS) and the 3rd (MODPATH) methods resulted in an intense elongation of the protection areas, which is totally attributed to the increased hydraulic gradient.
observed in that portion of the aquifer (Figure 6). It is noted that these two methods, in contrast to the 1st method (CFR), take into account the natural flow of groundwater.

Additionally, strong differentiation among the delineated protection areas is observed in the case of the wells W1, W3 and W11 located in the eastern part of the study area (Figure 8). In this case, the implementation of the 1st (CFR) and the 2nd (SVS) methods led to protection zones of similar shape and extent due to the small hydraulic gradient observed in that region (Figure 6), which totally affected the results of the 2nd method (SVS). In general, as it can be concluded from Table 4, the application of the 1st method (CFR) resulted both in the largest protection areas in the majority of the wells (8 wells) and in the largest protection areas extent in the whole region (447,522 m²), leading to the conclusion that this method generally resulted in over-estimated calculations.
Table 4. Extent (in $m^2$) of the protection areas resulting from various delineation methods

<table>
<thead>
<tr>
<th>Well</th>
<th>Type</th>
<th>1st Method</th>
<th>2nd Method</th>
<th>3rd Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Domestic</td>
<td>49,260</td>
<td>36,467</td>
<td>10,992</td>
</tr>
<tr>
<td>W2</td>
<td>Domestic</td>
<td>49,260</td>
<td>41,015</td>
<td>43,990</td>
</tr>
<tr>
<td>W3</td>
<td>Domestic</td>
<td>49,260</td>
<td>38,189</td>
<td>17,894</td>
</tr>
<tr>
<td>W4</td>
<td>Domestic</td>
<td>49,260</td>
<td>36,350</td>
<td>18,718</td>
</tr>
<tr>
<td>W5</td>
<td>Domestic</td>
<td>49,260</td>
<td>43,762</td>
<td>9,070</td>
</tr>
<tr>
<td>W6</td>
<td>Domestic</td>
<td>11,785</td>
<td>24,244</td>
<td>21,344</td>
</tr>
<tr>
<td>W7</td>
<td>Domestic</td>
<td>11,785</td>
<td>21,950</td>
<td>20,247</td>
</tr>
<tr>
<td>W8</td>
<td>Livestock</td>
<td>51,741</td>
<td>61,633</td>
<td>20,155</td>
</tr>
<tr>
<td>W9</td>
<td>Livestock</td>
<td>51,741</td>
<td>41,140</td>
<td>31,164</td>
</tr>
<tr>
<td>W10</td>
<td>Industrial</td>
<td>37,085</td>
<td>31,017</td>
<td>14,827</td>
</tr>
<tr>
<td>W11</td>
<td>Industrial</td>
<td>37,085</td>
<td>31,131</td>
<td>15,018</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>-</td>
<td>447,522</td>
<td>406,898</td>
</tr>
</tbody>
</table>

In Figures 7 and 8, in addition to the wellhead protection areas, the potential point and non-point pollution sources detected in the study area are depicted in order to track down those sources that are located in the interior of the delineated protection areas. As it is obvious, the majority of the potential pollution sources are sited out of the extent of the protection areas deriving from the application of the three methods, leading to the conclusion that they do not pose a threat to the abstraction wells. Nevertheless, there are some specific pollution sources located within the protection areas and, therefore, they have to be controlled and managed accordingly. Table 5 presents the pollution sources located in the interior of the various protection areas, as they are listed on Table 1.

Table 5. Pollution sources located in the interior of protection areas (based on Table 1)

<table>
<thead>
<tr>
<th>Well</th>
<th>Type</th>
<th>1st Method</th>
<th>2nd Method</th>
<th>3rd Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2</td>
<td>Domestic</td>
<td>32</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>W5</td>
<td>Domestic</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>W6</td>
<td>Domestic</td>
<td>39</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>W8</td>
<td>Livestock</td>
<td>31</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>W9</td>
<td>Livestock</td>
<td>14</td>
<td>14</td>
<td>-</td>
</tr>
</tbody>
</table>

The first conclusion stemming from Table 5 is that the protection areas deriving from the 1st method include the highest number of pollution sources in their extent, verifying the trend of this method to provide over-estimated calculations. More specifically, five different pollution sources, i.e., No. 32 (cheese dairy), No. 2 (distillery), No. 39 (cesspools), No. 31 (window glass factory) and No. 14 (cattle farm), are located within the protection zones of five different wells, i.e., W2, W5, W6, W8 and W9, three of which are domestic wells. The second conclusion is that only in the case of one well, i.e., W6 (domestic well), all three methods resulted in protection areas in the interior of which a pollution source, i.e., No. 39 (cesspool), is located.

Based on the above analysis, the following measures are proposed: a) the suspension of the operation of well W6 and the construction of new one/ones outside the settlement, which is also strengthened by the fact that the existence of a domestic well in a residential area is completely intolerable; and b) the continuous monitoring of the quality of the groundwater abstracted from wells W2 and W5 (domestic wells), and only if it is considered absolutely necessary, based on the outcome of the groundwater chemical analysis, the termination of the operation of the nearby pollution sources, i.e., No. 32 (cheese dairy) and No. 2 (distillery). The second measure is based on the fact that not all methods resulted in protection areas in the interior of which the aforementioned pollution sources are located. With regard to the remaining wells, i.e., W8 and W9, since they are used for livestock purposes, the water quality standards are not as high as in the case of domestic wells and, therefore, the pollution sources do not pose serious threat.
4.3 “Pollution” zones

Except for the delineation of wellhead protection areas, the determination of “pollution” zones surrounding the potential pollution sources (both point and non-point pollution sources) was performed in order to provide better protection for the local groundwater resources. This fact is considered to be very important in the case of constructing new wells and especially water-supply wells. To define these zones, the MODPATH code was used keeping the simulation conditions identical to those in the protection areas delineation process and performing a forward particle-tracking simulation. Figure 9 shows the results of the “pollution” zones delineation procedure. As it is obvious, the majority of these zones are of small extent, due to the low values of groundwater flow velocity, with the exception of the zones related to the non-point pollution sources, i.e., No. 39 (cesspools), No. 40, No. 41 and No. 42 (abandoned mines). Therefore, great caution has to be given if a well is planned to be constructed in the vicinity of these pollution sources.

Figure 9. “Pollution” zones surrounding the various pollution sources located in the study area

5. CONCLUSIONS

The present study deals with the protection of groundwater resources in the Upper Anthemountas aquifer through: a) the delineation of wellhead protection areas of several domestic, livestock and industrial wells; and b) the management of potential point and non-point pollution sources detected in the region, especially of those located in the interior of the protection areas. For the delineation procedure, three different methods were implemented, the calculated fixed radius (CFR) method, the simplified variable shapes (SVS) method and numerical modeling by applying, in the later case, the MODPATH code and performing a backward particle-tracking simulation. In order to apply MODPATH, a steady-state model was developed on a basis of a previous one which was improved for the needs of this study. Furthermore, the determination of specific areas surrounding the pollution sources (“pollution” zones) was attempted in order to provide further protection regarding the future use of local groundwater resources. To this task, the MODPATH code was again used and a forward particle-tracking simulation was conducted.

The results from the delineation procedure and the implementation of the three different methods clearly showed the strong differences existing among them, which refer both to the form and the
size of the protection areas. This is directly related to the nature of each method and the type of parameters taken into account, while it significantly affects the level of protection of each method. Therefore, great caution is suggested in selecting and implementing the proper delineation method.

Moreover, the delineation procedure, in conjunction with the process of detecting and recording the various potential pollution sources existing in the study area, led to the conclusion that the majority of the selected wells are not significantly affected from the detected pollution sources. An exception to this is one domestic well located in the Galarinos settlement, which is directly threatened from the various cesspools existing in this settlement. This well has to stop operating and new wells have to be constructed at some distance from the settlement. Finally, the determination of the “pollution” zones showed that the detected non-point pollution sources constitute the major threat to local groundwater resources and, therefore, they have to be taken seriously into consideration in the case of constructing new water-supply wells.

ACKNOWLEDGEMENTS


REFERENCES


