

IMPACTS OF RAINFALL CHANGES ON GROUNDWATER BALANCE OF COASTAL AQUIFERS: A CASE STUDY OF THE THERMAIKOS GULF, NORTH GREECE

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ABSTRACT

Groundwater is one of the major parameters in maintaining ecology in many regions. As climate is one of the main factors which affects groundwater resources, the main objective of the present study is to assess the impact of rainfall changes on the groundwater system by projecting the future changes in the 21st century (2021-2050 and 2071-2100). For this reason, the RegCM3 climate model precipitation data, which showed a reduction in rainfall, was entered in the steady-state groundwater flow model MODFLOW for the case study of a coastal aquifer in the eastern part of the Thermaikos Gulf (North Greece). The uprising urbanization in combination with the intensive cultivation have led to the overexploitation of the coastal aquifer and seawater intrusion. The groundwater flow simulation by using the MODFLOW code indicates a negative water budget and estimates the quantities of the seawater intrusion. According to the RegCM3 climate model, the precipitation reduction is estimated to be 4% during the period of 2021-2050, while the precipitation decrease is expected to be 22% during the period of 2071-2100. Furthermore, the natural recharge of the coastal aquifer is expected to be influenced by the precipitation reduction. Finally, the seawater intrusion amounts are expected to increase during these future periods and more specifically during the second period of 2071-2100.

Keywords: Groundwater, MODFLOW, RegCM3, Simulation, Steady-State, Water balance

1. Introduction

Groundwater is the main source of irrigation, livestock, industrial and domestic uses in many countries as well as in Greece. Precipitation is a crucial parameter in determining the availability of groundwater and soil moisture. The increasing demands for fresh water have led to its overexploitation which causes a permanent drawdown of the water table. Furthermore, the prediction for the future decrease of precipitation in Greece due to climate change (Tolika *et al.*, 2008; Zanis *et al.*, 2009) consists a current stress on groundwater resources (IPCC, 2008). Climate change can increase the amounts of runoff even in areas with high amounts of rainfall and snow (Sarkar, 2015) in disadvantage of infiltration and thus in the recharge of the aquifer.

The coastal aquifers are seriously affected by groundwater drawdown as it can cause seawater intrusion. Seawater intrusion depends on the balance of fresh and salt water. The disturbance of this equilibrium at the expense of fresh water is the main reason for the salinization of coastal aquifers. Consequently, to

prevent salinization a positive balance of groundwater balance must be ensured so as to acquire a sustainable exploitation of a coastal aquifer.

Groundwater balance is accomplished by using disparate methods and groundwater flow models. The applications of groundwater flow models have risen considerably due to the fact that they can offer solutions to water resource problems. Two-dimensional and three-dimensional models (Anderson, 1979; McDonald and Haurbaugh, 2003; Pechlivanidis *et al.*, 2011) have been developed to study and simulate the behaviour of groundwater flow systems. Groundwater simulation is a substantial and valuable tool for planning groundwater management (Panagopoulos, 2012) as well as predicting the impact of climate change and human activities on the groundwater balance (Pechlivanidis *et al.*, 2015; Roy *et al.*, 2015). However, most of these model applications estimate the reaction of the aquifer system under different subjective hypothetical scenarios such as changes in precipitation and pumping rates (Abdulla and Al-Assa'd, 2006). In 1988 McDonald and Haurbaugh developed the USGS Modular Three-Dimensional Finite Difference Ground Water Flow Model, known as MODFLOW, that is worldwide used to simulate the groundwater flow and flow budget of the aquifer. The steady-state MODFLOW-2000 is used to define the flow balance (Lachal *et al.*, 2012), whereas the sensitivity of the model is audited by changing the recharge according to the results of land use change models (Dams *et al.*, 2008). The recharge of an aquifer is strongly influenced by the decrease of the precipitation amounts due to climate change (Ekhardt and Ulbrich, 2003).

The most applicable tools for the evaluation of future global scale climate change and development of climate scenarios remain the General Circulation Models (GCMs) and Regional Climate Models (RCMs). The need for regional projections of the changes has led to the development of downscaling methods. The downscaling process is divided into subcategories: the dynamical approach and the statistical-empirical processes (IPCC, 2007).

The aim of this study is to estimate the impacts of rainfall change on groundwater balance of a coastal aquifer in the Thermaikos Gulf (North Greece). The selected coastal region is suitable for the scope of this study as the available hydrological and hydrogeological data are satisfactory. For this reason rainfall data, drilling data, lithological profiles, groundwater measurements and data from pumping test analyses were used and analyzed in a GIS environment. A part of the aforementioned data was collected in the frame of a research program (Geology Department, Aristotle University of Thessaloniki) concerning water resources management in the area during the period of 2012-2014, which was funded by the Municipality of Thermaikos (Voudouris, 2014).

2. Materials and methods

2.1. Study region

The study region is an eastern suburb of the second largest city in Greece, Thessaloniki, which is located in northern Greece at the eastern part of the Thermaikos Gulf and covers an area of 135 km² (Figure 1). According to the National Statistic Service of Greece, the permanent population is about 50.000, whereas in the summer period an increase of 70% is observed according to information from the local municipality. The economy of the region is principally dependent on agriculture and tourism underlying the great significance of the seawater intrusion future projections. The rural land is 6800 ha (hectares) and vegetable products such as vineyard, cereals and oil trees are cultivated. The water demands are met by exploitation of the porous aquifer through a large number of boreholes. The high dependence of the area on groundwater quantities renders a rational management of the coastal aquifer considering the climate change impacts and uprising urbanization of the area. Moreover, during the last decade seawater intrusions have been reported in the area (Pavlou *et al.*, 2013; Kazakis *et al.*, 2016). The altitude of the area ranges from 0 m to 213 with a mean slope of 1.85%. The surface runoff is temporal during winter, with a moderate developed dendritic drainage network which flows into the Thermaikos Gulf. The mean annual temperature for the period of 1965-2014, was 15 °C and the mean annual rainfall was 475 mm.

Based on Thornthwaite-Mather method (1955), the mean actual evapotranspiration is 75% of the annual rainfall. From a geological point of view, the study area consists of Quaternary sediments (alluvial deposits of gravel, sand and conglomerates) in the coastal area and Neogene (sands, marls, clays and sandstone) formations in the hilly part.

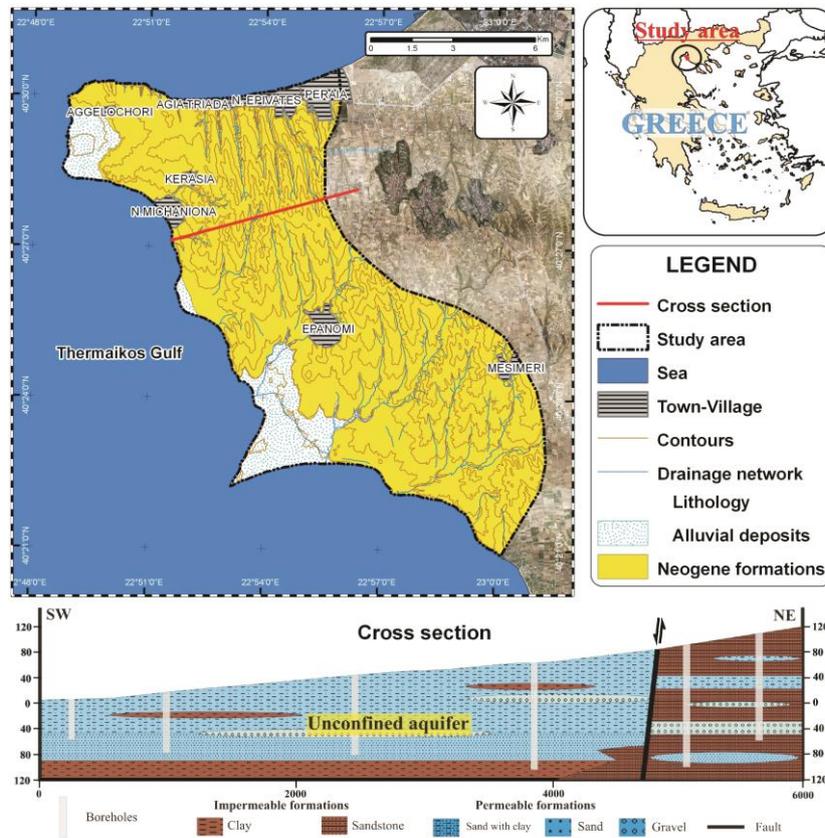


Figure 1. Geological formation of the study area and a hydrogeological cross section (modified from Kazakis *et al.*, 2016) of the aquifer

2.2. Climate data

Daily precipitation dataset from a regional climate model (RCM) simulations have been taken into consideration in this study. The RCM simulations were carried out with the use of the regional RegCM3 climate model in the framework of the CCSeaWavs NSRF-EU project (<http://thalis-ccseawavs.web.auth.gr/en/>). The RegCM3 model was firstly created by Giorgi *et al.* (1993a, b) and was later modified and improved by Giorgi and Means (1999) and Pal *et al.* (2007) (<http://www.ictp.trieste.it/~pubregcm/RegCM3/>). The RegCM3 climate model has been dynamically downscaled to a high spatial resolution of 10 km x10 km, it is driven by ECHAM5 Global Climate Model (GCM) and it follows the A1B emission scenario for future climate projections. The A1B is based on the assumption of a world of rapid economic growth and introduction of new technologies, which are used with a balance across all sources (IPCC, 2007).

The data correspond to the control period of 1961-1990, and the future projection for two periods of 2021-2050 and 2071-2100. Four Grid points were selected to analyze the precipitation regime in the research area. The RCM data was evaluated by using the precipitation data obtained from the official WMO meteorological station of the Hellenic Meteorological Service at Thessaloniki airport “Macedonia” (Mikra station). The particular station is the closest station to the study region and was selected as reference station using the period of 1961-1990 as control period.

2.3. Hydrogeological data

The main porous aquifer system is developed within alluvial deposits and is divided into the upper unconfined aquifer and the deeper confined aquifer below 200 m. The mean thickness of the unconfined aquifer is approximately 80 m (Kazakis *et al.*, 2013; Kazakis *et al.*, 2015). The hydraulic head presents particular fluctuations of maximum and minimum +25m and -35 m above sea level respectively. Groundwater levels were measured by subtracting groundwater table (meters below the ground surface) from land surface elevations (from DEM). The groundwater flow direction is NE-SW, while at the coastal area the flow direction changes and turns from the sea to the land due to overexploitation (Voudouris, 2014). The yield of the boreholes ranges between 15-120 m³ h⁻¹ and the specific capacity (discharge / drawdown) ranges between 28 m² day⁻¹ and 230 m² day⁻¹. Storativity values vary from 0.01% to 5% and the mean hydraulic conductivity is measured $k=10^{-5}$ m s⁻¹ ($k=0.86$ m day⁻¹), as deduced from pumping test analyses (Kazakis *et al.*, 2013).

2.4. Groundwater recharge

Recharge (R) is defined as the downward flow of water reaching the water level, adding the groundwater storage (Healy, 2010). The aquifer is recharged mainly by rainfall infiltration, infiltration through torrent beds, lateral subsurface inflows and irrigation returns. The infiltration coefficient depends on slope, soil texture and permeability, rainfall, lithology, vegetation, etc. The soil textures of the study area are mainly medium and were obtained from Kazakis, 2013, Voudouris, 2014 and Kazakis, 2014. Taking into account the slope of the terrain and aquifer type (Voudouris 2014), the infiltration coefficient estimated from 18% to 22% of the annual rainfall. These values are in accordance with similar lithological formations of Greece as deduced from hydrologic balance and bibliography (Voudouris *et al.*, 2007). The analysis was applied on the basis of a raster grid with a cell size 100 m x100 m in GIS environment. Lateral subsurface inflows were calculated by using Darcy law (Voudouris *et al.*, 2007). Irrigation returns are estimated to be 10% of the irrigated water (Voudouris, 2006). The streambed infiltration is assumed small (5% of the annual rainfall), due to the temporal character of surface runoff. So, the total annual recharge (R) was estimated from the following equation:

$$R=Q_{inf} + Q_{lat.subs} + Q_{str.inf}+ Q_{irr.ret}$$

Where Q_{inf} =annual water volume of infiltration (annual rainfall multiplying by infiltration coefficient in each grid cell), $Q_{lat.subs}$ =lateral subsurface inflows, $Q_{str.inf}$ =streambed infiltration and $Q_{irr.ret}$ =water of irrigation return.

2.5. Methodology of groundwater flow simulation

In the present study, the MODFLOW 2000 was employed to simulate the groundwater system of the coastal aquifer in the eastern part of the Thermaikos Gulf. The model application required the collection of physical and hydrogeological parameters and properties of the aquifer. Physical parameters consist of infiltration coefficient, aquifer thickness, hydraulic conductivity and pumping rates. Also, piezometric data, a geological and topographic map, lithological profiles and the location of boreholes were used to simulate the groundwater system and were obtained from Kazakis *et al.* (2013), Pavlou *et al.* (2013) and Koumantakis (2006).

The MODFLOW 2000 code on the GMS program was used for the groundwater flow simulation of the unconfined aquifer of the study area. A conceptual model approach was used to schematize the unconfined alluvial aquifer of the study area which consists of one layer with a thickness of 80 m. The dimensions of the numerical model are 19.4 km × 19.8 km and an area of 384.12 km². The grid contains 198 rows and 194 columns and the dimensions of the cells are 100 m × 100 m. The active cells were defined by using the IBOUND array in MODFLOW and cover an area of 137 km². The DEM (Digital Elevation Model) of the basin was used for the determination of the layers top elevation which corresponds to the surface elevation. The boundary conditions were defined from previous piezometric and geological data and lithological profiles of the study area (Venetsanou, 2014). The lithological profiles were also used for the determination of the bottom elevation of the aquifer. The major part of the eastern boundary is vertical to the piezometric contours and consequently the flow direction is parallel and was defined with

no-flow (Figure 4). The central part of the eastern boundary was defined as constant head with a variable head elevation between 15 to 25 m.

The coastal line was simulated as constant head boundary (CHB) with 0 m head elevation and illustrates the lateral groundwater inflows or outflows. The mean value of hydraulic conductivity (0.86 m day^{-1}) was used as the initial value for the steady state simulation. By using DEM and the raster calculator tool from ArcGIS 10.2, the infiltration was estimated by multiplying the rainfall with the infiltration factor of each formation and ranged between 83 mm to 100 mm per yr (Kazakis, 2014). The total groundwater abstractions of the aquifer are estimated to be $25 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ for irrigation, domestic, industrial and livestock uses. Based on previous studies (Voudouris and Kazakis, 2011) the irrigation abstractions are up to $20 \times 10^6 \text{ m}^3$, whereas 10% consists the returns to the aquifer due to percolation. The exploitation of the aquifer is obtained through numerous boreholes with a variable pumping rate of $15\text{--}120 \text{ m}^3 \text{ h}^{-1}$ (Kazakis *et al.*, 2013).

The model was calibrated by the use of 27 observation wells (Figure 4) in steady state condition using a trial-and-error process of adjusting the pumping rates and wells allocation in the study area. Furthermore, minor adjustments were made on the thickness of the aquifer and the boundary conditions that were used in the initial runs. For the estimation of the hydrodynamic behaviour in the aquifer developed in the study area, for the future periods of 2021-2050 and 2071-2100, the MODFLOW 2000 code was combined with the results of the rainfall from the climate model RegCM3. Consequently, two scenarios were obtained by reducing the infiltration in the MODFLOW while concurrently the other parameters remained stable.

3. Results

3.1. Climate model

The precipitation data for each grid point was evaluated in comparison to the reference station data. Among the 4 selected grid, the average annual precipitation ranges from a low of 550 mm at grid 2, to a high of 700 mm at grid 1 for the control time period of 1961-1990. The overall average annual precipitation for these grids is 630mm. Boxplots of the annual total rainfall at each grid point were generated to illustrate the variability in annual rainfall among the 4 grids and the station (Figure 2).

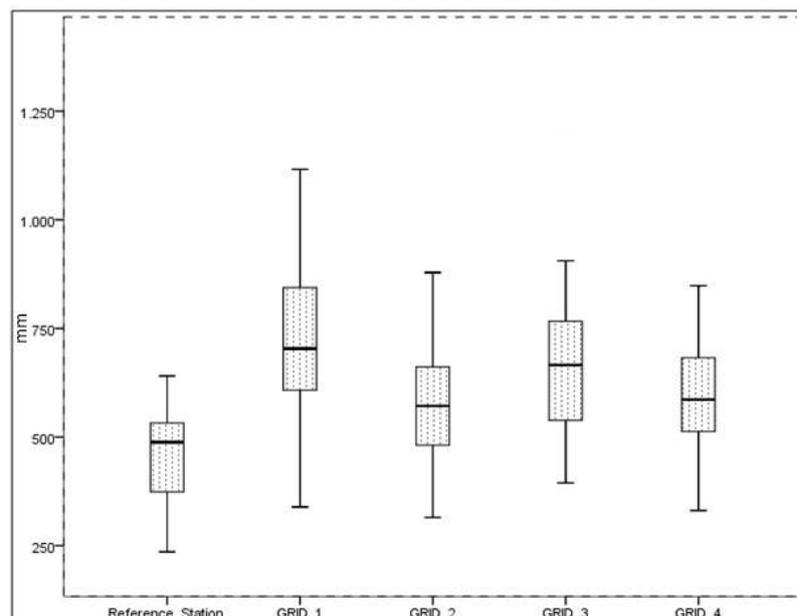


Figure 2. Boxplots of the total annual rainfall (mm) for the reference station and the 4 grid points

The boxplots clearly show that grid 1 has the highest average annual total rainfall, while the average annual rainfall at grid 2 is notably lower than the rest of the grid points. Moreover, the similarity in annual precipitation between the station and the grid 2 is apparent. The RegCM data seems to overestimate precipitation during the wet period of the year, while the RegCM precipitation for the dry period presents great similarity to the observed one (not shown). According to Torma *et al.*, (2008); Zanis *et al.* (2009) and Torma *et al.* (2009) the climate model RegCM3 overestimates the precipitation when the default parameterization is used.

For each year in the periods of 2021–2050 and 2071–2100, the absolute precipitation difference (ΔP) in precipitation with respect to the average value of the control period (1961–1990) was calculated as follows:

$$\Delta P = x_i - \bar{x}$$

Where x_i is the annual precipitation for each yr for the two future periods and

\bar{x} is the average annual precipitation for the reference period of 1961–1990.

The annual change in precipitation for each of the future periods is analyzed in Figure 3. This figure indicates that there was a decreasing trend in absolute precipitation differences over the period of 2021–2050 while an increase trend was noted from 2071 to 2000. The mean precipitation for the control period and the future periods (2021–2050 and 2071–2100) is around 569 mm, 546 mm and 443 mm respectively. For the first future period, the annual precipitation is lower than the mean annual precipitation of the control period for the half of the time period; the corresponding percentage reduction is almost 4%. According to Figure 3, there is a strong inter-annual variability of the ΔP corresponding to the regional precipitation variability. On the contrary, even when the absolute precipitation differences (ΔP) increase during the second future period, there is a precipitation total reduction of about 22%. The increasing trend of the second future period is equal to 2.8 mm per year, but this upward trend is not effective in balancing the overall reduction of the precipitation in the region.

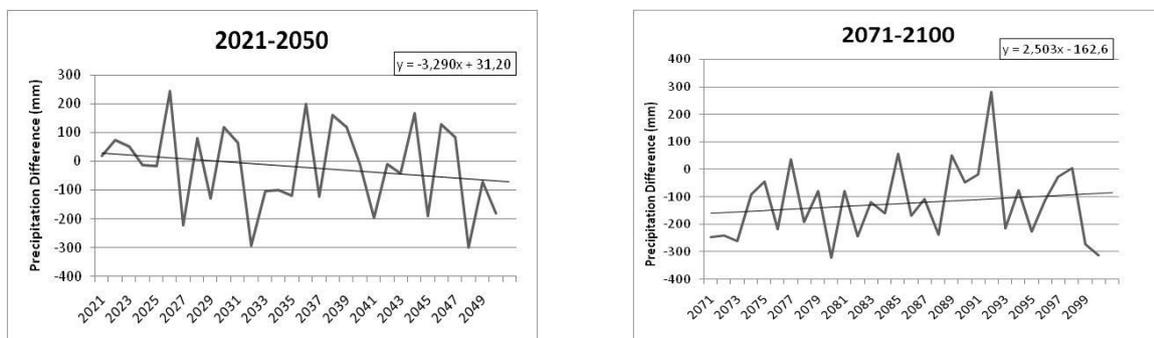


Figure 3. The annual change in precipitation for both future periods

3.2. Groundwater simulation

The boundary conditions of the costal aquifer were estimated after the steady-state simulation of the flow. After the calibration, the differentiations in the thickness of the aquifer were insignificant. The water budget with the inflows and outflows of the aquifer were calculated using the flow budget of the model (Table 1). According to the results present in Table 1, 54.8% of the total input in the aquifer of $25.65 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ is the recharge amount ($14.06 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) which is in accordance with Kazakis (2014) results. The inflows from the eastern part (Specified Heads) represent about $8.23 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ (about 32% of the total input in the aquifer). The inflows from sea (Specified Heads) were calculated at $3.36 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$. The main output of water is the groundwater abstraction for domestic and irrigation uses and amounts to $24.64 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ (about 96% of the total input aquifer).

The total water budget shows a negative groundwater balance which is supplemented with seawater intrusion. The seawater inflows are located in the northern and southern part of the coastline with the

highest amounts of inflows present in the northern part. Pavlou *et al.*, (2013) showed that the chloride ion concentration is up to 1000 mg l⁻¹, indicating seawater intrusion and salinization of the coastal aquifer. Figure 4 presents the groundwater flow direction which is mainly from east to west in the hilly zone and reverses in the coastal area. The local variability of the groundwater flow direction depends on the flow rate and the density of the boreholes. The negative piezometric heads in the northern and south-central part of the aquifer vary from -10 m to -30 m and are in accordance with the literature (Kazakis *et al.*, 2013; Pavlou *et al.*, 2013).

Table 1. Water budget of the aquifer system

<i>Water budget of the aquifer system</i>				
Reference period	Inputs (×10 ⁶ m ³ yr ⁻¹)	Outputs (×10 ⁶ m ³ yr ⁻¹)	Inputs (%)	Outputs (%)
Recharge	14.06	0.00	54.80%	0.00%
Specified Heads	11.59	-1.02	45.2%	4.00%
Wells	0.00	-24.64	0.00%	96.00%
Total Source/Sink	25.65	-25.66	100.00%	100.00%

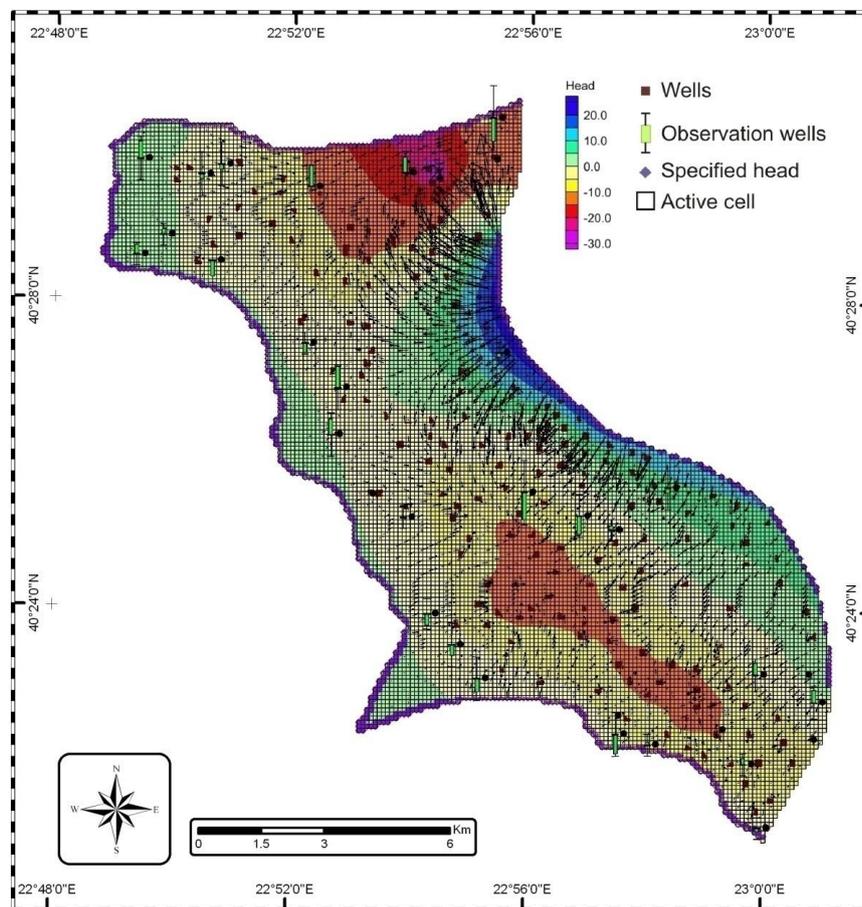


Figure 4. MODFLOW steady state model

3.3. Groundwater budget scenarios

Assuming that infiltration is reduced proportionately to rainfall, the resulted alteration of the rainfall from the climate model was transformed to infiltration alteration of the study area and was used to parameterize the recharge of the groundwater model (MODFLOW 2000). The change of the model recharge, which is based on the climate model, is more reliable than a hypothetical change. In addition, the

sensitivity of the model to these changes also provides the sensitivity of groundwater balance to climate changes.

The groundwater budget, head and flow direction (Figure 5) were re-estimated for the two studied periods (2021-2050 and 2071-2100). For the first future period, according to the RCGM3 projections, the precipitation will be reduced by 4% whereas the infiltration coefficient will remain stable (18%-22%). As a consequence, the recharge will be equal to $13.5 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$, the inflows from the sea is expected to increase by 6% ($3.6 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) and the inflows from the East and North East (Specified Heads) will increase by 3% ($8.5 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$) (Table 2). The highest amounts of seawater intrusion (Specified Heads) are predicted to occur in the northern part of the coastline, while no significant alternations are shown in the central part of the aquifer. The groundwater flow direction remains unaffected by the reduction of the recharge.

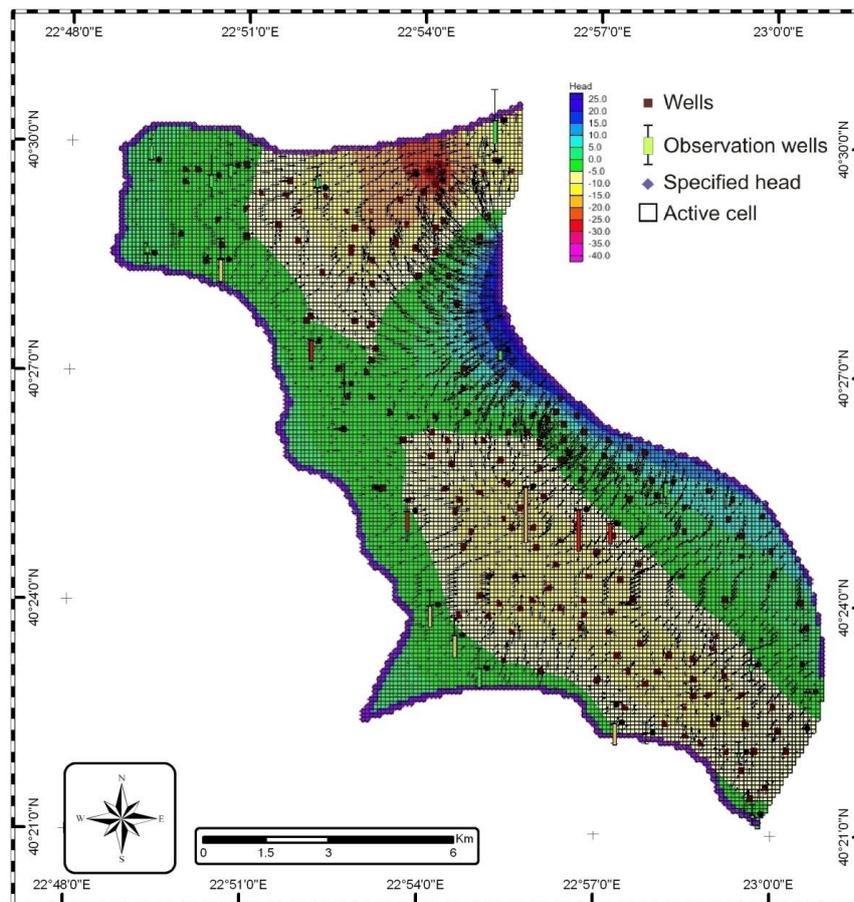


Figure 5. MODFLOW steady state model based on the RegCM3 models results for the period 2071-2100

For the future period of 2071-2100 the reduction of precipitation is estimated to be 22%. Consequently, the recharge will be $10.9 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$. The seawater intrusion is estimated to increase dramatically. The seawater intrusion (Specified Heads) is predicted to amount to $4.79 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$. The inputs from the East and North East (Specified Heads) are predicted to amount to $9.4 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$. The negative groundwater balance is expected to broaden during the future period of 2071-2100. The total inputs are expected to amount to $25.13 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ whereas the total outputs to approximately $25.3 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ (Table 2).

Regarding the simulation results, the negative hydraulic head expands in a parallel zone to the coast line with a mean width of 2 km. The main groundwater flow direction presents no difference from the initial model with minor local exceptions. The negative impacts of a potential reduction of rainfalls and consequently of the infiltration on the groundwater balance in the coastal aquifer of the study area are well established with the combination of the groundwater flow and climate models (Taylor *et al.*, 2013)

and are vulnerable to salinization (Sherif *et al.*, 2012; Singh, 2014). Therefore, these aquifers are more sensitive to the climate change than the inland aquifers. The result of this study is essential for a sustainability plan for the groundwater of this region as well as that of areas with similar characteristics.

Table 2. Prediction of water budget

<i>Water budget of the aquifer system</i>				
Future periods	2021-2050		2071-2100	
Inputs/Outputs ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	Inputs ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	Outputs ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	Inputs ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)	Outputs ($\times 10^6 \text{ m}^3 \text{ yr}^{-1}$)
Recharge	13.50	0.00	10.97	0.00
Specified Heads	12.1	-0.92	14.19	-0.56
Wells	0.00	-24.64	0.00	-24.64
Total Source/Sink	25.5	-25.56	25.13	-25.20

3.4. Limitations

This research, however, has some limitations which can improve in future studies. Firstly, a transient calibration of the MODFLOW can offer more comprehensive results for the hydrodynamic behaviour of the aquifer (El Yaouti *et al.*, 2008) nevertheless, the availability of data is the main disadvantage in most of the cases as well as in this region. Additionally, a more detailed study of soil water dynamics of the prevailing land use and its influence on infiltration rates would better define the future irrigation needs and thus the allocation of the crops. Considering that seawater intrusion is the major hazard of the coastal aquifer, the application of others groundwater flow models (SEAWAT, SUTRA, etc) could be used for further research of the seawater intrusion in the study area. Finally, a further combination of a land use change model with the applied models can offer a more comprehensive prediction concerning the groundwater balance of the studied aquifer.

4. Conclusions-discussion

In the present study, an attempt was made to estimate the future groundwater balance of a coastal aquifer in the eastern part of the Thermaikos Gulf. For this purpose, the groundwater flow model, MODFLOW 2000 and precipitation data of climate model RegCM3 were coupled and applied. The main conclusions deriving from the present study are:

- The groundwater flow simulation of the coastal aquifer in the research area indicated a sufficient presence of the existing groundwater piezometric conditions. The observed and calculated piezometric heads are in good agreement. The negative groundwater budget and the seawater intrusion are proven by the simulation. The inflows from the sea were calculated at $3.36 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$.
- According to RegCM3 projections, the precipitation will be reduced by 4% during the period of 2021-2050, while the precipitation will decrease by 22% during the period of 2071-2100.
- The precipitation decrease affects the recharge reduction of the aquifer in the study area.
- The groundwater balance will be more deficient during the future periods of 2021-2050 and 2071-2100. Furthermore, the inflows from the sea as well as from Eastern and North-Eastern neighboring areas will increase. More specifically, for the second future period, seawater intrusion is expected to amount to $4.79 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$.

The groundwater simulation with the use of the MODFLOW 2000 model in the region specified the quantities of seawater inflows and can be used to change the exploitation plan of the basin, the allocation of the boreholes and also define an artificial recharge plan for the aversion of the salinization in aquifers. Protection meters are necessary but they should be based on quantitative data which can be obtained from a simulation model such as MODFLOW. Furthermore, they can be used as a tool for a sustainable management of groundwater resources. Specifically, the artificial recharge can be used in the areas with

negative piezometry to increase the groundwater resources and limit the seawater intrusion phenomena. The decrease of pumping rates in the central and seaside parts of the aquifer in combination with a better allocation of the required cultivation high water amounts for irrigation (alfalfa, cereal) are the appropriate measures for the limitation of seawater intrusion and have been well tested in other regions (Nocchi and Salleolini, 2013). Furthermore, the reuse of the treated wastewater is a measure to reduce the groundwater abstraction for irrigation purposes.

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