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Modelling Groundwater - Surface Water Interactions Under Climate Change Scenarios: insights from Axios Delta, Greece

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ABSTRACT

Competing multi-sectorial water demands as well as demands for ecosystem services in coastal aquifers exert significant pressures to local water resources. Climate change is already altering spatiotemporal rainfall and runoff distributions intensifying the management challenge. In this context, this work is looking at the impact of water allocation practices on the aquifer of the Axios river delta under climate change impact scenarios. The area is characterized by agricultural activities, primarily water intensive rice cultivation. Urban water supply is supported by the exploitation of the local aquifer. Reduced precipitation is expected to increase the risk of salinisation of this coastal aquifer. At the same time, a decrease in river flow was recorded during the last decades. Numerical simulations of groundwater – surface water interactions are carried out to understand process dynamics. A drought scenario is simulated to assess the impact of climate change and the corresponding drought management response plan on the shifting fresh/saltwater interface. The drought response scenario involves banning irrigation and increasing groundwater abstraction. The groundwater model shows that flood irrigation forms a hydraulic barrier to saline intrusion. This type of groundwater model predictions can inform water resources management policies and examine the effectiveness of interventions to support sustainable socioeconomic activity while protecting environmental health.

Keywords: climate change impacts, groundwater modelling, seawater intrusion, drought management

INTRODUCTION

Despite the spatiotemporal uncertainty of climate projections, it is expected that more intense and frequent dry periods will affect groundwater resources (Green et al., 2011). This creates a research need for improved understanding of the joint behaviors of climate and groundwater (ibid). In the Mediterranean context, seasonal predictions show that temperature will rise in all seasons while precipitation is expected to decrease (Dubrovský et al., 2014). The same authors suggest that, in many parts of the region, increased mean daily precipitation sums on wet days occurring in some seasons may imply higher daily precipitation extremes, and decreased probability of wet day occurrence will imply longer drought spells across the Mediterranean. This change in precipitation temporal distribution will also result in decreased groundwater recharge as more rainfall will be converted into runoff. Meixner et al. (2016) showed that several western United States aquifers will see a future recharge reduction by 10-20%.

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Coastal aquifers are of particular importance to agricultural economy and human well-being, as these environments have a population density threefold the global density (Small and Nicholls, 2003). It is well documented that excess groundwater abstraction from coastal aquifers results in the inland-shifting of the freshwater-saltwater interface and saline intrusion (Barlow and Reichard, 2010; Post, 2005). The National Water Program of the US Environmental Protection Agency identifies sea level rise due to climate change as a risk for saline intrusion and points to the need for adaptation (EPA, 2012).

This risk has been demonstrated through transient simulation studies. Previous studies showed that the extent of intrusion will depend of the relationship between hydraulic conductivity, recharge and presence of streams (Masterson and Garabedian, 2007; Webb and Howard, 2011). Ferguson and Gleeson (2012) carried out the first comparison of the combined effect of sea level rise and overexploitation to demonstrate that, in most cases, it is human intervention through excess abstraction that dominates intrusion. Sea level rise dominates intrusion only in aquifers with very low hydraulic gradients.

This finding is significant as it highlights the need to guide adaptation efforts to the right direction. In this respect, understanding the process of upconing (i.e. the rise in the freshwater-saltwater interface that occurs beneath pumping wells where fresh groundwater is underlain by saltwater) can inform management options in the field (Jakovovic et al., 2016). In their modelling study (ibid), they found that the upconing zone of influence depends on pumping rate, distance from coast, regional flows and the position of the well above the interface. In another modelling study, intrusion showed dependency on the no-flow boundary conditions (Jakovovic et al., 2016). Werner and Simmons (2009) demonstrated that different types of influx/outflux boundary condition (fixed flux vs. fixed head) result in a significant difference on the scale of intrusion due to sea level rise. This result was corroborated in an examination of the most suitable boundary condition choice by Sun et al. (2017).

Further uncertainty is introduced in the representation of the seaside boundary between the aquifer and the sea. This is particularly true for confined aquifers discharging into the sea at deeper layers. Walther et al. (2017) found an influence of the seaside boundary slope on the simulation results of seawater intrusion in a freshwater aquifer by employing a series of slope variations. Liu and Mao (2011), found that significant vertical flows can be more important than horizontal gradients in inhibiting saline intrusion. The simulation study by Lu et al. (2012) showed that the relative distance between (i) the coast and well and (ii) the well and the inland boundary conditions can have an effect on the predicted position of the interface. This effect is eliminated for practically large distances between the well and inland boundary.

To support water balances that hinder seawater intrusion and water table drawdown, a series of adaptation options can be envisaged. These can range from use of water efficient crops, increase in water efficiency in irrigation and better managed pumping protocols (rates, depth, location, time of the year) through to efficiency in water supply for domestic and industrial uses. Davis et al. (2017) show that replacing crops can help align food security and environmental goals, while leading to a reduction of water consumption by 12% at a global scale. At the same time, soil aquifer treatment (SAT) and wastewater reclamation processes can play a vital role in supporting water balances (Ahuja, 2014; Intriago et al., 2018; Tram VO et al., 2014). The Shafdan SAT project in Israel has allowed crop irrigation in a water-scarce environment by supplying annually 125 hm^3 (DEMOWARE FP7 project, 2016).

This study explores the impacts of climate change on coastal aquifers with multiple competitive water uses (urban, agricultural, environmental) which give rise to multiple objectives and challenges. The study uses the Axios Delta aquifer in Northern Greece as case study. The seawater/freshwater interface is identified.

Effects of recharge reduction as a result of precipitation reduction and temperature increase are evaluated. A drought management scenario (European Commission - EuropeAid Co-operation Office, 2007) is also explored by introducing a ban in agricultural irrigation to maintain minimum environmental flows and allowing an increase in groundwater abstraction rates. The impact of these changes on the position of the interface is explored. The novelty of this study lies in the evidence provision for climate-induced risk of aquifer salinisation using downscaled climate information and simulating a drought management scenario.

By extension, this study offers the opportunity to assess current policies on drought mitigation and, in the future, to explore alternative pro-active adaptation scenarios.

METHODOLOGY

Geography of study area

Climate is transitional continental to Mediterranean on the Koppen-Geiger classification (Bear-ID Novatek, 2016; Kotinis-Zambakas et al., 1984). The mean annual precipitation is 443 mm (Chalastra Station, 1974-2004) (Grimpylakos et al., 2016). Figure 1 shows the location of Axios River Delta on the north coast of Greece where the Axios River discharges into the Mediterranean Sea in the Gulf of Thermaikos. The Delta is formed at the confluence of four rivers: Aliakmon, Loudias, Axios and Gallikos from west to east respectively. Aliakmonas contributes significant flows to the west delta, while Loudias is technically an artificial drainage channel. The Gallikos River originates from Kroussia Mountain and discharges into the Thermaikos Gulf. Its river basin covers an area of 950 km2. Axios is a transboundary river shared between the Republic of North Macedonia and Greece. Its catchment has an area of 24,437 km2, with only about 12% of this area in the Greek territory. Like Greece, North Macedonia makes abstractions from the river for agricultural use. This has resulted in uncertain flows reaching across the border depending on upstream abstractions requirements and seasonal conditions. Within the Greek territory, most abstractions take place at the mouth of the river as water intensive rice paddy fields cover the largest part of the deltaic valley.

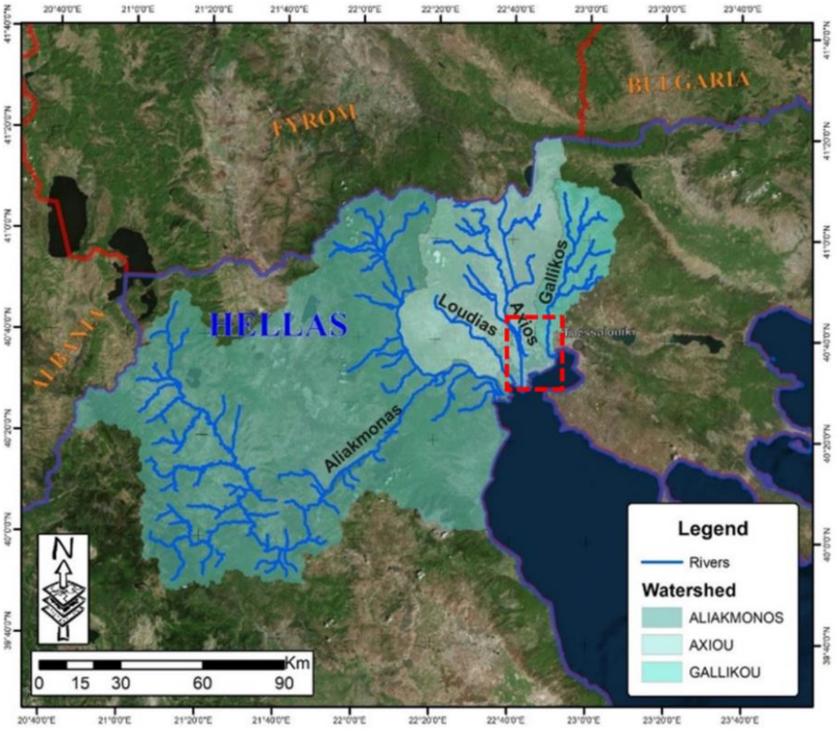

Figure 1. Axios, Aliakmonas, Loudias and Gallikos River catchments and discharge location at Thermaikos Gulf where the Delta is formed. The study area is highlighted in red.

Groundwater abstractions on the eastern part of the delta take place to cover urban water demands for the city of Thessaloniki. These groundwater abstractions act primarily as a redundancy measure during drought condition when the alternative major sources of water supply for the city are under pressure (EYATH, 2018). The Axios Delta also includes the Axios National Park (Axios-Loudias-Aliakmonas Management Authority, 2018) which has significant biodiversity value and offers extensive ecosystem services (Hadjicharalambous et al., 2015). Maintaining the functions of this ecosystem depends on the supply of sufficient water quantity of good quality. Hadjicharalambous et al. (2015) established the ecological flow characteristics for the Delta area which are required to support favourable conditions for local species. Kapetas et al. (2018) analysed the water budget of the delta to demonstrate there is potential risk of aquifer salinisation, particularly as climate change can alter river flow and rainfall patterns, and increased groundwater abstractions take place as a response. Sea level rise is also expected to shift the fresh-salt water interface.

Within the Delta area operates the Wastewater Treatment Plant of Thessaloniki. After treatment an amount of 180,000 m^3 per day discharges into the Thermaikos Gulf. Reclaimed water can be artificially recharged via deep boreholes and also used for irrigation covering a large part of irrigation needs in the study area (Spachos et al., 2012). This has already been successfully applied on a pilot scale.

Conceptual model

A schematic representation of East Axios Delta and its water fluxes is presented in Figure 2. Significant groundwater – surface water interactions take place with water exchange between the underlying coastal aquifer and the two rivers, namely Axios and Gallikos. Rice paddies are rainfed between November and April, but between May and October, significant transfers take place from both Axios River (abstractions at an upstream diversion dam named Agia Eleousa) and Aliakmon River. This deltaic environment is partially-flooded and has transitional waters as a result of freshwater inputs and sea water inputs (south-north) contributions. Subsurface flows with origin from the Sand Conglomerates and Red Clay series on the North of the domain also support a hydraulic gradient from North to South. The brackish nature of water composition in the south of the delta requires further field corroboration.

As the intention of this model is to represent processes and material properties at a large scale, there is no intention for a detailed representation of geological stratification. It is known from the examination of the bores that perched aquifers of smaller scale and clay lenses are present, however, their exact spread is unknown. Due to this uncertainty it was decided to represent the domain with a composite permeability value as obtained through the calibration procedure (see relevant section). Moreover, the extend of the aquifer under the sea is not well-established. Stratigraphy shows a maximum seafloor depth of 40 m. For the purpose of this model and due to this uncertainty, the aquifer is modelled with a vertical boundary along the coast line. Concentration along this boundary is lower than 35,000 mg/L (seawater) as fluxes from inland counter complete intrusion (see section below for the definition of boundary conditions).

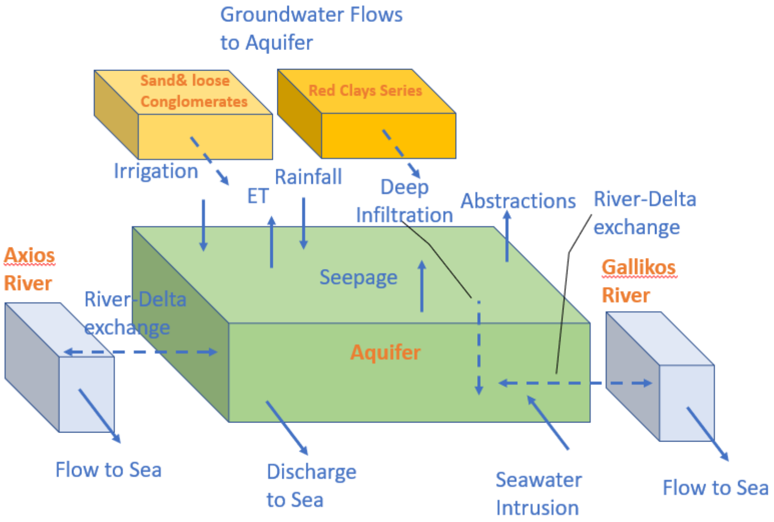

Figure 2. Conceptual diagram of water fluxes in and out of the Delta. Blocks represent geomorphological features (in orange text) while blue arrows represent water fluxes (in blue text).

Numerical modelling

The numerical model was built in Feflow (DHI Water and Environment, 2018). The model is based on a finite element discretization technique and consists of 100,470 elements of triangle side average length of 400 m. The model has 17 layers with distance between them increasing with depth. The Digital Elevation Model used has a 25 m spatial discretization. Spatial discretization was carried out to maintain adequate resolution without requiring excessive computational effort during the simulation runs. A 3D view of the model is provided in Figure 3.

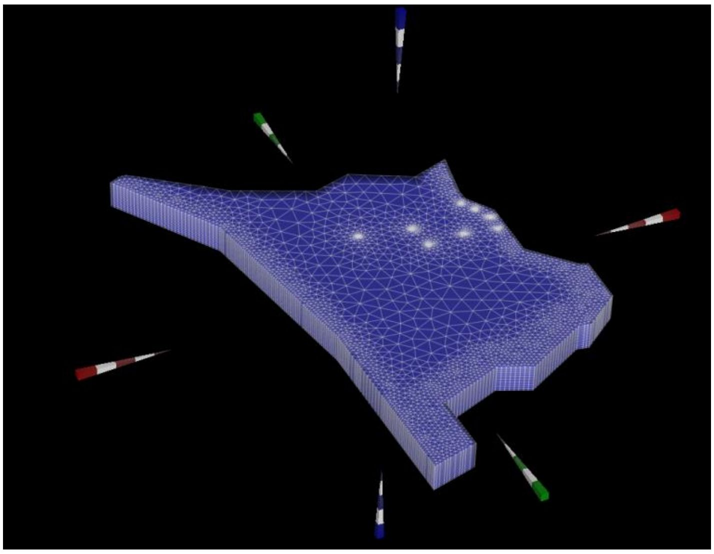

Figure 3. Three-dimensional view of the model domain. Rivers, coastal area and well locations have a greater spatial resolution.

The model solves the flow and transport equations. Boundary conditions (BCs) for the river locations are 3rd type Cauchy, equal to the elevation of the nodes. Fixed head BCs are used for the northern boundary (Sand Conglomerates and Clay Series) and the coastal boundary (corrected to account for seawater density, i.e. higher head with increasing depth). Concentrations BCs where set equal to 300 mg/L for the two rivers and equal to 17,500 mg/L for the coastal boundary. This is half the concentration of seawater and is an estimate given that water in the area is transitional as explained previously. Initial conditions for the domain were set at 1000 mg/L.

The model was calibrated at steady and transient state using the hydraulic heads measured at a number of wells (data provided by EYATH and Institute of Geology and Mineral Exploration). The minimum river flow estimates served as maximum river-aquifer exchange limits in the rate budget. The first two steps below are part of the calibration process. Inclusion of mass concentration increases water levels due to higher density of water (step 4). The procedure to calculate the saline wedge location involved the following steps:
Step 1: Steady state calibration not involving mass transport
Step 2: Transient state calibration not involving mass transport
Step 3: Transient state model involving mass transport but no variable density calculation
Step 4: Transient state model involving variable density calculation run for 100 years (by the completion of this period, an apparent steady state was reached)
Step 5: A steady state model is obtained using the predicted head and concentration from Step 4 as initial conditions

Downscaled climate information

Precipitation forcing is taken from global climate model simulations run as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5: Taylor et al., 2011), which was used to inform the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC). In this study we use the CMIP5 historical experiment (1850-2005) which includes observed anthropogenic and natural atmospheric forcings (e.g., carbon dioxide) and a medium-mitigation future scenario, Representative Concentration Pathway (RCP, 2005-2100), which approximately results in a radiative forcing of 4.5 W m-2 at year 2100 relative to pre-industrial conditions (hereafter referred to as RCP4.5). To assess the fidelity of the multiple climate models that are available, biases in simulated precipitation at the nearest grid point to Chalastra from each climate model were compared to the observations. From this validation analysis, the Max Planck Institute for Meteorology Earth System Model MR (MPI-ESM-MR) was chosen.

Drought impact simulation

An additional simulation is performed for the dry year 2051. The simulation represents the implementation of the drought management plan scenario. The expected annual rainfall in the area for that year is 233 mm, i.e. approximately half the current average annual value. In this respect, irrigation is ceased, and the fields are only rainfed. The wells operate at double the daily rate to supply the city of Thessaloniki and compensate for the partial loss of surface water resources. Potential sea level rise is not considered to isolate the impact of the management scenario. Moreover, the groundwater contributions of the adjacent hydrogeological units in the northern boundary are kept constant for the purpose of this simulation (it is currently unknown how much the levels would drop in a short term). The scenario is calculated under steady state; this simulation does not provide physically valid results, rather it is performed to understand the extreme bounds of the drought's impact. The long-term impact of climate on the shift of the saline wedge would require a transient simulation and would provide a more accurate representation of the future conditions. This is not done in the context of this article.

RESULTS

Calibration

The steady state flow model was fit to the observation well data as part of the calibration process. There is limited seasonal variability up to a maximum of 1.50 m between the autumn (Nov.) and spring (May) measurements. Figure 4 shows the pressure distribution across the domain. The low hydraulic gradient from inland towards the coast (north to south) allows a significant inland flow of the saline front (south to north).

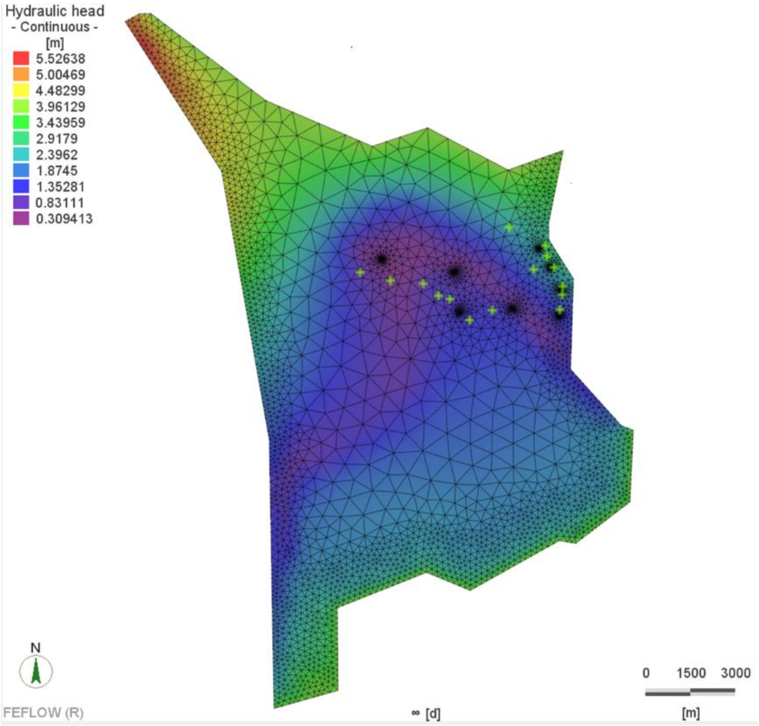

Figure 4. Hydraulic head distribution at 250 m (aquifer bottom). Head along the coast increases at deeper layers due to the higher density of water. Green crosses represent observation points used in the calibration process (Figure 5).

Figure 5 shows the comparison of the observed and computed heads at these locations under the steady state model (average values between May and November). The transient model (step 2 in Methodology) was able to approximate the inter-seasonal variability. On a domain scale, an abstraction of $1.6 \cdot 10^5$ m^3/d takes place at the well locations, $3.2 \cdot 10^5$ m^3/d are recharged from precipitation and irrigation, $1.2 \cdot 10^5$ m^3/d flow into the domain from the neighbouring hydrogeological units (northern boundary), and the rivers contribute a net of $4.8 \cdot 10^6$ m^3/d. The coastal boundary forms an additional source at the lower layers where head is higher and a sink close to sea level. The area is covered with a network of drainage canals which were modelled as seepage faces. This allowed maintaining head at a lower level than the elevation at each corresponding node.

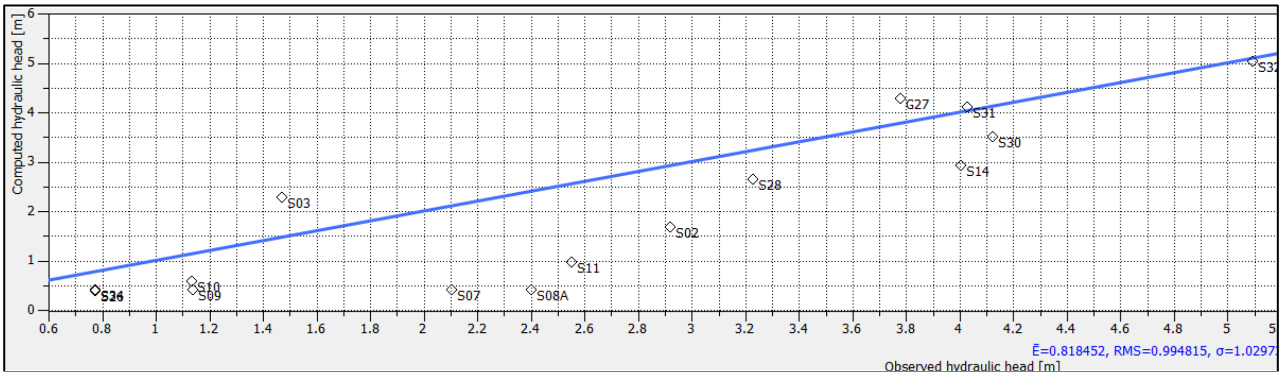

Figure 5. Calibration curve obtained for the steady state flow model

Freshwater-seawater interface

Figure 6a presents the concentration distribution across the domain at a depth of 250 m. At this depth the saline front is more spread inland than in the layers above as a result of the higher hydraulic gradient and flow. A cross-section is provided in Figure 6b to present the vertical variation of the front's progression. The wedge has a steep gradient of approximately 1:2. Some numerical dispersion was observed at a limited number of nodes where the concentration gradient was very high (e.g. river discharge into the sea). This was necessary to allow the model to compute a numerical solution. At these limited number of node locations, concentration can be higher than 17,500 mg/L (upper limit) or lower than 300 mg/L (lower limit).

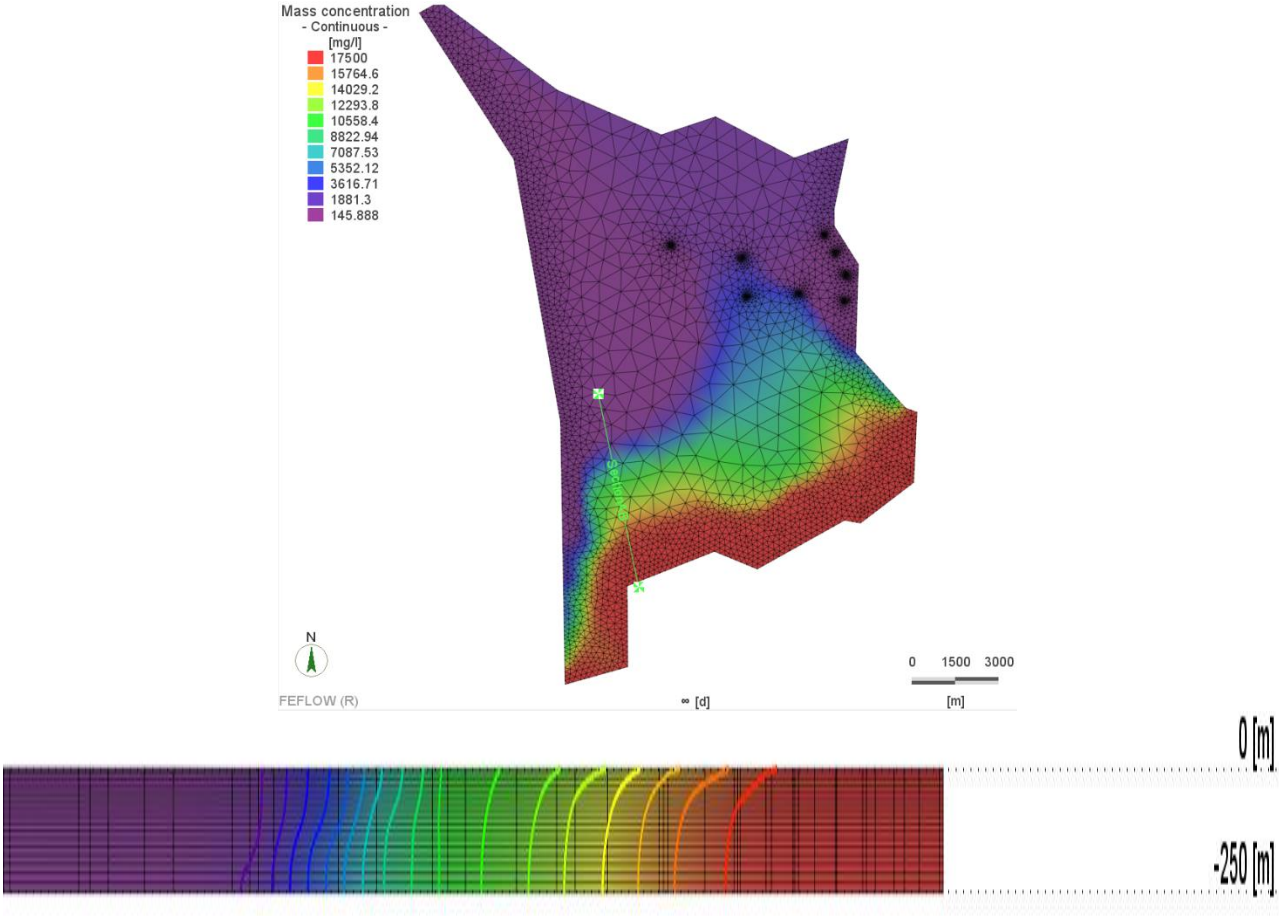

Figure 6 (a). Concentration distribution at a depth of 250 m at present steady state, **(b)** cross-sectional view for cross-section shown in "a".

Drought impacts on interface

The simulation of the drought scenario described above results in an inland shift of the saline wedge, as can be seen in Figure 6(b). This shift is approximately 1 km. The upconing phenomenon is not explored here as simulations at different locations and depths would be required to provide an analysis of the phenomenon.

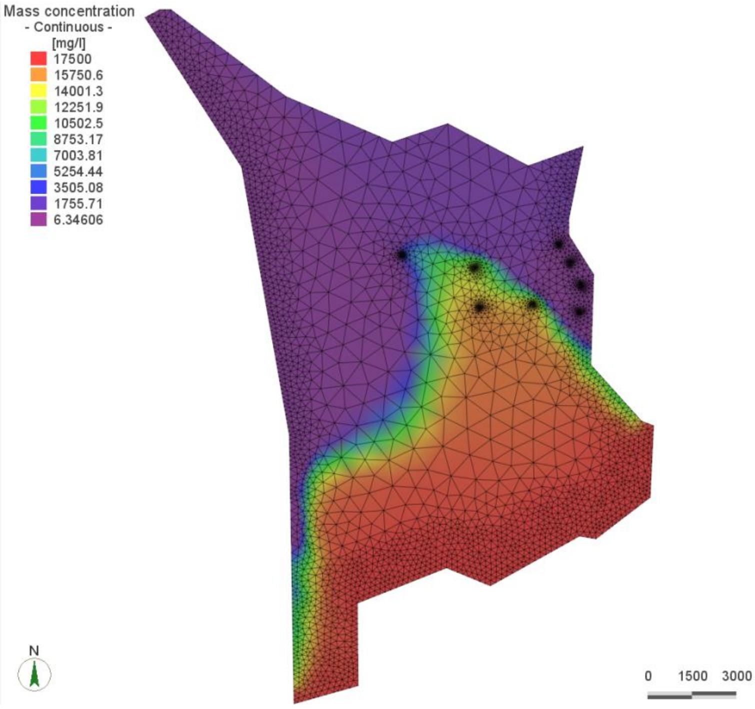

Figure 6 (b). Concentration distribution at a depth of 250 m for future steady state assuming extensive drought period.

DISCUSSION

The modelling findings suggest that the deltaic aquifer of Axios has an extensive zone of brackish water due to the interfacing between freshwater resources and seawater. Freshwater inputs contributing to the deltaic aquifer include a combination of percolating irrigation and precipitation water, flows arising from the river-aquifer exchange and flows from the adjacent hydrogeological units. The relative contribution of these sources was established through the calibration of the groundwater model and based on the conceptual model of the area. There are uncertainties regarding these influxes and outfluxes that could be reduced by a more extensive monitoring network.

The transition zone is extensive as the hydraulic gradient is minimal and this allows significant influx of saline water, particularly at the lower layers of the aquifer where the head is higher due to the higher water density. Results show that flood irrigation, although arguably a water intensive process, supports diffuse percolation and recharge, forming in this way a hydraulic barrier to the intrusion process. This became evident in the drought impact scenario assessment where the relevant boundary condition was significantly reduced. In this case the saline wedge shifted inland.

CONCLUSIONS

This study points to the need for a better understanding of the groundwater-surface water interactions in sensitive coastal aquifers. The risk of saline intrusion as a result of combined overexploitation (excessive abstraction and irrigation) and climate change (sea level rise, reduced flows, reduced precipitation) is particularly eminent. Sea level rise was not explored as part of this study. The local conditions of minimal topographic and hydraulic gradient suggest its impact might be significant (Ferguson and Gleeson, 2012) and, therefore, future work will benefit from assessing relevant sea level rise scenarios.

Extensive monitoring is required to provide the evidence-base for informed conceptual models and numerical models, such as the presented. These models can then be used to test the impact of different management scenarios on aquifer salinisation and depletion. Currently, business-as-usual and drought mitigation plans are not based on a solid evidence base. Evidence based decision-making will require the strengthening of partnerships to developed shared interests/visions among stakeholders that are currently involved in water management. Such stakeholders might currently have conflicting interests reflected in their competing water demands (irrigation, ecosystem, urban water supply).

Models such as the presented can form the basis for the assessment of alternative water management practices and climate impact scenarios. For instance, the effectiveness of managed aquifer recharge via treated water reclamation, as proposed by the regional water company (EYATH, 2012), can be tested and designed. Finally, long-term transient state simulations can test climatic impacts based on the downscaled information of this study.

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