METHODS TO DEFINE THE AREAL DISTRIBUTION
OF THE SALT INTRUSION: EXAMPLES FROM SOUTH GREECE

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Abstract

The purpose of this work is to describe methods for defining the areal salinity distribution by seawater intrusion. Groundwater samples were collected and analyzed from two representative aquifers of Greece: the aquifer of the Quaternary deposits in Glafkos basin (NW Peloponnesus) and the carbonate aquifer of Chersonisos (Crete island). Both areas are characterized by ongoing urbanization, tourism development and intensive agriculture that have considerable environmental impact on the form of groundwater overexploitation. Seawater is the principal pollutant, both in the alluvial and in the karst aquifers. In order to define the extent of seawater intrusion zone, several parameters were used: T.D.S., Cl− concentration, Br− concentration, and analysis of the salinity factor and hydrochemical sections. Experimental and theoretical semivariograms of the selected parameters were computed. Maps showing their geographical distribution were produced, using the ordinary kriging method. From these maps, the seawater intrusion zone is defined. Seawater intrusion is extended from the coastline to the recharge area at a distance greater than 4.5 km in the karst aquifer, while in the alluvial aquifer is extended at a distance greater than 1.1 km.

Keywords: Coastal aquifers, seawater intrusion, areal distribution, hydrogeochemistry, geostatistics, South Greece.

Introduction

The problem of seawater intrusion has been widely recognized in coastal aquifers, which constitute the main source of drinking water and agricultural irrigation in many countries. Seawater intrusion may be considered as a type of environmental pollution due to human activities (overexploitation of coastal aquifers) and/or to geological factors (tectonic movements, sea level rise, etc…).
A large proportion of the Mediterranean coastline is reported to be affected by seawater intrusion (Custodio, 1987, Bosch & Custodio, 1993, El-Baruni, 1995, Tulipano, 2003). In the South of Greece there are several coastal areas where water is a more precious resource than in other regions (Stamatis and Voudouris, 2003). Water demand in these areas has increased during the last decades due to rapid urbanization, accelerated tourism development, agricultural activities and a continuous increase of the population since the 1970s.

Water needs are mainly covered by groundwater abstracted from aquifers via numerous wells and boreholes. As a result, a negative water balance is established in the coastal aquifer systems, triggering seawater intrusion, which has negative consequences on the socioeconomic development of these areas. Excess pumping from the coastal aquifers causes interface between sea- and fresh-water to advance landward until a new equilibrium is reached (Ergil, 2000). A decline in groundwater levels has been observed since the 1980s, due to overexploitation of agricultural and municipal water intakes in coastal areas of Greece, combined with prolonged drought periods (Lambrakis et al., 1997).

The aim of this study is to describe the extent of salinization by seawater intrusion. Therefore, field research was undertaken and water samples were collected from two representative aquifers of Greece: the aquifer of the Quaternary deposits in Glafkos basin (NW Peloponnesus), and the carbonate aquifer of Chersonisos in Crete island. Firstly, the hydrochemistry of the aquifers was characterized. In both aquifers water quality has been deteriorated as a consequence of seawater intrusion.

**Geological-hidrogeological setting**

The Glafkos plain aquifer (25 km²) is located in the Southwestern part of Greece (Peloponnesus) and is formed by alluvial deposits (Figure 1). Unconsolidated alluvial sediments with silty and clayey intercalations are dispersed throughout the Glafkos plain, especially in the coastal area. Based on stratigraphic boreholes logs, the aquifer thickness exceeds 200 m, increasing from the northern and southern boundaries towards the central part (see the geological section in Figure 1). In the semi-mountainous and mountainous parts of the basin, limestones of Mesozoic and Neogene sediments crop out (Lambrakis et al., 1997).

The aquifers of the alternating coarse-grained alluvial beds may be regarded as one unified aquifer system. The presence of silts and clays implies the occurrence of artesian conditions in the coastal part of the aquifer. Groundwater recharge of the aquifer takes place mainly by seepage through the riverbed and direct infiltration during rainfall. The mean annual precipitation is 695 mm. The main urban center of the area is the city of Patras, with 163,500 inhabitants. In the coastal part of this aquifer, seawater intrusion is recorded due to over-pumping combined with prolonged dry periods.

Based on drilling data, the depth of the boreholes reaches from 40 to 140 m below sea level. Estimates for the yield of the boreholes range from about 60 to 180 m³/h. Reported transmissivity estimates range from 50 to 2500 m²/d from pumping tests (Voudouris, 1995). The beginning of the decline of groundwater level coincides with the increase of groundwater extraction by the Patras municipality (1984-1986) and with the beginning of the drought period (1989-1992). In 1994, the total annual amount of groundwater extracted for domestic and industrial purposes decreased due to quality deterioration and decline in industrialization, respectively (Mandilaras et al., 1999).
The carbonate aquifer in the northern central part of Crete island (municipality of Chersonisos) is formed by limestones of the Tripolis zone (Figure 2). This aquifer lies between a distance of 0.7 km from the coast and the mountainous area, and it is in direct hydraulic continuity with seawater in the western part of the border area. The Tripolis series consist of faulted and karstified Upper Triassic-Upper Eocene age thick-bedded limestones, dolomites and calcareous dolomites, showing high permeability due to their well developed wide jointing and karstification (Alexopoulos, 2001). The Phyllite-Quartzite series form the impervious basic layer. The exploitation of the carbonate aquifer started in the last decades by deep boreholes; the depth ranging from 130 to 400 m. The yield of the boreholes ranges from 15 to 90 m³/h, as deduced from pumping tests (Voudouris, 2003). The karst aquifer of Tripolis zone is in direct hydraulic communication with marly limestones, which are hosted in Neogene deposits. These limestones are characterized by enhanced secondary porosity and have major hydrogeological significance. Platy limestones (Plattenkalk) crop out in the southeastern part of Chersonisos area, showing important productivity at depths exceeding 350 m b.g.s.

The semi-arid climate prevailing in Crete island is characterized by low precipitation (the mean annual rainfall in the coastal area is 450 mm) and high evapotranspiration. The prolonged dry periods have led to excessive pumping in the carbonate aquifer, resulting in the lowering of the groundwater level and seawater intrusion (Lambrakis, 1998).

Figure 1. Geological map of the Glafkos basin (alluvial aquifer).
Sixty one (61) groundwater samples were collected from the Glafkos plain aquifer (May 2001) and twelve (12) from the karst aquifer of Chersonisos area (April 2002). The collection of water samples from separate depths was unfeasible. The samples were collected from boreholes that were in use and were taken at the borehole pump outflow. In-situ analyses of temperature, pH and electrical conductivity (EC) were performed, as well as laboratory analysis of the parameters $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$, $HCO_3^-$, $Cl^-$, $SO_4^{2-}$, $NO_3^-$ and $Br^-$. Based on ion determinations, total dissolved solids (TDS), Revelle index ($R$) and ionic strength ($I$)

**Hydrochemistry**

**Water sampling-chemical characteristics-geostatistics**

Sixty one (61) groundwater samples were collected from the Glafkos plain aquifer (May 2001) and twelve (12) from the karst aquifer of Chersonisos area (April 2002). The collection of water samples from separate depths was unfeasible. The samples were collected from boreholes that were in use and were taken at the borehole pump outflow. In-situ analyses of temperature, pH and electrical conductivity (EC) were performed, as well as laboratory analysis of the parameters $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$, $HCO_3^-$, $Cl^-$, $SO_4^{2-}$, $NO_3^-$ and $Br^-$. Based on ion determinations, total dissolved solids (TDS), Revelle index ($R$) and ionic strength ($I$)
were calculated. All chemical analyses were carried out in the Laboratory of Hydrogeology at the University of Patras. The statistical characteristics (minimum, maximum, mean values and standard deviation) for each chemical parameter are quoted in tables 1 and 2.

The Revelle index (Revelle, 1941) is given by \( R = \frac{rCl^-}{(rHCO_3^- + rCO_3^{2-})} \), where \( r \) is expressed in meq/L. Freshwater has Revelle coefficient of lower than 1, while seawater has a value greater than 150.

Ionic strength is computed by using the formula \( I = 0.5 \sum M_i Z_i^2 \), where \( M_i \) is the molar concentration of the \( i \)-th ion (mol/L) with charge \( Z_i \). Typical freshwater has ionic strength of less than 0.005 (Domenico and Schwartz, 1990). Based on chemical analyses of seawater from Patraikos Gulf, the ionic strength values range from 0.65 to 0.78.

The box plot is a visually effective way to summarize the distribution of chemical data. Figure 3 shows the box plot of electrical conductivity for each aquifer. The upper and lower quartiles of the data define the top and the bottom of a rectangle (box). The line inside the box represents the median value and the size of the box the spread about the central value. As it can be seen from this figure, groundwater in both alluvial and karst aquifers has high electrical conductivity value; the highest values are found in the coastal zone. Furthermore, the majority of the samples presents Revelle coefficient values greater than one and ionic strength values greater than 0.005, indicating seawater intrusion.

![Box plot of electrical conductivity (µS/cm) data. a) Alluvial aquifer. b) Karst aquifer.](image)

Given that both areas are dominated by urbanization, as well as rural land uses, high nitrate concentrations can be attributed to: 1) the use of fertilizers, and 2) infiltration of municipal wastewater into groundwater from septic tanks.

In both aquifers strong correlations are observed between some parameters directly related to salinity (Cl\(^-\), Na\(^+\), K\(^+\), SO\(_4^{2-}\), Mg\(^{2+}\), TDS and EC), i.e. between Na\(^+\) and Cl\(^-\) (\( r = 0.99 \)), EC and Cl\(^-\) (\( r > 0.95 \)), Na\(^+\) and K\(^+\) (\( r = 0.71 \) and 0.96). Correlation between Ca\(^{2+}\) and Mg\(^{2+}\) is not significant (\( r = 0.46 \) and 0.53, respectively). The Mg\(^{2+}\)/Ca\(^{2+}\) ratio (in meq/L) increases with the proportion of seawater in the mixture, since the ratio of seawater is close to 5, whilst in freshwater it tends to be lower than 1. The correlation coefficient between SO\(_4^{2-}\) and Cl\(^-\) is 0.86 for the alluvial aquifer and 0.73 for the karst aquifer. The SO\(_4^{2-}\)/Cl\(^-\) ratio decreases as the seawater proportion in the mixture increases (Leboeuf et al., 2003).
**Glafkos alluvial aquifer**

According to Table 1, the alluvial aquifer system of the Glafkos plain contains fresh to brackish water. The electrical conductivity (EC) values range from 358 to 4960 µS/cm (Figure 3a). High values of electrical conductivity along the coastline are attributed to seawater intrusion, as a result of the intensified exploitation. Conductivity values between 2000 and 5000 µS/cm correspond to mixtures of freshwater and seawater. The fluctuation of pH between 6.83 and 8.8 shows that groundwater is slightly acid to alkaline. Furthermore (Table 1) groundwater contains Ca²⁺ (33-190 mg/L), Mg²⁺ (4-65 mg/L), Na⁺ (2-882 mg/L), HCO₃⁻ (171-305 mg/L), SO₄²⁻ (0.2-216 mg/L) and NO₃⁻ (3-50 mg/L). The Cl⁻ concentration ranges from 3.9 mg/L to 1465 mg/L; the mean value is 74.3 mg/L (Figure 4a).

| Table 1. Statistical characteristics (mg/L) for chemical parameters (alluvial aquifer). |
|---------------------------------------------------------------|----------------|----------------|----------------|----------------|
| pH | 6.83 | 8.80 | 7.5 | 0.3 |
| EC (µS/cm) | 358 | 4960 | 821 | 718 |
| Na⁺ | 1.9 | 882.3 | 54.1 | 129.8 |
| K⁺ | 0.01 | 14.0 | 2.4 | 2.7 |
| Mg²⁺ | 3.7 | 65.2 | 13.2 | 8.0 |
| Ca²⁺ | 33.4 | 190.3 | 67.7 | 26.1 |
| Cl⁻ | 3.9 | 1465 | 74.3 | 229 |
| Br⁻ | 0.047 | 2.91 | 0.28 | 0.49 |
| SO₄²⁻ | 0.2 | 216 | 37.9 | 27.1 |
| NO₃⁻ | 3.1 | 50.2 | 20.7 | 10.3 |
| HCO₃⁻ | 171 | 305 | 229 | 29 |
| TDS | 270.5 | 3070 | 512 | 436 |
| Revelle index | 0.025 | 9.2 | 0.56 | 1.65 |
| Ionic strength | 0.0008 | 0.007 | 0.0025 | 0.00 |

**Figure 4.** Histogram of Cl⁻ concentration (mg/L). a) Alluvial aquifer. b) Karst aquifer.
Groundwaters are of various hydrochemical types as illustrated by the Durov diagram in Figure 5: Ca-Mg-HCO\textsubscript{3} (freshwater of recent infiltration), Na-HCO\textsubscript{3} (this type indicates ion-exchange phenomena and characterizes a transition zone), and Na-Cl (typical brackish water in which the ions Na\textsuperscript{+} and Cl\textsuperscript{-} predominate). According to Lambrakis et al. (1997), the piezometric lines of the alluvial aquifer (up to 3 km from the coast) were negative and the fresh- to seawater interface moved landwards to a distance of 2.5 km from the shoreline at the end of the drought period 1989-1992.

**Chersonisos carbonate aquifer**

As it can be seen from Table 2, major ion concentrations in this aquifer are: Ca\textsuperscript{2+} (69-154 mg/L), Mg\textsuperscript{2+} (12-96 mg/L), Na\textsuperscript{+} (11.5-485 mg/L), HCO\textsubscript{3}\textsuperscript{-} (218-435 mg/L) and SO\textsubscript{4}\textsuperscript{2-} (20-256 mg/L). The high K\textsuperscript{+} (0.1-26 mg/L) and NO\textsubscript{3}\textsuperscript{-} (7-36 mg/L) concentrations can be attributed to human activities. The electrical conductivity values range from 481 to 3440 µS/cm (Figure 3b), and its distribution shows a gradual increase from the mountainous area towards the coastline. The Cl\textsuperscript{-} concentration ranges from 19 mg/L to 785 mg/L; the mean value is 371 mg/L (Figure 4b).

<table>
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<tr>
<td>Na\textsuperscript{+}</td>
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<tr>
<td>NO\textsubscript{3}\textsuperscript{-}</td>
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Groundwater of the karst aquifer in Chersonisos area is classified into the following types, as illustrated by the Durov diagram (Figure 6): Ca-HCO\textsubscript{3} fresh water from mountainous area, suitable for both drinking and agricultural purposes, which indicates the limestone origin of the aquifer; and Na-Cl brackish water suitable for agricultural purposes.
In the mountainous area, which is in the southern part of the study area, groundwater is fresh without traces of human contamination. Near the shoreline, groundwater is brackish, affected by seawater intrusion.

**Geostatistics**

Variograms provide a measure of quantifying the observed relationship between the values of the hydrochemical parameters of groundwater samples and the parameters of the nearby samples. Variogram analysis consists of the experimental variogram calculated from the data and the variogram model fitted to the data.

The semivariogram $\gamma(h)$ is defined as (Lin, 2002):

$$\gamma(h) = \frac{1}{2} \text{Var}[Z(x) - Z(x+h)]$$

where $h$ denotes the lag distance which separates pairs of points, $\text{Var}$ represents the variance of the argument, $Z(x)$ is the observed value of the regionalized parameter at location $x$, and $Z(x+h)$ represents the value at location $x+h$.

The best-fit semivariograms of TDS, Cl$^-$, Br$^-$ and salinity factor (alluvial aquifer) and TDS, Cl$^-$ (karst aquifer) are displayed in figures 7 and 8. The theoretical model chosen has an exponential or spherical type; the directional tolerance is 90 degrees. Tables 3 and 4 show the values of specific parameters used to calculate the experiments semivariograms in each aquifer. The nugget effect is small for all the parameters.

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<td>2500</td>
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</table>

Contour maps were constructed using the kriging method, which is a special geostatistical method of making estimates of spatially distributed values from point values. Based on the semivariogram used,
optimal weights are assigned to known values in order to calculate unknown ones (Ceron et al., 2000). In the present study, the Surfer program is used for drawing the areal distribution of the groundwater TDS, Cl\(^-\), Br\(^-\) and salinity factor scores contours, applying the kriging interpolation technique.

**Representation of seawater intrusion results**

The areal distribution of seawater intrusion is determined by using several methods, as follows:

- The contour map of the Cl\(^-\) concentration (mg/L)

A considerable increase of Cl\(^-\) concentration provides a good indication of seawater encroachment. The distribution of chloride shows a general increase in the concentration, while the hydraulic gradient decreases towards the coastline. The Cl\(^-\) concentration of 50 mg/L in groundwater is used as an index for seawater intrusion, considering that the Cl\(^-\) concentration in rain water is 1.7 mg/L and the concentration in surface water (Glafkos river) is 4.1 mg/L.

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**Figure 7.** Experimental and theoretical semivariograms (alluvial aquifer).
The initial slope of the theoretical semivariogram (spherical) for the Cl$^-$ concentration in the alluvial aquifer (Figure 7) is steep, indicating that the data set changes more rapidly because of the high values of the Cl$^-$ concentration, which are gathered in a small part of the coastal area. The semivariogram become stationary for lag about 800 m. In the alluvial aquifer, seawater intrusion extends in a smaller area than in the karst aquifer. From the sample semivariogram for Cl$^-$ concentration in the karst aquifer of Chersonisos area (Figure 8), it appears that the theoretical model (exponential) does not fit very well to the experimental model. This indicates that the density of point samples is not adequate. In both aquifers, a geometric anisotropy is recorded in a direction parallel to the coastline.

Figures 9 and 10 show the Cl$^-$ concentration contours in both aquifers. It is clear that groundwater salinity is increasing as we move from the recharge area to the drainage area, towards the Glafkos alluvial plain. Along the flow path from the coastline to the recharge area (with a distance of about 1100 m), the Cl$^-$ concentration decreases from 1465 to 50 mg/L. The location of the 50 mg/L isoline refers to the extent of the seawater/freshwater interface. The spatial distribution of Cl$^-$ in the alluvial aquifer (Figure 9) shows two main local trends: 1) a steep gradient of high values in the coastal area, and 2) a zone of low concentration values of Cl$^-$ (<50 mg/L) in the eastern part of the area. The spatial distribution of Cl$^-$ in the karst aquifer (Figure 10) shows that the low concentrations are grouped near the mountainous area and the high concentrations are near the shoreline.

- The contour map of groundwater TDS (mg/L)
A measure of salinity is given by the Total Dissolved Solid (TDS) content. The location of the contour of TDS=1000 mg/L marks the area under the influence of seawater intrusion. With respect to TDS, the semivariograms (figures 7 and 8) follow a similar pattern to semivariograms for Cl$^-$, and reach a maximum at 1500 m in the alluvial aquifer and at 3500 m in the karst aquifer.

The spatial distribution of TDS in both alluvial and karst aquifer shows very well the differentiation of groundwater quality between the coast and the freshwater recharge area. Salinity contents (as TDS) reach its maximum value of 3070 mg/L (alluvial aquifer) and 1990 mg/L (karst aquifer) in the coastal part of the
Figure 9. Distribution of Cl\textsuperscript{-} concentration (mg/L) in the alluvial aquifer.

Figure 10. Distribution of Cl\textsuperscript{-} concentration (mg/L) in the karst aquifer.
aquifers. It is remarkable that the 1000 TDS mg/L isoline advances about 800 m and 4 km from the sea in the alluvial and in the karst aquifer, respectively. In summertime the isoline advances more than in wet period, for the same year. The TDS isolines are conic under a point where large quantities of groundwater are extracted (Calvache and Bosch, 1991). The seawater intrusion has been favoured by some preferential paths, depending upon the hydrogeological conditions of each area (Voudouris, 2003).

- The contour map of the Br⁻ concentration (mg/L)

The presence of Br⁻ in groundwater of coastal areas is generally attributed to seawater intrusion processes. Typical concentration of Br⁻ in groundwater is 0.01 mg/L. In seawater, the average concentration of this ion is 65 mg/L (Morell et al., 1986).

The Br⁻ concentration in groundwater from the alluvial aquifer was determined by ion electrode measurements and ion chromatography with similar results. The Br⁻ concentration ranges from 0.047 to 2.91 mg/L, depending on the degree of invasion of seawater. There is a good linear relationship between Br⁻ and Cl⁻ ($r^2=0.92$) in the alluvial aquifer, due to the common origin of both ions from seawater. The spatial distribution of Br⁻ concentration shows that the higher values are recorded near to the coastline and close to that which determines the Cl⁻ concentration (Figure 11).

![Figure 11. Distribution of Br⁻ concentration (mg/L) in the alluvial aquifer.](image)

The $r_{Cl}/r_{Br}$ ratio ($r$ = meq/L) in groundwater ranges from 330 (freshwater recharge area) to 756 (coastal part of the aquifer affected by seawater intrusion). Surface water from Glafkos river has $r_{Cl}/r_{Br} = 295$ and seawater from Patraikos Gulf has $r_{Cl}/r_{Br} = 608$. The occurrence of Cl/Br ratios in groundwater from the coastal area, that are similar to the seawater from the Gulf area, indicates that seawater is the main source of chloride. The $r_{Cl}/r_{Br}$ ratio determined at three sample sites in Chesapeake Bay (USA) ranged from 490
to 601 (Andreasen and Fleck, 1997). According to Alcalá and Custodio (2004), in waters whose salinity is related with the presence of marine water the rCl⁻/rBr⁻ ratio is similar to that of seawater (655±4).

- Hydrochemical section from the sea to the freshwater region.

The variation of major ions concentration across the studied area is examined, indicating the extent of seawater intrusion. Hydrochemical sections from the sea to the freshwater recharge area for both aquifers are presented in figures 12 and 13. In the recharge area, it can be seen that the prevailing ions are Ca²⁺ and HCO₃⁻. Moving seawards, Na⁺, K⁺ and Cl⁻ are the prevailing ions. As it is expected, electrical conductivity follows a similar pattern; hence it is low in freshwater recharge area and progressively increases towards the coastline. The Mg²⁺ concentration in seawater is high. Where seawater mix with freshwater in the process of landward advancing the concentration of Mg²⁺ decreases rapidly (Xue et al., 1993).

**Figure 12.** Hydrochemical section from the sea to the recharge area in the alluvial aquifer (direction AB as seen in Figure 9).

**Figure 13.** Hydrochemical section from the sea to the recharge area in the karst aquifer (direction CD as seen in Figure 10).
Multivariate analysis

The statistical technique of factor analysis has been applied in order to interpret the hydrochemical data. R-mode factor analysis offers a comparison of the relations among the parameters in terms of the samples (Voudouris et al., 1997). Thus, the large data set is reduced to a small number of coherent groups of parameters (factors) and is easier to measure the influence of the whole group on particular samples (factor scores). The hydrogeological interpretation of the factors gives an insight into the main process, which may control the distribution of hydrochemical parameters (Voudouris et al., 2000).

The R-mode factor analysis was applied to the data set of chemical analyses. Seawater intrusion processes which take place in the aforementioned aquifers were identified and represented by the salinity factor. High scores of this factor can be attributed to seawater intrusion. In both, the alluvial and the karst aquifers, the first factor accounts for 56.7% and 57.1% of the total variance, respectively. This factor is interpreted as the salinity factor because of exhibited high loading (>0.90) on EC, Na⁺, Mg²⁺, K⁺, Cl⁻ and SO₄²⁻ (Voudouris at al., 2000). A map (Figure 14) was constructed showing the geographical distribution of the factor scores. As it is deduced from this map, the coastal area of the alluvial aquifer is characterized by high values (>+1). This map of the scores distribution for the salinity factor determines zones of high salinity, which are attributed to seawater intrusion.

From the above mentioned methods it is clear that in the alluvial aquifer of Glaφkos basin, along the flow path from the coastline to upstream, with a distance between 550 and 1100 m, the Cl⁻ concentration decreases from 1465 to 100 and 50 mg/L, respectively. In the karst aquifer, the Cl⁻ concentration decreases from 785 to 50 mg/L for a distance of 4.5 km, approximately.
Conclusions

A study was carried out in South Greece (Peloponnesus and Crete) to determine the hydrochemical parameters of two representative aquifers (alluvial and karst) and to define the areal distribution of seawater intrusion. Both areas are characterized by ongoing urbanization, tourism development and intensive agriculture.

The study of chemical analyses has shown that seawater contamination is a feature affecting both aquifers. Groundwaters are of various hydrochemical types, as illustrated by the Durov diagram: Ca-HCO$_3$ water type in the recharge area, Na-HCO$_3$ type in the transition zone, as well Na-Cl type near the coast in both areas.

Experimental and theoretical semivariograms of the selected parameters (Cl$^-$ concentration, TDS and Br$^-$ concentration) were computed. Maps showing their geographical distribution are illustrated using the ordinary kriging technique. It is shown that mineralization of groundwater generally increases from the recharge area to the coastline, in the direction of the flow. In the freshwater recharge area, Cl$^-$ concentrations and TDS values are low. Moving seawards, Cl$^-$ concentrations and TDS values increase.

Application of the R-mode factor analysis showed that the factor with high loading on EC, Mg$^{2+}$, Na$^+$, Cl$^-$, SO$_4^{2-}$ and K$^+$ can be associated to a salinity factor. The areal distribution of this factor shows that high positive scores mainly enclose the coastal part of both aquifers, indicating the occurrence of the seawater intrusion process.

Based on the distribution maps, the seawater intrusion zone extends up to 1.1 km from the shore in the alluvial aquifer and up to 4.5 km in the karst aquifer.

References


