A METHODOLOGICAL FRAMEWORK TO EXPLORE THE LONG-TERM EFFECTS OF SEAWATER INTRUSION ON GROUNDWATER QUALITY AND AGRICULTURAL PRODUCTIVITY

KASAPAKI M.[1], LATINOPOULOS D.[1], SIARKOS I.[2] and LATINOPOULOS P.[2]

[1]School of Spatial Planning and Development, Faculty of Engineering
Aristotle University of Thessaloniki, GR-541 24, Thessaloniki, Greece.
[2]School of Civil Engineering, Faculty of Engineering
Aristotle University of Thessaloniki, GR-541 24, Thessaloniki, Greece.
E-mail: dlatinop@plandevel.auth.gr

ABSTRACT

Seawater intrusion is a major problem in semi-arid coastal aquifers and can be considered as a contamination phenomenon that may render groundwater unsuitable for both drinking and irrigation, reducing thus the freshwater stocks in coastal areas. In economic terms the case of seawater intrusion is a water quality externality that arises when groundwater is overexploited (i.e. when groundwater is “mined” faster than naturally recharged) due to the “tragedy of the commons” effect.

This appears to be the case in the coastal aquifer of the N. Moudania Basin (Chalkidiki, Greece), where groundwater - which is the main source of freshwater in the area – is also an important factor for economic and demographic growth. Water demand is constantly increasing due to both agricultural and tourism activities causing groundwater levels to fall below sea level and seawater to intrude inland. However, agriculture is by far the main land use, the main water user, and the most important activity for the rural population in the study area. Therefore, any future policy measure aiming to avoid the salinity threat should focus predominantly on irrigated agriculture.

The aim of this study is to develop a methodological framework that will be able to examine the spatial and temporal effects of seawater intrusion on groundwater quality and rural economy. Specifically, a simulation model of groundwater flow is first applied in order to compute the groundwater flow field and then a simulation model of the salt transport is implemented in order to project the future movement of seawater intrusion front for a long time-period. The well-known MODFLOW and MT3DMS codes are used through GMS 8.1 (Groundwater Modeling System) to simulate the seawater movement. The results of this analysis can be also transferred to a GIS environment in order to create various salinity maps. By using these maps it is possible to examine the spatial patterns of future salt contents in both farmlands and groundwater under various agricultural management scenarios. Then, the effect of salinization to crop productivity can be estimated by combining the above mentioned salinity results with spatially referenced crop data, as well as with a set of water-salinity crop-production functions. Finally, by using economic data it is possible to estimate the spatial variability of future agricultural productivity costs due to the salinization problem under various water management scenarios.

Keywords: coastal aquifer, numerical simulation, GIS, economic analysis, agricultural productivity.

1. Introduction

Seawater intrusion constitutes an important environmental problem affecting significantly the groundwater potential of many coastal areas in the world. It is caused mainly by the intensive exploitation of groundwater resources, which disturb the established balance between fresh and sea water (Kopsiaftis *et al*., 2009). Seawater intrusion lowers the quality of fresh groundwater resources causing, among others, the area of profitable farm lands to shrink and the efficiency of crop production to reduce (Cobaner *et al*., 2012). The main aim of this paper is thus to develop a novel approach for evaluating the impacts of seawater intrusion to agricultural productivity. In this context, two main challenges can be identified: first, the future movement of the seawater intrusion front should be forecasted for a long-time period by means of numerical models and secondly, the potential economic effects of salinization to crop productivity (i.e. to farmers' income), and their spatial characteristics should be estimated.

2. Methodology

To achieve the above mentioned objectives a methodological framework was developed that integrates a groundwater flow model, a salt transport model and a spatially explicit agro-economic model (Figure 1). In the following sections these three models are described in detail.

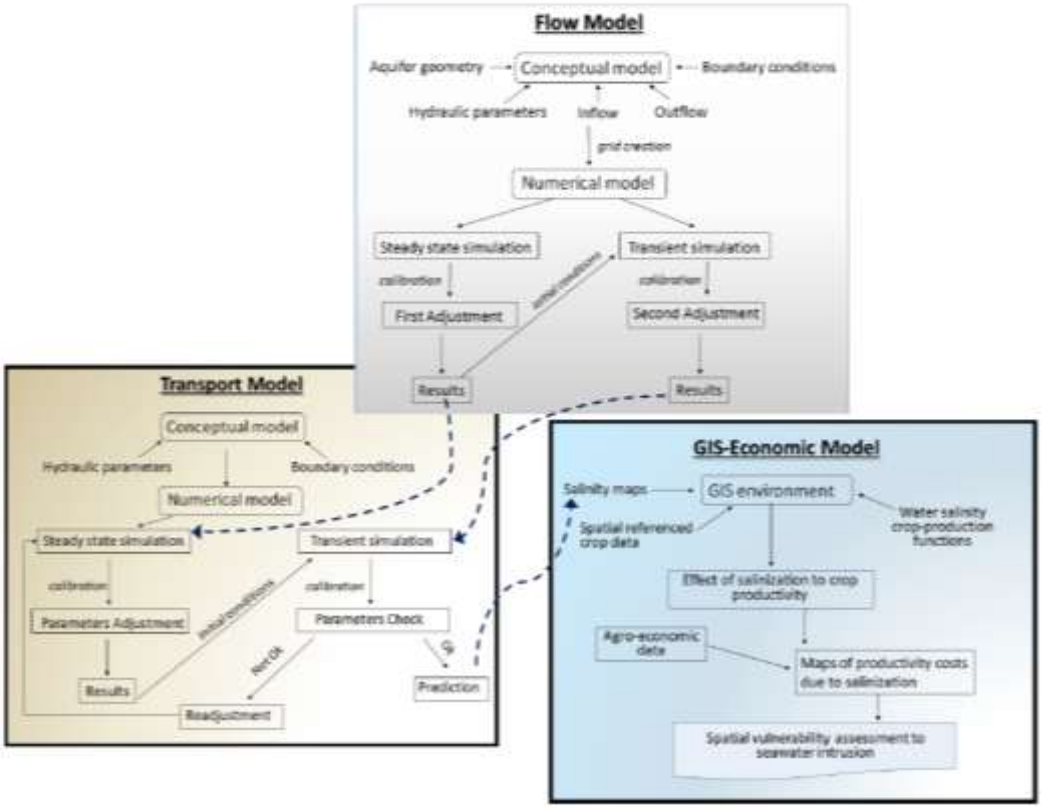

Figure 1: Methodological framework.

2.1. Groundwater flow model

First of all, the conceptual model of the coastal aquifer under study regarding the groundwater flow problem must be defined in order to simplify the complex field problem and organize the associated field data. The necessary data for the flow model development are the following: geometry and stratigraphy of the coastal aquifer, its hydraulic parameters (e.g. hydraulic conductivity and storativity), as well as its sources of recharge (e.g. infiltration due to rainfall) and discharge (e.g. wells, springs). Finally, the boundary conditions must be set, so as to define the way in which the coastal aquifer communicates with neighboring regions (Kaluarachchi and Almasri, 2002). Secondly, the mathematical model must be formed based on the developed conceptual model. For the transition into a mathematical model, a process of spatial discritization has to be carried out and a grid has to be created, so as to assign the values of the parameters described above to the grid cells. According to the developed methodology, the groundwater flow model may be conducted in two stages (Latinopoulos and Siarkos, 2014):

1st stage: A steady state simulation is carried out in order to get the initial head values for the transient simulation, as well as to adjust specific model parameters (e.g. hydraulic conductivity) through the calibration procedure.

2nd stage: A transient-state simulation is performed in order to adjust the rest of the flow model parameters (e.g. specific yield, recharge, discharge) through the calibration process, as well as to observe the aquifer response at different time periods under different stresses.

2.2. Salt transport model

As shown in Figure 1, the transport model is based exclusively on the flow model, since the developed velocity field is required in order to solve the transport equation. With regard to the already formed conceptual model, several parameters of the coastal aquifer system, concerning the transport problem, have to be added (e.g. effective porosity, dispersivity coefficients) (Kaluarachchi and Almasri, 2002), while the boundary conditions must be also defined (Sanford and Pope, 2010). The numerical grid remains the same and the simulation process can be separated again into two stages:

1st stage: A transport model based on the steady-state flow simulation is developed in order to get the initial concentration values for the transient transport model, as well to perform an initial adjustment of the transport parameters through the calibration procedure.

2nd stage: A transport model based on the transient flow simulation is formed in order to check the calibrated values of the transport parameters resulting from the steady-state transport model. This check is carried out through the calibration procedure and if it leads to the conclusion that the values of parameters respond to reality, then the model can be used for forecasting seawater intrusion. Otherwise, the transport parameters are readjusted using the first transport model and are modified until the check through the second transport model leads to the expected results.

2.3. GIS-economic model

In this model, the electrical conductivity (EC) of groundwater (i.e. of irrigation water), resulted from the transient transport model, is integrated into a GIS environment (e.g. ArcGIS, MAPINFO, etc) in order to study the spatial patterns of EC in the study area. Hence, a set of contour maps can be generated – using spatial interpolation methods - to represent the levels of groundwater salinity for different time periods (e.g. 20, 30 or 50 years) under various agricultural management scenarios. Then, the average EC values are calculated for each plot/parcel and used together with spatially referenced crop data aiming to determine the spatial effects of salinization to crop productivity. In this context, a set of water-salinity crop-production functions can be used following the guidelines of Ayers and Westcot (1976). The economic impact of this productivity loss in each plot/parcel is also estimated based on local/regional agro-economic indicators (or actual data when available). The results of this analysis can be displayed on thematic maps attempting to show the regional variations of relative crop yield (as affected by soil salinity) and, consequently, the regional variations of agricultural productivity costs (i.e. loss of farmers' income as compared to the current situation). The outcome of this analysis may serve, among others, as a GIS-based model for assessing the vulnerability of the study area (coastal aquifer) to seawater intrusion.

3. Results

The proposed methodology was applied in the coastal aquifer of N. Moudania, located in Northern Greece. In this area, groundwater is intensively used in order to meet the increased agricultural water needs and seawater intrusion constitutes a characteristic problem along the coastline (Siarkos and Latinopoulos, 2013). In this study, the groundwater modeling software GMS 8.1 was used. GMS, as a graphical interface and data visualization package, supports multiple groundwater models including MODFLOW and MT3DMS. Figure 2 illustrates an example of the groundwater modeling approach by presenting the results of the transport model, which is used to forecast seawater intrusion (chloride concentrations at the beginning and at the end of the simulation period). The results from the flow and transport simulation models are then entered into MapInfo Professional (version 9.0) for spatial analysis and mapping. Then, combining simulation results and actual agro-economic data (crop maps, regional production functions, regional economic indicators, etc) enables to estimate the future costs of seawater intrusion for a 30-year period (2014-2044). The results of this procedure are presented in Figure 3 as thematic maps of: (a) current (2014) and future relative (2044) crop yields, (b) annual agricultural productivity costs at the end of the 30-year period.

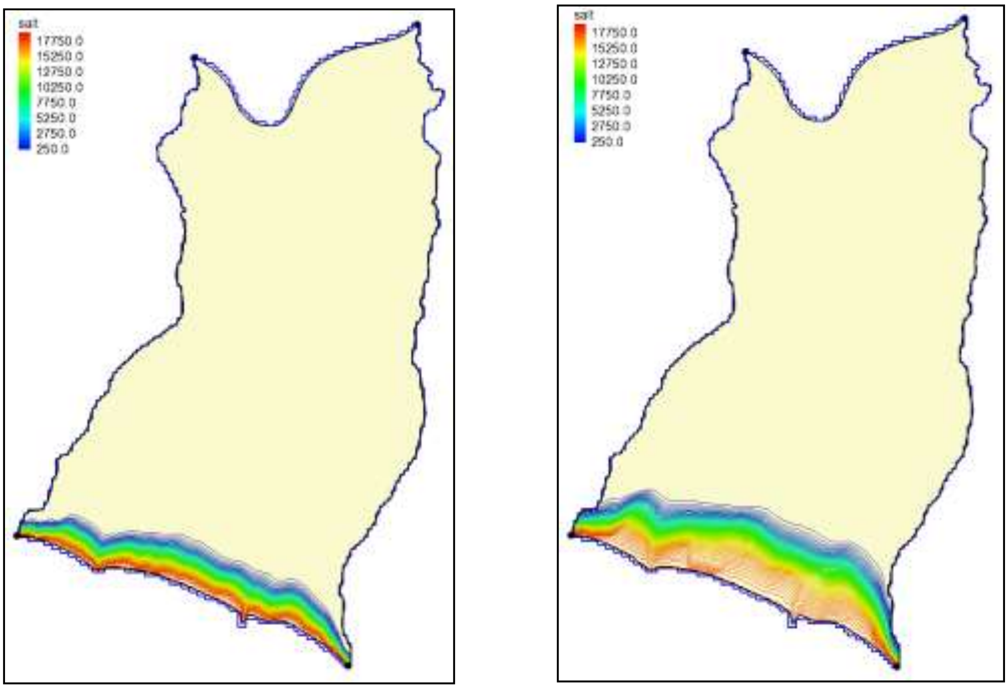

Figure 2: Seawater intrusion at the beginning (left) and the end (right) of the simulation period.

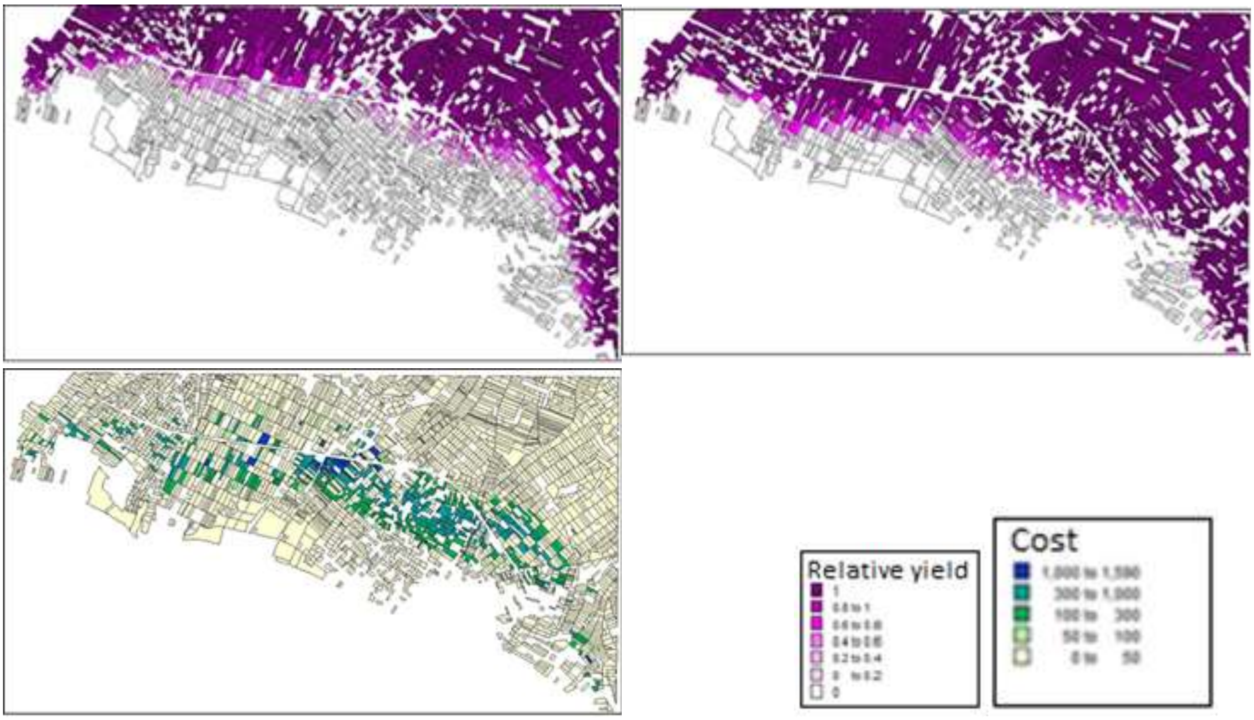

Figure 3: Current (up, left) and future (up, right) relative crop yields and salinization costs (down).

4. Conclusions

In this study, numerical models are coupled with a GIS-based economic model in order to estimate the influence of seawater intrusion in agricultural productivity. As it can been concluded, the developed methodological framework constitutes a valuable modeling tool, which can be used both for projection and management. Its application in the N. Moudania aquifer shows that the problem of seawater intrusion, if the current regional water use practices continue, will be intensified in the future incurring high costs for society in terms of both domestic water supply and irrigated agriculture.

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