Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.23116

133 (2018) 315–326
November

Using a hydroeconomic model to evaluate alternative methods applied for the delineation of protection zones

Ilias Siarkos[a,]*, Stefanos Sevastas[a], Dionysis Latinopoulos[b]

[a]*School of Civil Engineering, Aristotle University of Thessaloniki, GR54124 Thessaloniki, Greece, Tel. +30 2310661833; email: isiarkos@civil.auth.gr (I. Siarkos), Tel. +30 2310326576; email: sevastas@civil.auth.gr (S. Sevastas)*
[b]*School of Spatial Planning and Development, Aristotle University of Thessaloniki, GR54124 Thessaloniki, Greece, Tel. +30 2310994248; email: dlatinop@plandevel.auth.gr*

Received 14 April 2018; Accepted 11 September 2018

ABSTRACT

The delineation of wellhead protection zones, especially for water-supply wells, is included nowadays among the most well-known and applied techniques for protecting groundwater quality. To this task, various methods have been developed and are currently implemented, ranging from simple and low-cost to more complex and costly ones. As these methods vary regarding their degree of accuracy and protection, the comparison and evaluation of their outcomes are required, which are usually based on technical criteria (i.e., extent, shape, and form of protection zones). The study takes a step forward by comparing and evaluating three different delineation methods not only on the basis of the morphological features of the protection zones but also considering some economic and environmental aspects. In this framework, a hydroeconomic model was developed and an economic-environmental indicator – expressed as the ratio of the total cost of implementing a protection zone to the associated environmental benefits – was introduced. In the empirical application of this paper, the protection zones of two water-supply wells, both located in agricultural land, were determined. Furthermore, the application cost and the environmental impact (i.e., decrease in nitrate concentrations) of the protection zones were estimated by implementing set-aside programs specifically designed for each zone.

Keywords: Groundwater protection; Wellhead protection zones; Nitrate contamination; Hydro-economic modeling; Nea Moudania aquifer

1. Introduction

Groundwater resources pollution caused by numerous human activities, such as agricultural, industrial, commercial, and domestic activities, constitutes a major environmental issue, greatly affecting the available and exploitable amounts of freshwater [1–5]. Due to this fact, awareness regarding the significance of preserving groundwater quality is constantly arising, thus resulting in the increase of efforts introduced both in local and regional scale for achieving groundwater resources protection [6–8]. Besides, groundwater protection is strictly imposed by the European Union Framework Directive 2000/60/EC and all relevant European and national legislation, while it is essential due to the increasing water demand observed nowadays [3,4,9,10].

A practice usually implemented by the competent authorities in order to preserve groundwater resources and avoid their further deterioration involves the delineation of specific areas of protection around abstraction wells, known as Wellhead Protection Areas (or Zones), WHPAs (or WHPZs) [1–5,8,11,12]. The ultimate goal of this practice is the proper control of potential pollution sources situated in the interior of these areas, by establishing land use management strategies based on the type of pollution sources (i.e., agricultural, industrial, or domestic pollution sources, point or nonpoint pollution sources) and their potential groundwater pollution

---

* Corresponding author.

Presented at the 6th International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE-2017), 25-30 June 2017, Thessaloniki, Greece.

risk [9,11,13,14]. Through this practice, management of pollution sources is achieved on local scale, which is more cost-effective and socially acceptable than universal controls over land use on a regional level [7,15,16].

Several methods have been developed and implemented so far for the delineation of WHPAs. More specifically, the US EPA [12] proposed six alternative delineation methods: (1) arbitrary fixed radius, (2) calculated fixed radius (CFR), (3) simplified variable shapes (SVS), (4) analytical methods, (5) hydrogeologic mapping, and (6) numerical modeling. These methods vary in terms of: (1) cost, amount, and diversity of data required, (2) the time investment and the level of expertise considered essential for their implementation, and (3) their degree of complexity and their precision [1,2,7,12]. In general, there is an increase in complexity and cost from the top to the bottom of the above list [12,14]. A detailed description of the aforementioned methods with regard to their technical characteristics (i.e., equations, parameters, and implementation procedure), as well as their advantages, disadvantages, and implementation costs are provided by US EPA [12]. Furthermore, a brief evaluation of both their accuracy and various parameters affecting it is presented in Raymond et al. [11].

Since a variety of delineation methods exist, the selection of the most appropriate one for each case is not a trivial task. According to Hasfurther et al. [17], selecting a delineation method is based on user expertise, available resources and data, as well as on the desired degree of accuracy and protection, whereas it is directly linked to the criterion used for the delineation (i.e., distance, time-of-travel (ToT), drawdown, and flow-system boundaries) [9,12,14]. In addition, the choice of method is tied less to the protection goal than to the accuracy of delineation desired, and the financial resources available for delineation [12]. The differentiation of these methods regarding their degree of accuracy and protection often leads to their comparison, as well as to the evaluation of their results. This is actually translated to the evaluation of the extent and form of the protection areas deriving from each method. Numerous studies dealing with this issue can be found in literature (e.g., Refs. [1,2,8,10,11,18–20]). What is generally missing and should be thoroughly investigated is the evaluation of these methods by using not only technical features but also environmental and economic criteria. Therefore, taking a step further from previous studies, herein the comparison and evaluation of delineation methods are based not only on the morphological characteristics of the zones (i.e., extent, shape, and form) but also on their implementation cost and their environmental impact. In order to achieve this and facilitate the whole evaluation procedure, a hydroeconomic model was developed and a specific indicator incorporating both economic and environmental aspects was introduced.

Moreover, taking into consideration the characteristics of the reference area and the fact that the protection zones is chosen to be situated in agricultural land, their implementation cost was estimated based on the type of crops cultivated, while assuming that a regulatory set-aside program is applied providing an annual compensation to farmers for their income foregone. On the other hand, the estimation of the environmental impact was based on the reduction of nitrate concentrations in groundwater abstracted from the protected wells as a result of the set-aside program. This reduction is attributed to the fact that taking land out of production results in the termination of the use of fertilizers and, therefore, in the decrease of the nitrate load introduced to the aquifer.

As it is well known, the excessive use of fertilizers in rural areas for enhancing crop production leads to the contamination of groundwater resources, with nitrates being one of the most common contaminants [21–24]. High mobility of nitrates in the environment aggregates the problem [25,26]. Moreover, nitrates in drinking water have been linked to human health problems including methemoglobinemia, gastric cancer, and non-Hodgkin's lymphoma [23,25,27]. Therefore, the implementation of proper management strategies to control nitrate contamination is considered of utmost importance. Nevertheless, these strategies should be carefully investigated and analyzed, especially in the case they are associated with agricultural development, since they: (1) affect both the economic development and the social cohesion of rural areas and (2) create conflicts between farmers and municipal and government authorities [21,22,28]. To avoid these conflicts and result in efficient and cost-effective solutions most groundwater regulations require the delineation of WHPAs with the purpose to prohibit or restrict specific activities within these areas [12,22].

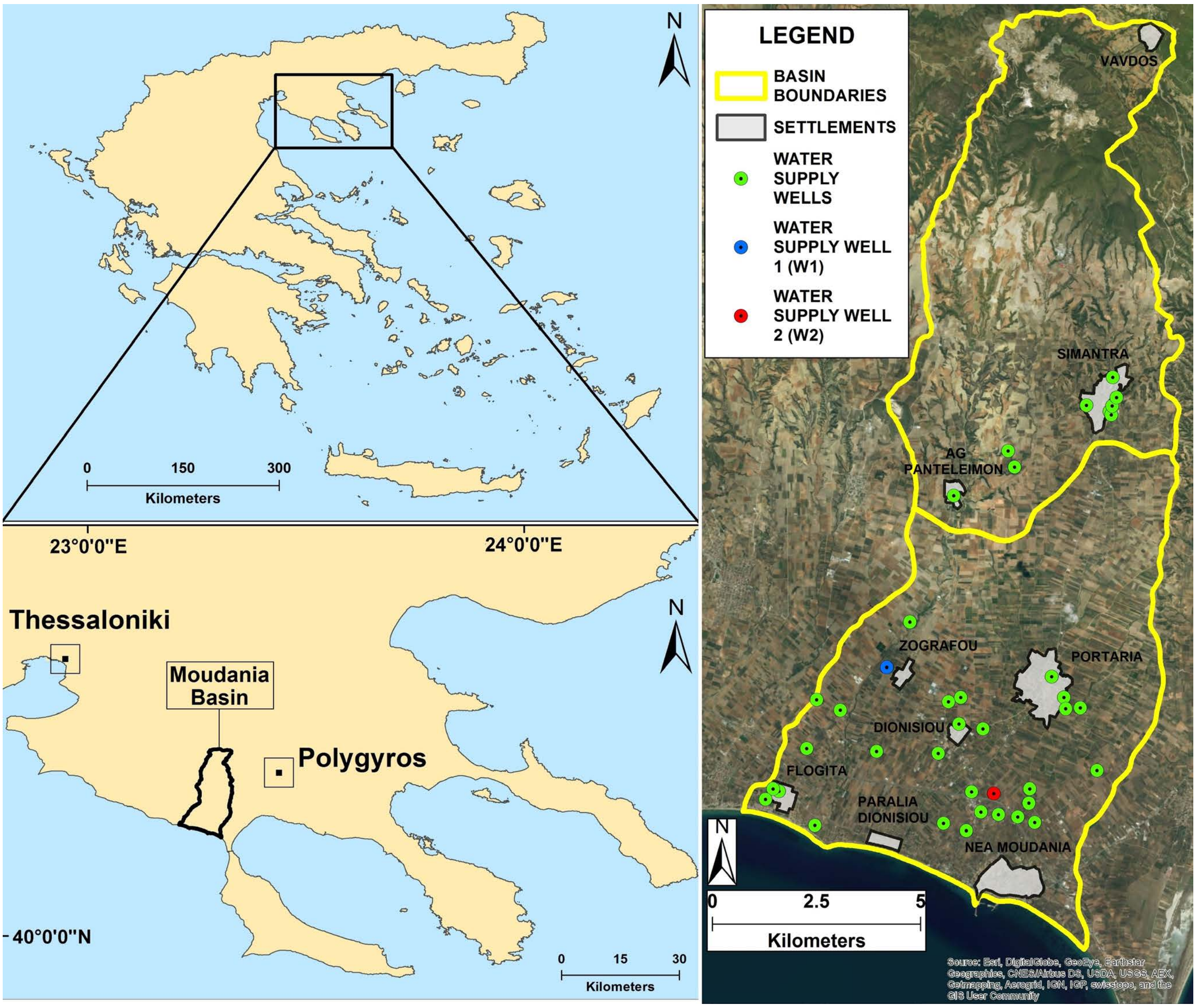
The goal of this study is thus to compare and evaluate the application of various methods used for the delineation of WHPAs taking into consideration not only technical issues but also economic and environmental aspects associated with the implementation of protection areas. Therefore, this study aims to: (1) make the comparison and evaluation of the delineation methods more robust, and (2) provide more reliable conclusions about the credibility and applicability of each method. The implementation of the whole procedure is performed in the aquifer of Nea Moudania in the Halkidiki Peninsula (northern Greece), which is faced with severe quantitative and qualitative problems due to intensive agricultural activities taking place in the region.

2. Materials and methods

2.1. Study area description

The hydrological basin of Nea Moudania is located in the south-western part of the Halkidiki Peninsula, northern Greece. It belongs to a broader region known as "Kalamaria plain," which is the main agricultural area of Halkidiki. The basin covers about 127 km^2, with a mean topographic elevation of 211 m above mean sea level and a mean soil slope of 1.8%. Fig. 1 depicts both the location and the boundaries of the Nea Moudania basin, which is divided into two subregions: the hilly area in the north and the flat area in the south. The climate of the study area is semi-arid to humid, typically Mediterranean, and the average annual precipitation is 417 mm for the flat area and 504 mm for the hilly one. It is characterized by a scalable elevation of the terrain from the coastal to the inland area and a dense hydrographic network, especially in the hilly area, draining directly to the sea [4,29,30].

The whole basin is a typical rural area, where agriculture dominates both the local economy and land use (76%).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Fig. 1. Location of the Nea Moudania basin, as well as of the water-supply wells operating in the study area and the two wells selected for the protection zones delineation and evaluation procedures (Wells W1 and W2).

Of the remaining land, 20% is woodland, while 4% accounts for urban and touristic development. Currently, water needs in the region (irrigation, domestic, and livestock needs) are exclusively covered by the Nea Moudania aquifer system, which is considered to be semi-confined, consisting of successive water-bearing layers separated by lenses of semi-permeable or impermeable materials. Uncontrollable irrigation, in conjunction with the low rate of aquifer replenishment, has caused a quantitative degradation of the local groundwater resources, since a net deficit in the aquifer's water balance is observed [29,30]. In addition, deterioration of groundwater quality occurs in the reference area due to both nitrate contamination and seawater intrusion [4,14,29,30]. With regard to nitrate contamination, several recent investigations conducted in the region (e.g., Refs. [9,30–32]) showed high nitrate concentrations, especially in areas where crop productivity and, therefore, application of fertilizers are intense.

For the exploitation of groundwater resources, a large number of abstraction wells operate in the region. Referring to year 2001, there are totally 518 wells, 39 of which are municipal domestic wells, supplying with freshwater eight individual settlements situated in the region (Fig. 1) [29]. Two of these wells (highlighted in Fig. 1) were selected for our analysis. Their selection was based on the fact that: (1) they are located in agricultural land and (2) nitrate concentrations in the groundwater abstracted from them are rather high (>25 mg/L) [32], thus rendering the implementation of preventive measures necessary.

2.2. Methodology

The procedure followed in this study aims to compare and evaluate three alternative methods applied for the delineation of WHPAs, taking into consideration the morphological features of the zones along with their implementation cost and their environmental impact. This procedure comprises the following steps:

Step 1 – Delineation of protection areas around two water-supply wells (both located in agricultural land) by applying three different delineation methods, that is, the CFR method, the SVS method and, finally, numerical modeling, and using the ToT criterion. The first two methods were applied within the framework of the US EPA Well-head Analytic Element Model, WhAEM [33,34], while for the implementation of the third method the MODPATH (a particle tracking post-processing package) code [35] was used. In the latter case, the simulation of the groundwater flow of the aquifer under study is required. To this task, a steady-state groundwater flow model based on a previously developed model was formed by applying the MODFLOW (modular three-dimensional finite-difference groundwater flow model) code [36]. Furthermore, three types of protection zones were established based on the different value of ToT used in each case (i.e., 5, 10, and 15 years), thus resulting in the development of nine protection areas per well.

Step 2 – In this step an economic analysis of the implementation of protection zones is performed. As already stated, among the various agricultural land use policy measures (strategies) that can be applied in the protected areas, the one selected in this study is the implementation of a set-aside program. According to this program, protection is achieved by introducing a compulsory set-aside scheme for a predetermined number of years and by compensating farmers for their foregone income. The annual (social) cost of this program is equal to the actual gross margin of the protected area. Therefore, the current cropping patterns in the parcels that are regulated by the protection zones – as estimated in all three methods – are first identified and then the actual gross margin of each protected area (generated in Step 1) is calculated. Long-term costs are then estimated by discounting future income losses to present values. It should be noted that in the long term, this is a quite expensive policy (related to other measures such as the compulsory purchase of agricultural land or the regulatory pumping restriction policies) but it is an approach that approximates real social costs. Besides, as the aim of this paper is to compare the economic results of the different delineation methods rather than estimating the most efficient land use policy, the selected approach was also considered appropriate due to its simplicity.

Step 3 – Calculation of the nitrate concentrations in the groundwater abstracted from the wells selected for the delineation procedure. In this context, a nitrate transport model, formed on the farm level (i.e., the nitrogen load was calculated in each parcel based on the type of crop and the amount of fertilizers applied), was developed. This model was based on the aforementioned steady-state groundwater flow model, as well as on a nitrate transport model, which was previously developed for the reference area. In this transport model, which was formed on a regional scale, the study area was divided into zones, while the nitrogen load was calculated in each zone (based on the parcels' extent and the type of crops). The widely used three-dimensional multispecies transport model MT3DMS [37] was used for the development of the new model. The newly formed model was run both before and after the implementation of the set-aside policy, allowing for the determination of the difference in nitrate concentrations of the abstracted groundwater between the no-protection and the protection status. This difference occurs since after the implementation of the set-aside policy no fertilizers are applied anymore and, therefore, no nitrate load is introduced to the aquifer.

Step 4 – The final step of our analysis consists of calculating an evaluation indicator, which will incorporate both economic (total social cost) and environmental (total nitrates reduction) results. This indicator/criterion was estimated as the ratio of the total cost of implementing a protection zone to the associated environmental benefits (i.e., the decrease of nitrate concentrations) over the time period (5, 10, or 15 years). Therefore, the higher the ratio the less (cost) efficient the delineation method will be. In other words, higher values indicate that for a certain decrease of nitrate concentrations (over a given time period) higher social costs are required. This indicator was estimated for each protection zone and was used to evaluate the three different delineation methods, thus providing an indirect (and actually an inverse) assessment of the "value for money" of these methods.

3. Protection zones delineation and evaluation procedures

3.1. Delineation of protection zones

In this study, three different methods were implemented in order to determine WHPZs. These methods are: (1) the CFR method (first method), (2) the SVS method (second method), and (3) the MODPATH code (third method). For the first two methods, the US EPA's WhAEM was used, while the third method was implemented within the framework of Groundwater Modelling System (GMS 8.1). It is worth mentioning that in all three methods the ToT is used as a delineation criterion. ToT is based on the maximum time for a groundwater contaminant to reach a well, using a less sophisticated evaluation of the physical processes of contaminant transport than most of the other relevant criteria. Of these physical processes, advection is the most comprehensive one [9,14,38]. A WHPA delineated through the ToT criterion is the area surrounding a well that contributes groundwater flow to the well within a specified time period. The size of this area is defined by the distance deriving from multiplying the specified value of ToT by the groundwater velocity [8,9,39].

3.1.1. Theoretical framework

Among the aforementioned methods, CFR and SVS are considered to be quite simplistic since they are based on analytical equations. However, the calculation of WHPA dimensions using the SVS method depends on several parameters, including the magnitude and direction of the ambient flow near the well or well field, which is challenging to characterize [34]. An in-depth description of the whole calculation sequence associated with the aforementioned methods is fully provided in Kraemer et al. [34] and Ceric and Haitjema [40], while their typical results are illustrated in Fig. 2. For each case presented in Fig. 2 different equations are used to determine the shape and size of ToT protection zones according to the value of the dimensionless travel time parameter, $\check{T}$ [34,40].

MODPATH is a particle tracking postprocessing package developed to compute three-dimensional flow paths using as input the results from steady-state or transient groundwater flow simulations conducted applying MODFLOW. MODPATH uses a semi-analytical particle tracking scheme through which an analytical expression of the particle's flow path is obtained within each finite-difference grid cell. Particle paths are determined 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 or backward in time considering they are affected by advection only [35,41].

3.1.2. Application in the study area

Since the third delineation method includes the application of MODPATH code, the simulation of groundwater flow applying the MODFLOW code is required. To this task, a steady-state groundwater flow model was built in order to get the hydraulic head distribution and thus obtain the required velocity field. As already mentioned, this model was based on a steady-state model previously developed for the reference area by Siarkos and Latinopoulos [29]. The previous study provides an in-depth description regarding (1) the construction of the aquifer's conceptual model as far as the groundwater flow problem is concerned and (2) the development and calibration of the steady-state model. The only modification that was made in this study (in the new model) is related to its spatial discretization, that is, the creation of the model grid. Namely, for the needs of this study, the model grid was reformed, so that each cell has a 25-m side instead of a 100-m side that was set in the previous model [29]. This modification was considered essential since the cells had to be smaller in size in order to achieve a more detailed land use classification, that is, a more accurate representation of the parcels where the set-aside program is applied. Besides, if cells were quite large in relation to the parcels' extent, serious problems in the development of the nitrate transport model would be caused, which would also affect the model results (i.e., nitrate concentrations). Through this modification and taking into consideration the extent of the model domain, the new model grid consists of 720 rows and 480 columns, and a total number of 151,514 active cells.

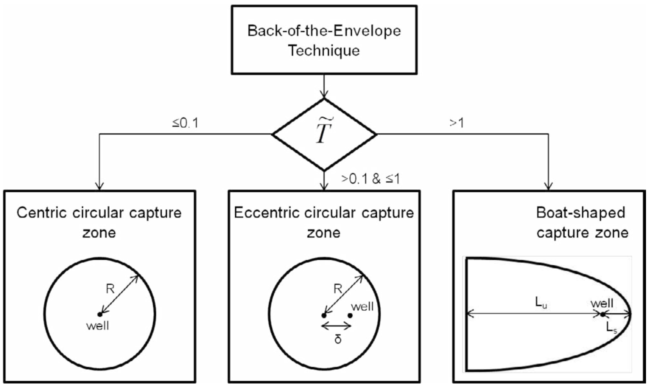


Fig. 2. Simplified delineation techniques [34].

The proper application of all three delineation methods also requires the availability/estimation of various parameters, such as hydraulic conductivity, effective porosity, aquifer thickness, and well pumping rates. In our case, the values assigned to these parameters were derived from Siarkos and Latinopoulos [29] as well. Finally, in order to apply the SVS method the hydraulic gradient has to be defined. To this task, the hydraulic head distribution resulting from the steady-state model was taken into consideration and used for the hydraulic gradient determination. The results of the whole procedure are shown in Fig. 3.

In all methods, 20 particles located in the center of each well were used to best visualize the particles' path lines [14,41]. Furthermore, three different types of protection zones (Zones 1, 2, and 3) reflecting the different values of ToT (5, 10, and 15 years) were created for each method. Regarding the values of ToT used, it is considered that a period of 5 years provides a remarkable level of safety, since the survival of most pathogens does not exceed 2 years. Likewise, the period between 10 and 15 years is considered sufficient for the degradation of the various polluting substances [12,14].

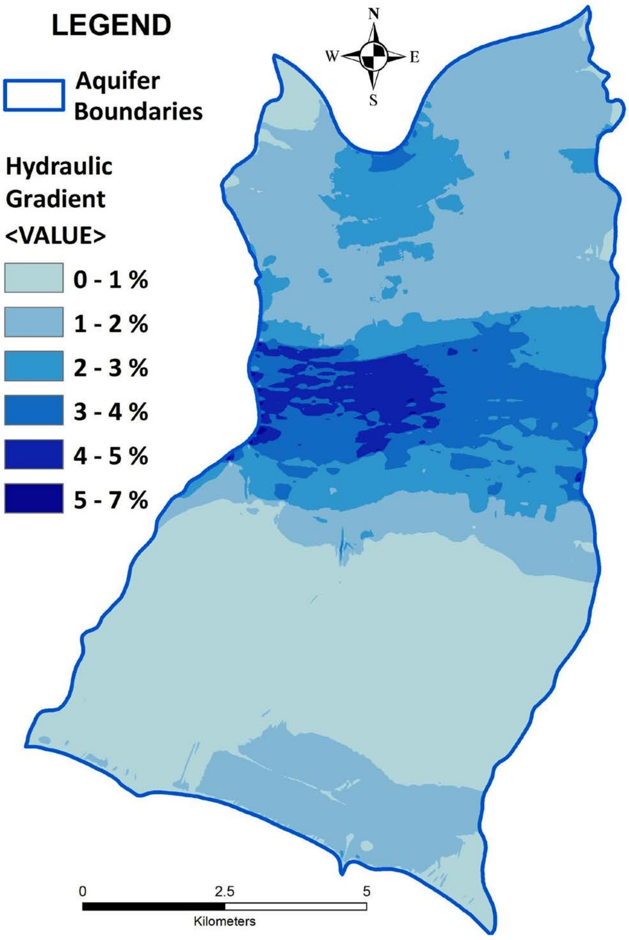


Fig. 3. Hydraulic gradient map based on hydraulic head distribution.

3.2. Evaluation of protection zones

In this study the evaluation of protection zones is accomplished by taking into account both economic and environmental criteria and considering that a set-aside policy is applied in those parcels affected by the protection zones. Therefore, the economic analysis is based on the fact that the cost of this policy is equal to the actual gross margin of the protected areas. On the other hand, the environmental analysis considers the potential future decrease of nitrate concentrations in the groundwater abstracted from the protected wells due to the set-aside program and the subsequent termination of fertilizers' use inside the regulated (protected) area.

3.2.1. Economic criteria

In this section, the social costs of the various delineation methods were determined in order to estimate the economic impact of each delineation method applied in this study. These costs were considered to correspond to the income foregone, if farmers were forced to remove their land out of production for a given period (from 5 to 15 years). It should be noted that the social costs are independent of the subsidy policies that may be implemented by local authorities (i.e., social costs do not change, whether they are paid by farmers or society). Farmers' foregone income (gross margin losses) was estimated in a per hectare basis, according to the actual cultivated crops in the parcels that are designated as part of the protection area. In this context, a Geographic Information System (GIS)-based analysis was used to locate the various crops in the reference area taking into consideration a database involving the crop spatial distribution patterns of the broader study area [42]. From this analysis four different crops were found in the protected areas: cotton, wheat, olive trees, and apricot trees. Then, a set of regional agro-economic indicators – including among others: crop yields, crop prices, labor costs, and other variable costs (e.g., costs of fertilizers, pesticides, and irrigation costs) – was used to estimate the annual gross margin (foregone income) for each of these crops. Per-hectare costs were then summed to calculate the total annual cost of each protection zone. Then, to estimate the long-term costs of each delineation method (i.e., the costs for the whole implementation period in each zone), all future (annual) income losses were discounted to a present value, by means of a social discount rate, which was assumed to be equal to 3%.

3.2.2. Environmental criteria

In order to estimate the environmental impact of the various delineation methods used in this study, a nitrate transport model was developed on the farm level based on: (1) the steady-state groundwater flow model mentioned in Section 3.1.2 and (2) a regional calibrated nitrate transport model, previously developed for the study area by Siarkos [32]. In the newly formed model, the model domain and the model grid were kept identical to those of the steady-state groundwater flow model. Moreover, the model was built maintaining exactly the same boundary conditions as the regional transport model (Fig. 4). With regard to various transport parameters (i.e., effective porosity and dispersivity), their values were set according to their adjustment during the calibration of the regional transport model [32]. In short, in the case of effective porosity and on the basis of the aquifer's conceptual model formed in Siarkos and Latinopoulos [29] and Siarkos [32], six distinct zones were created (Fig. 4). Different values of porosity were assigned to these zones according to the calibration results of the regional transport model. As shown in Fig. 4, the wells selected for the delineation procedure are included in two different zones, where effective porosity is equal to 0.05 (Well 1, W1) and 0.14 (Well 2, W2). Moreover, based on the same results, longitudinal dispersivity was set equal to 75 m for the whole region, while the ratio of transversal to longitudinal dispersivity was considered equal to 0.1 ($\alpha_T = \alpha_L/10$). Finally, molecular diffusion and denitrification were both considered to be negligible. The assumption

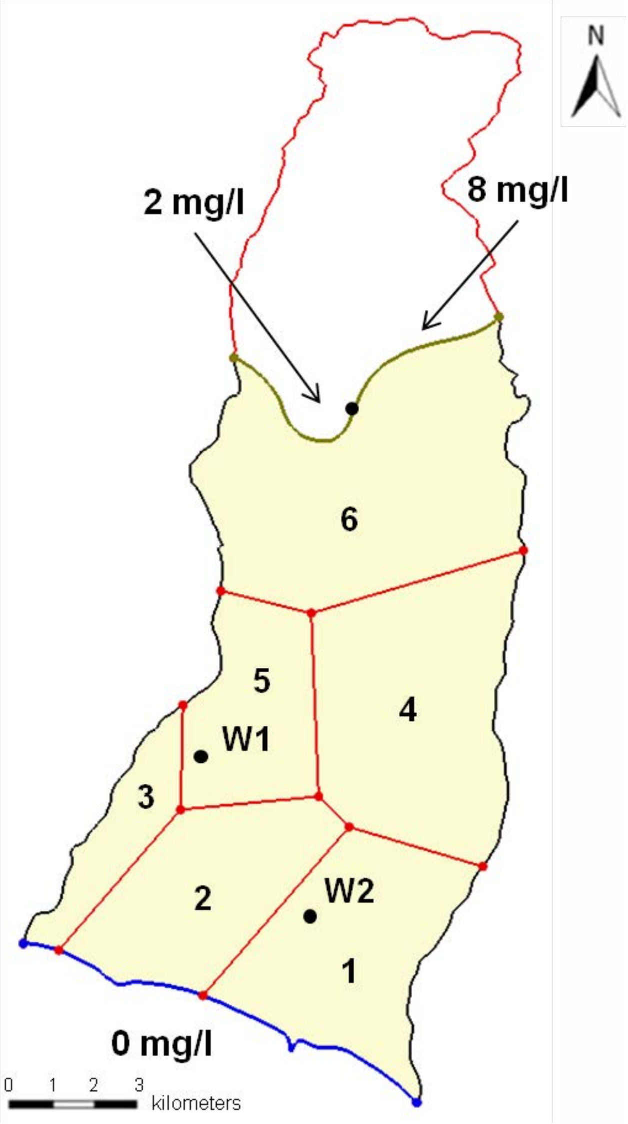


Fig. 4. The six distinct zones of the study area, along with the boundary conditions regarding the nitrate transport problem and the wells selected for the delineation procedure (W1 and W2).

that no denitrification occurs is mainly based on the fact that no presence of nitrites (NO_2^-) is observed in local groundwater resources according to the chemical analysis results of various studies conducted in the region [30–32]. Nitrites are used as indicators of denitrification since they constitute intermediate products of the whole procedure [43–45].

As known, once nitrogen enters the soil and before leaching to groundwater mostly as nitrate, it undergoes several biochemical transformations. These transformations include mineralization, immobilization, nitrification, denitrification, volatilization, crop uptake, and leaching from the soil zone [23,28,46]. It has been reported in many studies that approximately 30%–50% of the applied nitrogen fertilizer leaches to groundwater in the nitrate form [47]. In this study, based on the findings of Siarkos [32], approximately 40% of the total nitrogen load was assumed to reach the groundwater system. After estimating the nitrogen load by multiplying the fertilizer application rate for each crop (i.e., olive and apricot trees, wheat, and cotton) in each parcel with its areal extent and taking into account all the loses due to the aforementioned processes, the final nitrate load percolating into the groundwater system was estimated. At this point, it should be noted that a recharge concentration boundary condition was chosen to simulate nitrate leaching. In Table 1 the suggested amount of nitrogen per crop type is given. It is obvious that olive trees require much higher amount of nitrogen than the other three crops.

Since a mass transport model was developed, temporal discretization referring to the assignment of both the time duration and the time step of the simulation is also required. A 15-year simulation period was selected (2014–2028) which was divided into 180 monthly stress periods. The duration of the simulation period coincides with the highest value of ToT which is used in the delineation procedure. Finally, with regard to the initial conditions of the model the nitrate concentrations' distribution produced by the regional transport model and referring to January 2014, was used.

Through this model, the projection of nitrate concentrations' distribution can be performed under various conditions with regard to the nitrate load introduced to the aquifer. Namely, nitrate concentrations' distributions were projected before and after the implementation of set-aside programs. In the former case, nitrate load resulting from each parcel corresponds to current fertilization practices applied in the study area without considering any restriction measures. In the latter case, nitrate load in an area (i.e., in some parcels) defined by the extent and the form of protection zones was totally removed. This area differs for each protection zone resulting from each alternative delineation method. Due to this fact, a different environmental pressure (measured in terms of nitrate load introduced into the aquifer) is observed, thus leading to different environmental effect/impact (measured in terms of nitrate concentrations in the vicinity of the protected wells).

Table 1
Suggested amount of nitrogen per crop type (kg/acre) [48]

Olive trees	Apricot trees	Cotton	Wheat
75	15	5	15

4. Results and discussion

4.1. Delineation of WHPZs

All types of protection zones (5, 10, and 15 years) in the selected wells (W1 and W2) resulting from the application of the three different delineation methods are depicted in Fig. 5. Additionally, the extent of all zones resulting from each method is presented in Table 2.

From Fig. 5, it can be concluded that the protection zones resulting from the first method differ in shape with the corresponding ones resulting from the application of the other two methods. More specifically, an elongation of the protection areas is observed when using the second or the third method, which is totally attributed to the fact that these methods take into account the natural flow of groundwater. This elongation is greater in the case of W2 than in W1 due to higher values of groundwater velocity. As a result, the first method by ignoring the groundwater movement leads to the under-protection of the upstream regions and the over-protection of the downstream ones [12]. Moreover, from Table 2 it can be concluded that the first method results in protection zones of greater extent in comparison with the corresponding ones resulting from the other two methods. On the contrary, the third method results in protection zones with the smallest extent of all.

4.2. Economic analysis of protection zones

The results of the economic analysis are presented in Table 3. According to these findings, the CFR method usually results in significantly higher implementation costs as compared with the other two delineation methods, while the SVS method appears to be the lower cost method. Regarding Zone 1, the CFR method, on average (as shown in Fig. 6), results in: (1) 12.7% higher costs as compared with the SVS method and (2) 1.3% lower costs as compared with the MODPATH method (this is actually the only case where CFR was found less costly than some other method). The differences become more pronounced when considering the other two zones. Particularly, in Zone 2, the CFR method imposes 78.9% higher costs than the SVS method and 14.8% higher costs than the MODPATH method. Likewise, in Zone 3, the CFR method results in 95.9% higher costs than the SVS method and 66.7% higher costs than the MODPATH method. It is worth noting that the implementation of a CFR-based Zone 2 seems to be cost equivalent to the implementation of a SVS-based Zone 3. It is also interesting to note that even though the two wells generate significant different costs, the overall (economic) classification of the three methods remains the same.

4.3. Environmental analysis of protection zones

In Table 4 the nitrate concentrations in the selected wells at the beginning of the simulation period, as well as after 5, 10, and 15 years are shown. These values correspond to no protection status, that is, no restriction measures regarding the use of fertilizers were applied. It is obvious that, in all cases, nitrate concentrations in W1 are higher than the corresponding ones in W2. This is partly attributed to the fact that in the vicinity of W1 parcels mostly containing olive trees are located (Fig. 7). According to Table 1, olive trees require

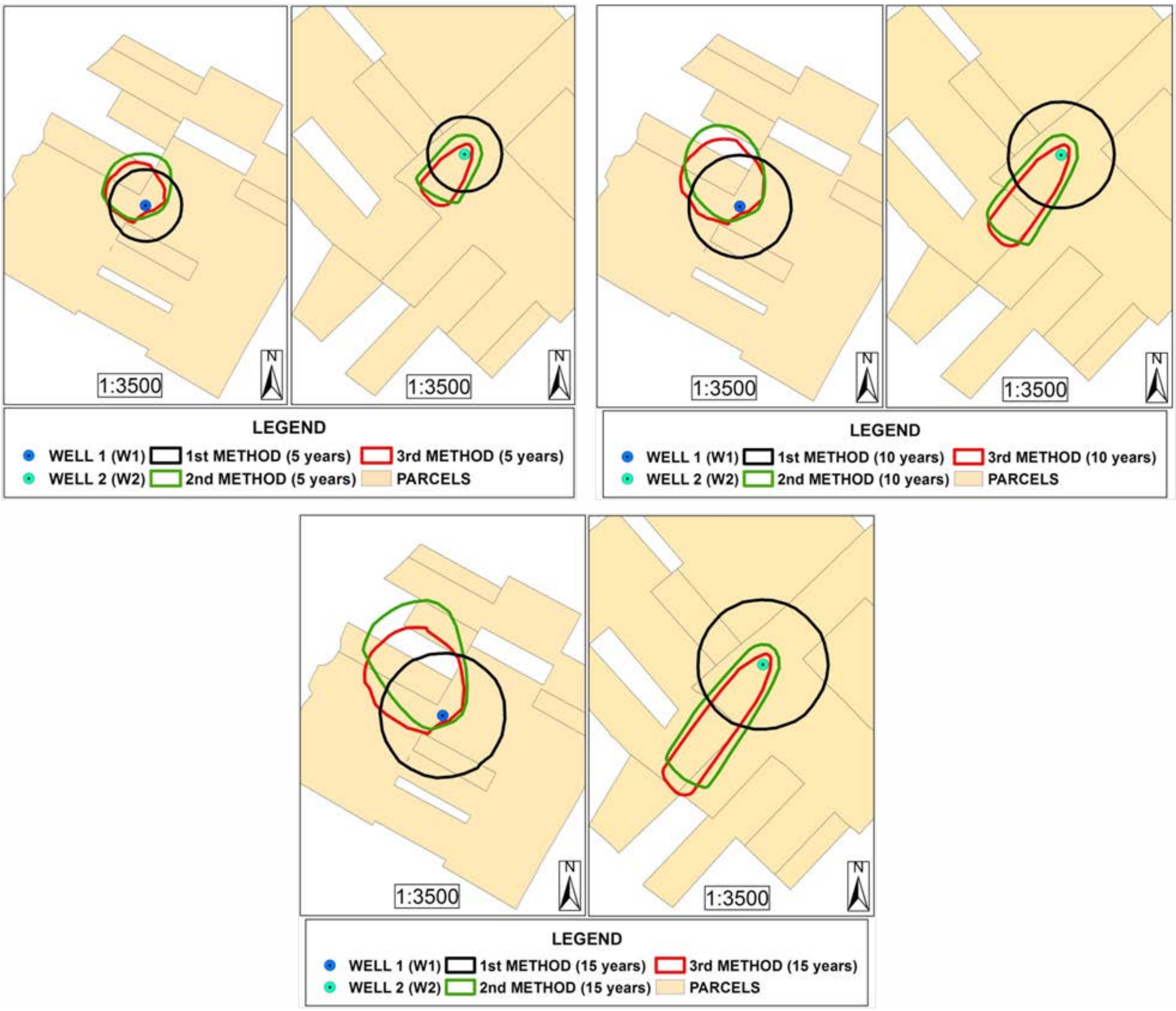


Fig. 5. All types of protection zones (5, 10, and 15 years) in the selected wells (W1 and W2) resulting from the application of the three alternative delineation methods.

Table 2
Extent (in m^2) of all types of protection zones (Zone 1 – 5 years, Zone 2 – 10 years, and Zone 3 – 15 years) for each delineation method

Well	CFR			SVS			MODPATH		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
W1	6,098	12,065	18,100	5,242	8,616	14,142	3,785	7,604	11,466
W2	6,573	13,037	19,651	4,104	7,678	10,785	2,754	5,368	8,067
Total	12,671	25,103	37,752	9,346	16,294	24,927	6,540	12,972	19,533

higher amount of nitrogen fertilizers, which results in higher values of nitrate load entering the aquifer. On the contrary, W2 is situated in a parcel where wheat is cultivated (Fig. 7) and the suggested amount of nitrogen is rather low.

In Table 5 nitrate concentrations in the selected wells for all types of protection zones and for each delineation method are presented. These values correspond to the protection status, that is, a set-aside scheme was applied in those parcels designated as part of the protection areas. According to these results and in comparison with the corresponding ones in Table 4, it can be concluded that the application of the set-aside program in the affected parcels leads to a reduction of nitrate concentrations in both wells for all types of protection zones and for each delineation method. This reduction is more substantial in the case of W1, since the restriction measures are applied in parcels where olive trees are located. Moreover, what is worth mentioning is that in the case of W1 the CFR method results in lower nitrate concentrations

Table 3
Annual and total implementation cost for all types of protection zones and for each delineation method based on the current cropping patterns

Well		CFR			SVS			MODPATH		
		Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
W1	Wheat (m^2)	7,593	7,593	7,593	5,097	8,198	8,198	5,097	5,097	8,198
	Olive trees (m^2)	16,793	24,206	27,713	17,319	17,319	17,319	12,299	21,812	21,812
	Annual cost (€/year)	5,435.78	7,806.45	8,927.99	5,582.50	5,609.20	5,609.20	3,977.11	7,019.36	7,046.06
	Total cost (€)	24,894.27	66,590.64	106,581.80	25,566.22	47,847.62	66,962.28	18,213.98	59,876.59	84,115.44
W2	Wheat (m^2)	19,070	19,070	24,551	12,639	18,112	18,112	12,639	18,112	18,112
	Olive trees (m^2)	2,552	9,521	21,556	0	7,559	7,559	7,559	7,559	7,559
	Cotton	0	0	0	0	0	0	0	0	6,430
	Apricot trees	5,004	5,004	5,004	0	0	0	0	0	0
	Annual cost (€/year)	980.32	3,209.01	7,104.99	108.82	652.00	2,573.31	2,526.19	2,573.31	2,573.31
	Total	4,489.59	27,373.49	84,818.94	498.37	5,561.69	30,720.04	11,569.21	21,950.88	30,720.04

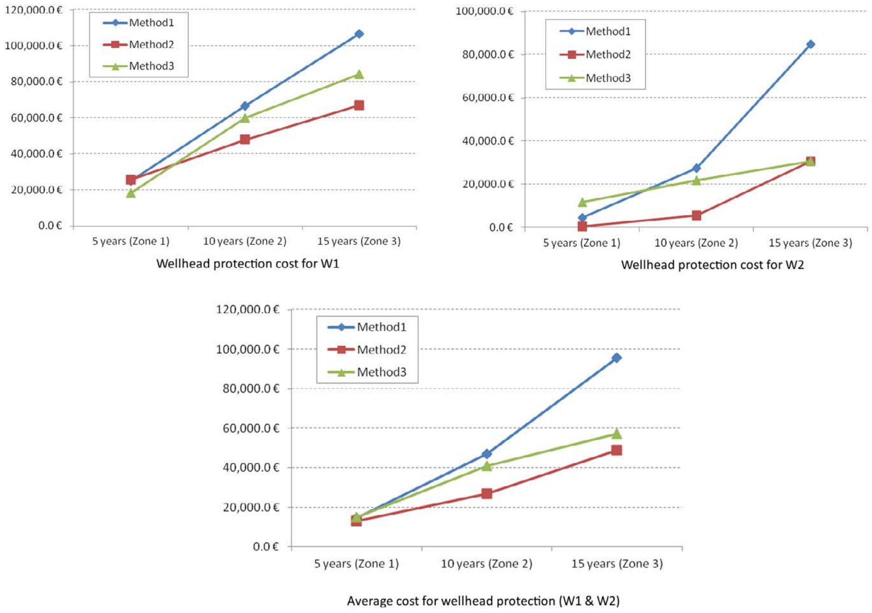


Fig. 6. Cost of wellhead protection under the three delineation methods.

Table 4
Nitrate concentrations (in mg/L) in the selected wells at the beginning of the simulation period (2014), as well as after 5, 10, and 15 years without the implementation of restriction measures

Well	0 years	5 years	10 years	15 years
W1	31.4	36.2	40.4	43.7
W2	25.2	26.6	27.9	28.8

than the other two methods for all types of protection zones, while in the case of W2 all methods provide almost similar results for all type of protection zones. These findings are also verified in Figs. 8 and 9, where the nitrate concentrations evolution over time before (no protection) and after the

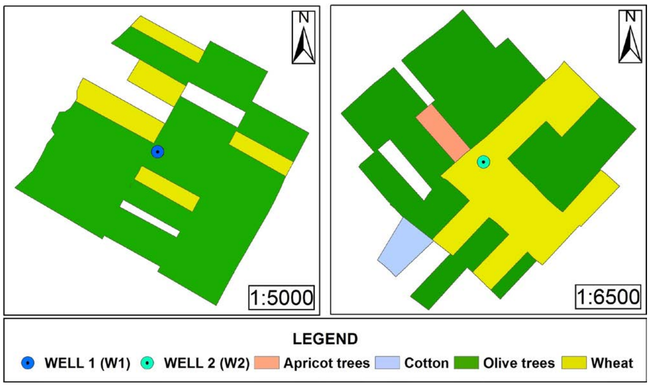


Fig. 7. Type of crops around the selected wells (Wells 1 and 2).

Table 5
Nitrate concentrations (in mg/L) in the selected wells for all types of protection zones (Zone 1 – 5 years, Zone 2 – 10 years, and Zone 3 – 15 years) and for each delineation method

Well	CFR			SVS			MODPATH		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
W1	31.4	31.7	31.1	32.1	33.4	35.0	32.9	31.8	32.4
W2	25.9	26.9	27.1	26.0	26.5	27.1	25.8	26.5	27.0

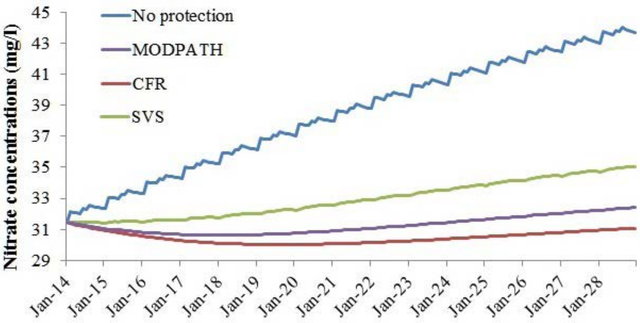


Fig. 8. Nitrate concentrations evolution over time before (no protection) and after the implementation of the set-aside policy for 15 years (third type of protection zones) in well W1.

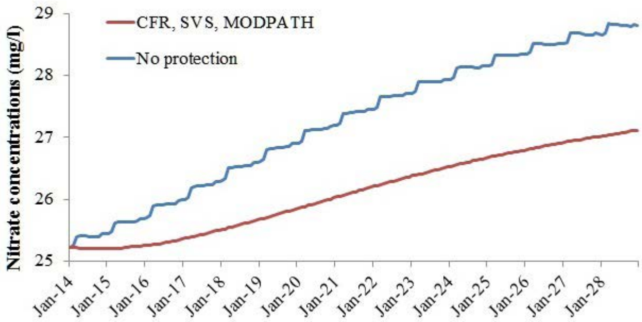


Fig. 9. Nitrate concentrations evolution over time before (no protection) and after the implementation of the set-aside policy for 15 years (third type of protection zones) in well W2.

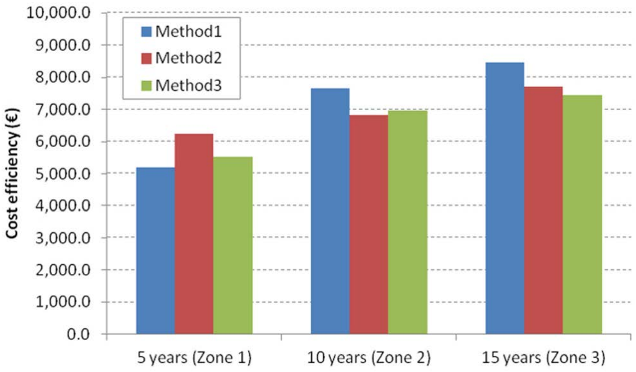


Fig. 10. Results of the economic-environmental indicator in well W1.

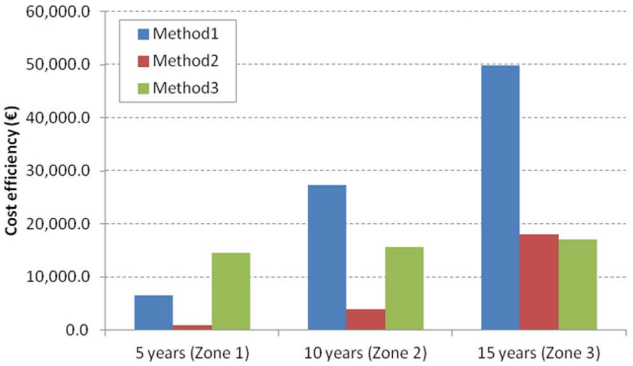


Fig. 11. Results of the economic-environmental indicator in well W2.

implementation of the set-aside programs for 15 years (third type of protection zones) in wells W1 and W2 are, respectively, depicted.

4.4. Economic-environmental indicator

As already mentioned, the final step of our analysis aims to combine the economic and environmental results into one decision criterion, that is, into one single evaluation indicator. This indicator was estimated for each protection zone, in each well (Figs. 10 and 11 present the results for wells W1 and W2, respectively) and can be used to evaluate the three different delineation methods. According to these results, the CFR (first method) is by far the less efficient one (i.e., the method with the higher cost for a given environmental benefit). Between the other two methods there is no clear-cut "winner," as the SVS (second method) seems to be more appropriate for the 10-year period, while the MODPATH (third method) is slightly better for the 15-year period. Finally, it should be noted that for the case of the 5-year period, all three methods seem to provide similar (average) values.

5. Conclusions

In this study, the comparison and evaluation of three alternative methods, that is, the CFR method, the SVS method, and numerical modeling (MODPATH), used for the delineation of WHPZs was attempted, considering also three types of protection zones based on different ToT values. To this task, a generic methodology was developed, according to which the comparison and evaluation of the aforementioned methods were based not only on technical features but also on environmental and economic criteria. In this context, a hydroeconomic model was developed and an economic-environmental indicator, expressed as the ratio of the total cost of implementing a protection zone to the associated environmental benefits, was introduced.

For the empirical analysis, two water-supply wells, both situated in agricultural land were selected, while the implementation of a set-aside program was preferred among other alternative restriction measures that can be applied in the case of agricultural nonpoint pollution sources. According to this policy, certain parcels, determined by the different protection zones, are taken out of production. This leads to the termination of the fertilizers' use, which, in turn, results in the termination of the nitrate load introduced to the groundwater system. The economic analysis is based on the assumption that the (social) cost of this policy is equal to the present value of farmers' foregone revenues (due to the set-aside schemes), while the environmental analysis considers the potential future decrease of nitrate concentrations in the groundwater abstracted from the protected wells.

According to our results and taking into consideration both economic and environmental aspects, it can be concluded that the CFR method is, in general, the less efficient one especially in the case of Type 2 (10 years) and Type 3 (15 years) protection zones. Even though, in the particular case of Well 1, its implementation results in lower nitrate concentrations, the costs in order to achieve these values are rather high in comparison with the other two methods. This is mainly attributed to the shape and the extent of the zones created by the CFR method, according to which, many parcels are affected and, therefore, selected to be taken out of production. With regard to the efficiency of the other two methods, that is, the SVS method and MODPATH method, the results are not entirely definite. In both wells, the SVS method appears to be more appropriate for the 10-year period, while the MODPATH method is slightly better for the 15-year period. Therefore, the SVS method is considered better for short (5 years) and intermediate (10 years) time periods, while the MODPATH method seems to be more suitable when a longer time period (15 years) is considered in the analysis.

In conclusion, this study provides useful insights regarding the comparison and evaluation of various methods applied for the delineation of WHPZs. Taking into consideration the implementation costs of the zones produced by various methods, as well as their environmental impact, the procedure followed in this study can be considered as a first step toward a complete and sound evaluation procedure, which will be able to provide reliable and realistic results.

Acknowledgment

An initial shorter version of the paper has been presented at the 6th International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE) and SECOTOX Conference, Thessaloniki, Greece, June 25–30, 2017.

References

[1] D. Paradis, R. Martel, G. Karanta, R. Lefebvre, Y. Michaud, R. Therrien, M. Nastev, Comparative study of methods for WHPA delineation, Ground Water, 45 (2007) 158–167.

[2] Y. Dong, H. Xu, G. Li, Wellhead protection area delineation using multiple methods: a case study in Beijing, Environ. Earth Sci., 70 (2013) 481–488.

[3] S. Sevastas, I. Siarkos, N. Theodossiou, I. Ifadis, Establishing wellhead protection areas and managing point and non-point pollution sources to support groundwater protection in the aquifer of Upper Anthemountas, Greece, Water Utility J., 16 (2017) 81–95.

[4] I. Siarkos, E. Terzanidou, S. Sevastas, D. Latinopoulos, Comparison and Economic Appraisal of Various Methods Used for the Delineation of Wellhead Protection Zones, In: Proceedings of the 6th International CEMEPE and SECOTOX Conference, Thessaloniki, Greece, June 25–30, 2017.

[5] J. Nel, Y. Xu, O. Batelaan, L. Brendonck, Benefit and implementation of groundwater protection zoning in South Africa, Water Resour. Manage., 23 (2009) 2895–2911.

[6] A.-G. Staboultzidis, Z. Dokou, G.P. Karatzas, Capture zone delineation and protection area mapping in the aquifer of Agia, Crete, Greece, Environ. Process., 4 (2017) 95–112.

[7] A.A. Fadlelmawla, M.A. Dawoud, An approach for delineating drinking water wellhead protection areas at the Nile Delta, Egypt, J. Environ. Manage., 79 (2006) 140–149.

[8] Y. Mogheir, G. Tarazi, Comparative identification of wellhead protection areas for municipal supply wells in Gaza, JWARP, 2 (2010) 105–114.

[9] I. Siarkos, D. Latinopoulos, M. Katirtzidou, Delineating cost-effective wellhead protection zones in a rural area in Greece, Water Environ. J., 28 (2014) 72–83.

[10] R.O. Strobl, P.D. Robillard, Comparison of several EPA-recommended and German well-head protection area delineation methods in agricultural settings, Water SA, 32 (2006) 507–517.

[11] H.A. Raymond, M. Bondoc, J. McGinnis, K. Metropulos, P. Heider, A. Reed, S. Saines, Using analytic element models to delineate drinking water source protection areas, Ground Water, 44 (2006) 16–23.

[12] US EPA, Guidelines for Delineation of Wellhead Protection Areas, Office of Water, Office of Groundwater Protection, U.S. Environmental Protection Agency, Washington, 1987.

[13] Y. Rajkumar, Y. Xu, Protection of borehole water quality in sub-Saharan Africa using minimum safe distances and zonal protection, Water Resour. Manage., 25 (2011) 3413–3425.

[14] I. Siarkos, P. Latinopoulos, Delineation of wellhead protection zones for the control of point pollution sources in the aquifer of N. Moudania, Greece, Eur. Water, 40 (2012) 3–17.

[15] J.L. Exposito, M.V. Esteller, J. Paredes, C. Rico, R. Franco, Groundwater protection using vulnerability maps and wellhead protection area (WHPA): a case study in Mexico, Water Resour. Manage., 24 (2010) 4219–4236.

[16] R.C. De Loe, S.E. Di Giantomasso, R.D. Kreutzwiser, Local capacity for groundwater protection in Ontario, Environ. Manage., 29 (2002) 217–233.

[17] V.R. Hasfurther, D. Foster, T. Edgar, C. Torrence, Wellhead Protection: Information and Guidelines for Wyoming Municipalities, Final Report for Wyoming Department of Environmental Quality, University of Wyoming, USA, 1992.

[18] M. Ferrante, E. Mazzetti, A. Fiori, M. Burini, B. Fioriti, A. Mazzoni, G. Schiro, G. Vacca, B. Brunone, S. Meniconi, C. Capponi, Delineation of wellhead protection areas in the Umbria region. 2. Validation of the proposed procedure, Procedia Environ. Sci., 25 (2015) 96–103.

[19] M. Mojarrad, G.R. Rakhshandehrou, R. Monadi, M.G. Musellu, Investigating Wellhead Protection Area (WHPA) Assessment Methods, Case Study: Beyza-Zarghan Drinking Wells, In: Proceedings of the 2nd International Conference on Water Resources and Wetlands, Tulcea, Romania, September 11–13, 2014.

[20] C. Miller, P. Chudek, S. Babcock, A comparison of wellhead protection area delineation methods for public drinking water systems in Whatcom County, Washington, J. Environ. Health, 66 (2003) 17–26.

[21] S. Pena-Haro, C. Llopis-Albert, M. Pulido-Velazquez, D. Pulido-Velazquez, Fertilizer standards for controlling groundwater nitrate pollution from agriculture: El Salobral-Los Llanos case study, Spain, J. Hydrol., 392 (2010) 174–187.

[22] A. Bonton, C. Bouchard, A. Rouleau, M.J. Rodriguez, R. Therrien, Calibration and validation of an integrated nitrate transport model within a well capture zone, J. Contam. Hydrol., 128 (2012) 1–18.

[23] M.N. Almasri, J.J. Kaluarachchi, Modeling nitrate contamination of groundwater in agricultural watersheds, J. Hydrol., 343 (2007) 211–229.

[24] K. Wick, C. Heumesser, E. Schmid, Groundwater nitrate contamination: factors and indicators, J. Environ. Manage., 111 (2012) 178–186.

[25] M. Matiaki, I. Siarkos, K.L. Katsifarakis, Numerical modeling of groundwater flow to delineate spring protection zones. The case of Krokos aquifer, Greece, Desal. Wat. Treat., 57 (2016) 11572–11581.

[26] C. Sharma, A. Mahajan, U.K. Garg, Fluoride and nitrate in groundwater of south-western Punjab, India – occurrence, distribution and statistical analysis, Desal. Wat. Treat., 57 (2016) 3928–3939.

[27] A.H. Wolfe, J.A. Patz, Reactive nitrogen and human health: acute and long-term implications, Ambio, 31 (2002) 120–125.

[28] M.N. Almasri, Nitrate contamination of groundwater: a conceptual management framework, Environ. Impact Assess. Rev., 27 (2007) 220–242.

[29] I. Siarkos, P. Latinopoulos, Modeling seawater intrusion in overexploited aquifers in the absence of sufficient data: application to the aquifer of Nea Moudania, northern Greece, Hydrogeol. J., 24 (2016) 2123–2141.

[30] P. Latinopoulos, Development of Water Resources Management Plan for Water Supply and Irrigation (In Greek), Research Project, Final Report Prepared for: Municipality of Moudania, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece, 2003.

[31] A. Xefteris, P. Anastasiadis, P. Latinopoulos, Groundwater chemical characteristics in Kalamaria plain, Halkidiki peninsula, Greece, Fresenius Environ. Bull., 13 (2004) 1158–1167.

[32] I. Siarkos, Developing a Methodological Framework Using Mathematical Simulation Models in order to Investigate the Operation of Coastal Aquifer Systems: Application in the Aquifer of Nea Moudania (in Greek), PhD Thesis, Aristotle University of Thessaloniki, Greece, 2015.

[33] H. Haitjema, J. Wittman, V. Kelson, N. Bauch, WHAEM: Program Documentation for the Wellhead Analytic Element Model, EPA/600/R-94/210, Office of Research and Development, US EPA, Washington, DC, 1994.

[34] S.R. Kraemer, H.M. Haitjema, V.A. Kelson, Working with WhAEM: Source Water Assessment for a Glacial Outwash Wellfield, Vincennes, Indiana, EPA/600/R-00/022, Office of Research and Development, US EPA, Washington, DC, 2007.

[35] D.W. Pollock, User's Guide for MODPATH, Version 3: A Particle Tracking Post-Processing Package for MODFLOW, the U.S. Geological Survey Finite-Difference Ground-Water Flow Model, Open-file Report 94–494, U.S. Geological Survey, Reston, VA, 1994.

[36] M.G. McDonald, A.W. Harbaugh, A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Techniques of Water Resources Investigations, Book 6, USGS, Reston, VA, 1988.

[37] C. Zheng, P.P. Wang, MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems – Documentation and User's Guide, Contract Report SERD-99-1, US Army Corps of Engineers, Washington, DC, 1999.

[38] K. Voudouris, G. Stamatis, Determination of the protection perimeter of water supply projects in the mineral water aquifer of Loutraki basin based on hydrogeological criteria, Miner. Wealth, 16 (2000) 13–36.

[39] K. Badv, M. Deriszadeh, Wellhead protection area delineation using the analytic element method, Water Air Soil Pollut., 161 (2004) 39–54.

[40] A. Ceric, H. Haitjema, On using simple time-of-travel capture zone delineation methods, Ground Water, 43 (2005) 408–412.

[41] T. Rayne, K. Bradbury, M. Muldoon, Delineation of capture zones for municipal wells in fractured dolomite, Sturgeon Bay, Wisconsin, USA, Hydrogeol. J., 9 (2001) 432–450.

[42] A. Tsitouras, Conducting Pilot Land Parcel Management Implemented under IACS 2007 in the EAS Chalkidiki Area of Responsibility, Institute of Soil Mapping and Classification, Hellenic Agricultural Organization (HAO) "DIMITER", Larisa, 2008.

[43] A. Tesoriero, H. Liecscher, S. Cox, Mechanism and rate of denitrification in an agricultural watershed: electron and mass balance along ground water flow paths, Water Resour. Res., 36 (2000) 1545–1559.

[44] C.A.J. Appelo, D. Postma, Geochemistry, Groundwater and Pollution, 2nd ed., Taylor & Francis Group, London, 2005.

[45] M.O. Rivett, S.R. Buss, P. Morgan, J.W.N. Smith, C.D. Bemment, Nitrate attenuation in groundwater: a review of biogeochemical controlling processes, Water Res. 42 (2008) 4215–4232.

[46] T.M. Addiscott, Nitrate, Agriculture and the Environment, CABI Publishing, Cambridge, 2005.

[47] M. Shamrukh, M.Y. Corapcioglu, F.A.A. Hassona, Modeling the effect of chemical fertilizers on groundwater quality in the Nile Valley aquifer, Ground Water, 39 (2001) 59–67.

[48] Ministry of Rural Development and Food, Available at: http://www.minagric.gr/index.php/en/.