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Title: Seawater intrusion in karst, coastal aquifers: current challenges and future scenarios in the Taranto area (southern Italy)

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Abstract: Arid and semi-arid regions in the Mediterranean area are characterized by very complex hydrogeological systems, about which limited knowledge is available due to the lack of data. Furthermore, in these areas management of freshwater resources, mostly stored in karst, coastal aquifers, is challenging if proper methods are not applied to detect possible critical situations of groundwater scarcity and deterioration.

In the area of the gulf of Taranto (southern Italy) these issues are particularly pressing, as the deep, karst aquifer is the only available source of freshwater and satisfies most of the human water-related activities. For these reasons, preserving this system through targeted management policies involves both natural and socio-economic aspects.

A variable-density flow model was developed with SEAWAT to depict the "current" status of the saltwater intrusion within the aquifer. No appreciable effects were found to occur on the solution of the transport component due to different mathematical conceptualizations of the flow boundary conditions along the coast. Groundwater salinity stratification was found to occur, with salinity levels higher than a reference threshold within a strip spreading from 4 to 7 km from the coast in the deep aquifer. Such phenomenon would also affect some submarine freshwater springs, like the Citro Galeso.

A sensitivity analysis was used on two simulated scenarios with decreased rainfall and increased pumping. Differences in the concentration field with respect to the "current" status can be appreciated most in zones where the hydraulic conductivity of the deep aquifer is higher and the amount of these differences depends on flow boundary conditions. Furthermore, the presence of freshwater springs was found to influence the concentration field in different scenarios, causing an opposite behavior at shallow and higher depths.

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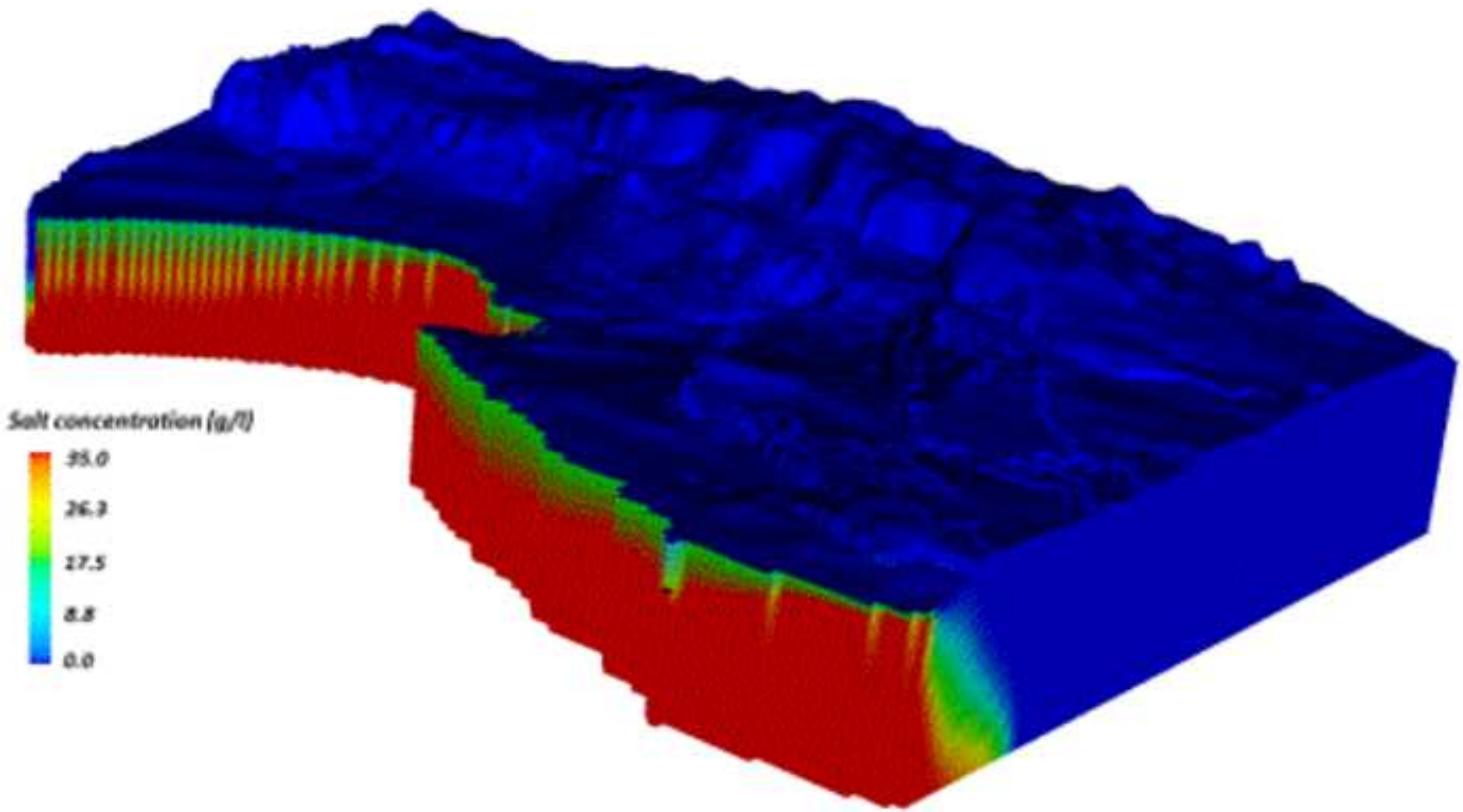
***Cover Letter**

This paper presents a solute transport model, which aims at assessing the occurrence of the saltwater intrusion phenomenon in the karst, coastal aquifer of the Taranto area (southern Italy).

In the study area, this issue is particularly pressing, as the deep, karst aquifer is the only available source of freshwater and satisfies most of the human water-related activities. For this reason, preserving such system through targeted management policies involves both natural and socio-economic aspects. In this framework, the scope of the analysis presented in this paper is to address and support planning and management decisions, in order to prevent and restore critical situations, with particular attention to groundwater quality of submarine freshwater springs.

A sensitivity analysis was further carried on to show the effects of different scenarios of natural forcing and human interactions, i.e., decreasing rainfall recharge and increasing groundwater abstraction, which are particularly severe in semi-arid, coastal areas where growing population pressure might cause notable groundwater level declines and deterioration in water quality.

*Graphical Abstract



***Highlights (for review)**

- Assessing saltwater intrusion phenomenon in a karst, coastal aquifer for management issues
- Assessing groundwater quality of freshwater springs
- Testing the effects of different kinds of boundary conditions to model the groundwater flow component
- Testing the effects of different scenarios of natural forcing and human interactions

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Seawater intrusion in karst, coastal aquifers: current challenges and future scenarios in the Taranto area (southern Italy)

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Abstract

Arid and semi-arid regions in the Mediterranean area are characterized by very complex hydrogeological systems, about which limited knowledge is available due to the lack of data. Furthermore, in these areas management of freshwater resources, mostly stored in karst, coastal aquifers, is challenging if proper methods are not applied to detect possible critical situations of groundwater scarcity and deterioration.

In the area of the gulf of Taranto (southern Italy) these issues are particularly pressing, as the deep, karst aquifer is the only available source of freshwater and satisfies most of the human water-related activities. For these reasons, preserving this system through targeted management policies involves both natural and socio-economic aspects.

A variable-density flow model was developed with SEAWAT to depict the "current" status of the saltwater intrusion within the aquifer. No appreciable effects were found to occur on the solution of the transport component due to different mathematical conceptualizations of the flow boundary conditions along the coast. Groundwater salinity stratification was found to occur, with salinity levels higher than a reference threshold within a strip spreading from 4 to 7 km from the coast in the deep aquifer. Such phenomenon would also affect some submarine freshwater springs, like the Citro Galeso.

A sensitivity analysis was used on two simulated scenarios with decreased rainfall and increased pumping. Differences in the concentration field with respect to the "current" status can be appreciated most in zones where the hydraulic conductivity of the deep aquifer is higher and the amount of these differences depends on flow boundary conditions. Furthermore, the presence of freshwater springs was found to influence the concentration field in different scenarios, causing an opposite behavior at shallow and higher depths.

Keywords: saltwater intrusion, karst coastal aquifers, Mediterranean area, sensitivity analysis, groundwater management

1. Introduction

Europe has a long coastline, both along the continent and islands, with areas that have been settled by humans since a long time ago. In the southern parts of Europe, especially along the Mediterranean shore, human water-related activities (e.g., irrigated agriculture and tourism) have largely increased freshwater demand in the 20th century; for instance, in southern Italy, about 45% of the total population is living in coastal areas settled since the mid-20th century (Custodio, 2010). In these areas available surface-water resources are often scarce or nonexistent making coastal aquifers important as they are often the only available freshwater resource for irrigation, tourism and other human activities. Subsequently, intensive exploitation of groundwater, and mismanagement have caused additional upset of the natural balance between surface water, groundwater, and seawater. This is particularly true for carbonate massifs, which are common along the European Mediterranean coast.

As a consequence, salinity problems in Mediterranean coastal areas have attracted the attention of researchers, professionals, and specialists in recent decades.

Geochemical and geophysical surveys are often used to map and monitor saltwater intrusion in coastal aquifers (see, e.g., Bouderbala, 2015 and references therein). Proper management of saltwater intrusion problems requires good knowledge of the aquifer system and the ability to forecast its future behavior under different scenarios of natural forcing and human interactions (Werner et al., 2012; Lambeck et al., 2011; Green and MacQuarrie, 2014; Okello et al., 2015). In this regard, numerical simulation is a commonly used tool to investigate saltwater intrusion in coastal aquifers and to assess alternative groundwater resource-management scenarios (Bear et al., 1999). Amongst available modeling approaches, variable-density groundwater flow models that track saltwater movement may be divided into interface models and dispersive solute-transport models (Bakker et al., 2013). In interface models, freshwater and seawater are separated by a sharp interface (see, e.g., Bakker et al., 2013; De Filippis et al., 2015; Masciopinto, 2006; Mehdizadeh et al., 2015), while in dispersive solute-transport models (e.g., SUTRA, Voss and Provost, 2010; FEFLOW, Diersch, 2014; SEAWAT, Guo and Langevin, 2002), fluid density can vary continuously or from cell to cell in a model domain. Generally, a 3D saltwater intrusion model is not simple to apply due to the complexity of the involved physical processes and the basin geometry, the scarcity of adequate hydrogeological field data, and the heterogeneity of hydrogeological characteristics (Dentoni et al., 2015).

This paper takes into account the implications on the groundwater quality and availability, related to the saltwater intrusion as a natural- and human-induced phenomenon. Here a large-scale variable-density flow model is proposed for the aquifer system of the province of Taranto with both technical-scientific and management-oriented aims. The numerical code SEAWAT was applied to develop a dispersive solute-transport model to assess the occurrence and extent of the saltwater intrusion in the aquifer of the Jonian coastal area of the Taranto province (southern Italy).

From a scientific point of view, the focus is on the sensitivity of model results to different boundary conditions along the coast, which are not easy to determine due to the complex geological setting. Such a complexity is very high in the most environmentally critical regions of Mar Piccolo and Mar Grande, two shallow lagoon-like basins of fundamental importance for ecosystem and socio-economic contexts (mussels cultivation). In particular, the main objective is to improve the reliability of the estimated extent of saline intrusion both horizontally (inland) and vertically (among and inside individual hydrostratigraphic units). From a practical point of view, the model is also used to assess the possible effects that changes related to climate variability and human pressure have on these freshwater underground resources.

2. Study area and objectives

This study focuses on a coastal, multi-layered aquifer located in southern Italy. The study area (Figure 1) extends over about 2800 km^2 and includes most of the province of Taranto (40°25′05″ N 17°14′27″ E), between the Murge plateau to the north and the Jonian coast to the south.

Figure 1. Location of the study area. The color map refers to the Digital Terrain Model (DTM, horizontal spatial resolution of 500 m). The dashed areas delineate the contaminated Site of National Interest, as declared by the Italian Ministerial Decree dated September 20th 2001. Boundary conditions along the northern, western and eastern boundaries are highlighted (modified after De Filippis et al., 2015).

Within the study area, the zones near the city of Taranto have been the subject of interest for the scientific community in recent decades (see, e.g., Alabiso et al., 1997; Cardellicchio et al., 2007; Cavallo and Stabili, 2002; De Serio et al., 2007; Storelli and Marcotrigiano, 2000; Umgiesser et al., 2007; Zuffianò et al., 2015). As already assessed in previous studies (see, e.g., Giudici et al., 2012; De Filippis et al., 2013; De Filippis et al., 2015), the Taranto area is one of the most sensitive coastal regions of southern Italy to seawater intrusion, because of the complex hydrostratigraphic configuration and the presence of highly water-demanding human activities (e.g., industry, agriculture). The presence of several kinds of polluting activities (i.e., commercial, shipping, industrial and urban-related) occurring near Taranto is noteworthy and makes such area "at high risk of environmental crisis" (Italian Ministerial Decree dated September 20th 2001, dashed areas in Figure 1) and an ideal target for scientific research. One of the most critical areas of concern is the highly vulnerable Mar Piccolo, which corresponds to a complex ecosystem, with strong interactions among several environmental components, including groundwater due to the presence of relevant submarine freshwater springs. For this reason, the study of this area was conducted with a multidisciplinary approach by several research units within the Flagship Project RITMARE (the Italian research for the sea).

In this paper, the relationship between groundwater and saltwater in the study area is analyzed with particular attention to three main factors: 1) the occurrence of high-flux freshwater springs within the Mar Piccolo seawater basin, 2) the presence of large fractures in karst formations, a characteristic which is shared with most of the European Mediterranean coast, and 3) extensive withdrawals and/or climate changes which contribute to modification of the equilibrium between fresh- and salt-water.

3. Methods

The aims highlighted in the previous section were achieved by developing a numerical model which solves the coupled equations for groundwater flow and salt transport, by using a dispersive solute-transport approach.

Among dispersive solute-transport models, some programs (e.g., SUTRA and FEFLOW) solve the flow and transport equations simultaneously, while others (e.g., SEAWAT) have the option to solve the transport equation separately using particle-based or finite-difference methods and compute a new flow field to represent a changing density field. The latter approach and the SEAWAT (Langevin et al., 2008) code are used in this paper.

3.1 Groundwater model setup

The geological, hydrodynamic and numerical features set to represent the aquifer system of the Taranto area with respect to groundwater dynamics are described in De Filippis et al. (2015).

The multi-layered aquifer system is characterized by a heterogeneous hydrogeological structure, which consists of the following hydrostratigraphic units (HUs):

- Cont&Terr HU, characterized by calcarenitic terraced deposits, covered by recent Continental deposits with generally low permeability;
- SubCl HU, made of impermeable Subappennine clays;
- GCalc HU, characterized by coarse-grained Gravina calcarenites containing shallow aquifers with limited extent;
- Gal HU, made of fine-grained and very compact limestones, marls and deposits of sandy clays belonging to the Galatone formation;
- AltLim HU, mostly corresponding to the karst Altamura limestone and containing the deep aquifer of the Salento peninsula. This HU is the most noteworthy, due to its karst features and because the deep aquifer feeds the submarine springs in the Mar Piccolo. Furthermore, it is the most susceptible to issues related to groundwater deficiency, due to climate changes and exploitation for human water-related activities.

The study area (Figure 1) was discretized using square cells with 500 m side-length in the horizontal plane. The vertical discretization extends from the ground surface, as determined by a Digital Terrain Model (DTM - Figure 1) down to 500 m below the mean sea level (msl). Notice that the ground surface varies in the study area from the sea level up to more than 500 m above msl in the northern part of the domain. 14 layers with variable thicknesses have been introduced (Figure 2).

The uppermost four layers correspond, from top to bottom, to the Cont&Terr, SubCl, GCalc and Gal HUs, while the AltLim HU was discretized in 10 layers (hereinafter referred to as AltLim HU_1, AltLim HU_2 and so on, from top down). This choice is due to the variable thickness of the

AltLim HU in the study area, from about 300 m along the coastline to more than 1000 m inland, where this HU widely outcrops (see Figure 2). Moreover, the saltwater intrusion particularly affects the AltLim HU and the additional vertical discretization is needed to improve the representation of this phenomenon.

Figure 2. Vertical discretization of the aquifer system - (top) east side view; (bottom) west side view.

The four uppermost layers were considered homogeneous, with hydraulic conductivities set to 10^{-4} m/s for the Cont&Terr and GCalc HUs and 10^{-6} m/s for the SubCl and Gal HUs. Hydraulic heterogeneity of the AltLim HU was taken into account by estimating its conductivity through a direct calibration method as implemented in the Comparison Model Method (CMM) embedded within the YAGMod computer code, whose application to the same case study is presented in detail by De Filippis et al. (2015).

For the aims of this discussion, the hydraulic conductivity field shown in Figure 3 is used for the AltLim HU and the related model layers. This field was estimated based on the available head observations and defined source terms, as reported in De Filippis et al. (2015), and was obtained by applying a sharp interface approach (specifically the Ghyben-Herzberg approximation) for the calculation of the saturated thickness of the deep aquifer.

Figure 3. (a) Hydraulic conductivity field of the AltLim HU estimated with the Comparison Model Method (modified after De Filippis et al., 2015). (b) Locations of the salinity vertical profiles drawn in Figure 6 (symbols), of the profiles of the cross sections shown in Figure 7 (lines) and of the inner area mapped in Figures 5 and 8 (red rectangle).

The conductivity field obtained for the AltLim HU (Figure 3) shows a large spatial variability, especially along the coastline, with values spanning over four orders of magnitude. The lowest values (of the order of 10^{-4} m/s) were calculated inland and along the extremely western Jonian coast, while the highest ones (of the order of 10^{-1} m/s) were along the central and eastern coastline.

Aquifer recharge and groundwater extractions estimated by De Filippis et al. (2015) are used. In particular, about 37% of the total annual rainfall was estimated to infiltrate over the study area, corresponding to a total inflow of almost 19 m^3/s. This areal recharge term was applied to the uppermost active model layer. Furthermore, total extracted flow rates over the whole Province for irrigation (1.33 m^3/s), industrial (0.86 m^3/s) and drinking (0.25 m^3/s) purposes were distributed according to different criteria (i.e., the land use map, the water need of different crops or the size of industries). The estimated withdrawal terms were equally distributed among layers from AltLim HU_1 to AltLim HU_10, as the deep aquifer is the most exploited at the large scale for human water needs (i.e., irrigation, industry, drinking water). As a further extraction term, terrestrial and submarine freshwater springs were simulated as discharging drains. Some of them, mostly located in the plain north-west of Taranto, are fed by the shallow aquifer in the Cont&Terr HU, with mean flow rates of the order of 0.1 m^3/s, except for the Tara spring, which is fed by the deep aquifer, whose measured flow rate is more than 3 m^3/s, and which feeds the Ilva plant, the steelwork with the highest output capacity in Europe. The springs located near Taranto are fed by the deep aquifer, with highest flow rates up to 0.75 m^3/s (see De Filippis et al., 2015 for details). For the development of the numerical model, drains conductances were set as explained below.

No-flow boundaries were imposed along the left and right boundaries of the domain. An inflow of about 1.13 m^3/s was estimated to occur from the Murge plateau, by multiplying the mean annual rainfall (about 600 mm/year) and the estimated recharge area identified by using measurements of water level under static conditions (Regione Puglia, 2009) beyond the northern boundary of the study area. This total inflow was simulated through recharge wells located within 75 cells in the central part of the northern boundary, with equal flow rates equally distributed among model layers

AltLim HU_1 to AltLim HU_10 (as the AltLim HU outcrops in that zone). No flow was imposed at the remaining cells of the same border (see Figure 1).

Boundary conditions along the coastline were conceptualized in two different ways to assess possible effects on the simulation of the transport process. In the first configuration (hereinafter referred to as gw_model1) Dirichlet boundary conditions were set along the coastline in all model layers with head values equal to the msl (hydraulic contact is assumed to occur at the coast). In the second configuration (hereinafter referred to as gw_model2) the same Dirichlet boundary conditions were set along the coastline in model layers Cont&Terr and SubCl HUs, while no-flow boundary conditions were applied to the underlying layers, due to the presence of a normal fault in the zone of the submarine springs within the Mar Piccolo, which could halt groundwater flow in the AltLim HU, at least at shallow depths, because a direct contact between such HU and the poorly permeable Subappennine clays would occur (Figure 4). With respect to what was done in De Filippis et al. (2015), here drain conductances were further decreased by ¼ to avoid negative hydraulic heads (i.e., below the msl) at some locations due to particular boundary conditions in gw_model1.

Figure 4. Schematic hydrogeological sketch nearby the Galeso spring (modified after Margiotta et al., 2010).

The groundwater flow model was run over six months at steady-state using three stress periods with time steps of two months. As mentioned in Guo and Langevin (2002), there is no option to run the transport model as steady-state in SEAWAT, so the transport component is run in transient conditions, even if the flow is specified as steady-state.

To reduce the model complexity and avoid many dry cells and numerical difficulties, the simulation was run with all layers under confined conditions. An unconfined simulation was performed to check the mass balance terms and showed good agreement between the confined and unconfined models. For example, the difference between the net aquifer balance simulated under confined and unconfined conditions is of the order of 10^{-5} m^3/s for gw_model1 and 10^{-6} m^3/s for gw_model2.

3.2 Transport model setup

In this work, an implicit finite-difference scheme is used, so that the flow and transport equations are repeatedly solved several times within the same time step until the maximum difference in fluid density between consecutive iterations is less than a user-specified tolerance, set to 10^{-6} kg/m^3.

The molecular diffusion coefficient was set to 10^{-6} m^2/s for each model layer: the longitudinal dispersivity (α_L) was assigned a value of 50 m, i.e., one tenth of the spatial horizontal discretization (Gelhar et al., 1992), the ratios between α_L and the horizontal and vertical transverse dispersivities were assigned the values of 0.1 and 0.01, respectively (Zheng and Wang, 1999).

Furthermore, both the advection and dispersion terms of the transport equation contain the effective porosity of the medium. Here the following values were assumed: 0.3 for Cont&Terr and GCalc HUs, 0.5 for SubCl and Gal HUs and 0.1 for the AltLim HU.

To calculate the sink/source terms, concentration must be defined for each sink/source of the groundwater model. Zero concentration was specified for the recharge from rainfall (i.e., Dirichlet transport boundary condition), while in the remaining sinks/sources cells concentration could vary freely, according to what was calculated through the transport equation.

Dirichlet transport boundary conditions were defined along the coastline for all layers by specifying a concentration of 35 g/L to represent seawater.

Both groundwater and transport models share the same time-discretization scheme, but the transport equation is solved under transient conditions and repeatedly within a time-step, as the transport solution has either stability constraints and/or accuracy requirements that are more restrictive than those for the flow solution. Each time-step is further divided into smaller transport-steps, during which heads are constant.

4. Results and scenarios

The two models developed with two different configurations of the flow component (gw_model1 and gw_model2) were used to test possible effects of flow boundary conditions on the transport model solution. In this regard, no remarkable differences were found in the simulated concentration field. As an example, in Figure 5 the 0.5 g/L salinity contour lines are drawn for both configurations (red line for gw_model1 and black line for gw_model2) and for different model layers in the inner zone shown in Figure 3.

Figure 5. Contour lines for a salinity of 0.5 g/L simulated with configurations set in gw_model1 (red lines) and gw_model2 (black lines), for the following model layers: (a) GCalc HU, (b) AltLim HU_1, (c) AltLim HU_5, (d) AltLim HU_10. Zoom of the inner area bounded in Figure 3.

Considering the contour line of 0.5 g/L as a reference threshold for salinity in groundwater (Cotecchia et al., 2005), we can assess that the saltwater intrusion phenomenon should affect also porous aquifers hosted in the GCalc HU. Focusing on the deep aquifer hosted in the AltLim HU, we can infer that the spreading of intrusion gradually advances towards inland, from about 4 km from the coast in AltLim HU_1 to about 7 km from the coast in AltLim HU_10.

Figure 6 shows three salinity vertical profiles at three different locations near the coast, while Figure 7 shows two 2D sections, where the locations of some drains are highlighted.

Figure 6. Salinity profiles along vertical grid columns at locations 1, 2 and 3 shown in Figure 3. Values simulated with the gw_model2 configuration.

Figure 7. 2D sections along the profiles drawn in Figure 3 (20-fold vertical exaggeration): (top) WE section; (bottom) SW-NE section. Values simulated with the gw_model2 configuration.

The salinity profiles shown in Figure 6 refer to locations inside the industrial and military area (Location 1), near the Tara terrestrial spring (Location 2) and in correspondence of the Citro Galeso submarine spring (Location 3). According to these profiles, there is an intense salinity stratification, with lower values in the upper model layers (from Cont&Terr HU to Gal HU) and concentration increasing gradually from AltLim HU_1 to AltLim HU_10. This conclusion is in accordance with previous works (see, e.g., Cotecchia et al., 2005 and references therein).

The cross sections shown in Figure 7 can help to estimate the extent of the saline plume through the model layers and with respect to the coastline. The locations of some submarine springs located within the Mar Piccolo are also highlighted, to draw conclusions about the quality of the outflowing freshwater. In this regard, the salt concentration simulated by the model at the elevation of the Galeso spring is about 1.2 g/L, which is within the interval reported in Umgiesser et al. (2007). As a further check, also the fraction of seawater was calculated at the elevation of the Galeso spring itself, as defined in Zuffianò et al. (2015), i.e., the relative concentration of chloride ions (mol/L) with respect to that of freshwater and saltwater. A value of 3.4% was obtained which, considering the model scale used in the analysis presented here, is in good agreement with 5% calculated in Zuffianò et al. (2015), based on field measurements and laboratory analysis.

Finally, a sensitivity analysis was performed to assess the effects of changing stresses on the model budgets. In particular, two scenarios were defined, decreasing rainfall recharge by 10% and increasing irrigation withdrawals by 25%, according to forecasts of the European Environment Agency (EEA) for the 21st century. Hereinafter the "current" scenario will be referred as "undisturbed conditions", while the other two scenarios will be identified as "decreased recharge" and "increased pumping".

Differences in the simulated concentration fields are difficult to show with color maps, therefore in Figure 8 the contour lines corresponding to a concentration of 10 g/L and 30 g/L are drawn for AltLimHU_1 and AltLim HU_7, respectively, for both gw_model1 and gw_model2, to show the effects of decreased recharge and increased pumping. The main differences in the simulated concentration can be observed in areas where the hydraulic conductivity of the AltLim HUs (see Figure 3) is higher, as here more recirculation can occur. Moreover, such differences are more evident for gw_model1 due to the particular flow boundary condition which further enhances this mechanism.

Figure 8. Salinity contour lines simulated for the three different scenarios: (a) 10 g/L for AltLim HU_1 and gw_model1; (b) 30 g/L for AltLim HU_7 and gw_model1; (c) 10 g/L for AltLim HU_1 and gw_model2; (d) 30 g/L for AltLim HU_7 and gw_model2. Zoom over the area bounded in Figure 3.

The salinity profiles shown in Figure 9 are evaluated at location 1 and refer to the three different scenarios.

Figure 9. Salinity profiles along vertical grid columns at location 1 shown in Figure 3. Values simulated with gw_model1 and gw_model2 configurations for the three different scenarios.

Figure 9 clearly shows that the effects of decreasing recharge and increasing pumping is reverse above and below a certain depth around 200 m below the msl. In fact, from the uppermost layer to the AltLim HU_7 (in gw_model1) or AltLim HU_8 (in gw_model2), the salinity levels simulated after decreasing recharge and increasing pumping are lower than those estimated under undisturbed condition. The major differences can be found within the AltLim HU_1 layer, probably due to the presence of drains, whose flow rates are lower due to a decrease in the hydraulic head. As an example, the salt concentration calculated in gw_model2 for the two scenarios is about 0.9 g/L at the location of the Citro Galeso spring, with respect to 1.2 g/L simulated under undisturbed conditions. At greater depths decreasing recharge or increasing pumping cause the concentration values to increase and, as stated before, differences with respect to the undisturbed conditions are more appreciable in gw_model1. Furthermore, the effects of decreased recharge and increased pumping are reverse according to depth and flow boundary conditions: in gw_model1, higher concentration values are simulated with decreased recharge at shallow depths and with increased pumping in the deepest layers and vice versa for gw_model2. This is mostly due to the effects of different boundary conditions on the increased pumping scenario: concentration values simulated with decreased recharge (see red profiles in Figure 9), indeed, do not show appreciable differences between gw_model1 and gw_model2, while remarkable differences arise for the increased pumping scenario. This is reasonable, as increased pumping has greater effects than decreased recharge on the simulated processes in the deep aquifer (AltLim HU_1 through AltLim HU_10), considering that rainfall infiltration occurs through a thick (about 100 m) impermeable layer (SubCl HU).

5. Conclusions

The recurrence of drought years, groundwater over-exploitation and the rise of water demand associated with growing population along the coasts might cause notable groundwater level declines and deterioration in water quality. In such areas, seawater intrusion has consequently occurred and advanced inland causing salinity problems. This represents a threat to agriculture and water resources as the coastal population mostly depends on groundwater for domestic use and irrigation. Therefore, management of water resources in the coastal aquifers of arid areas, like southern Italy, requires particular attention and sustainable management of groundwater is of paramount importance.

In this paper, the extent of the saltwater intrusion phenomenon was evaluated, especially focusing on the deep, karst aquifer of the Taranto area, which satisfies the main socio-economic activities (e.g., agriculture and industry) and feeds the most important freshwater springs of the Apulia region.

According to the developed variable-density flow model, a wide strip along the coast in the deep aquifer has salt concentration levels higher than the 0.5 g/L reference threshold. This strip spreads from about 4 km to about 7 km from the coast with increasing depth. Moreover, this model confirms the salinity stratification identified in some logs reported in the literature, as well as the fraction of seawater calculated for the Citro Galeso spring.

The model was run considering two different kinds of boundary conditions along the coast for the flow component, but had no remarkable effects on the transport solution.

A sensitivity analysis showed the effects of two possible future scenarios, representing respectively decreased recharge and increased pumping on the salt concentration field. Differences were found to be larger when using Dirichlet boundary conditions along the coast for the flow model and more significant in areas where the hydraulic conductivity of the deep aquifer is higher. Furthermore, the aquifer system was found to be negatively affected by these scenarios at great depths, i.e., higher salinity levels were simulated with decreased recharge and increased pumping below about 200 m depth with respect to the mean sea level, while the opposite was found at shallow depths. As an example, the salt concentration at the location of the Citro Galeso spring would be lower under perturbed conditions, so making "current" salinity values higher than those simulated with decreased recharge and increased pumping. Moreover, major differences with respect to undisturbed conditions were highlighted for the increased pumping scenario, which affects the deep aquifer much more than what decreased recharge does.

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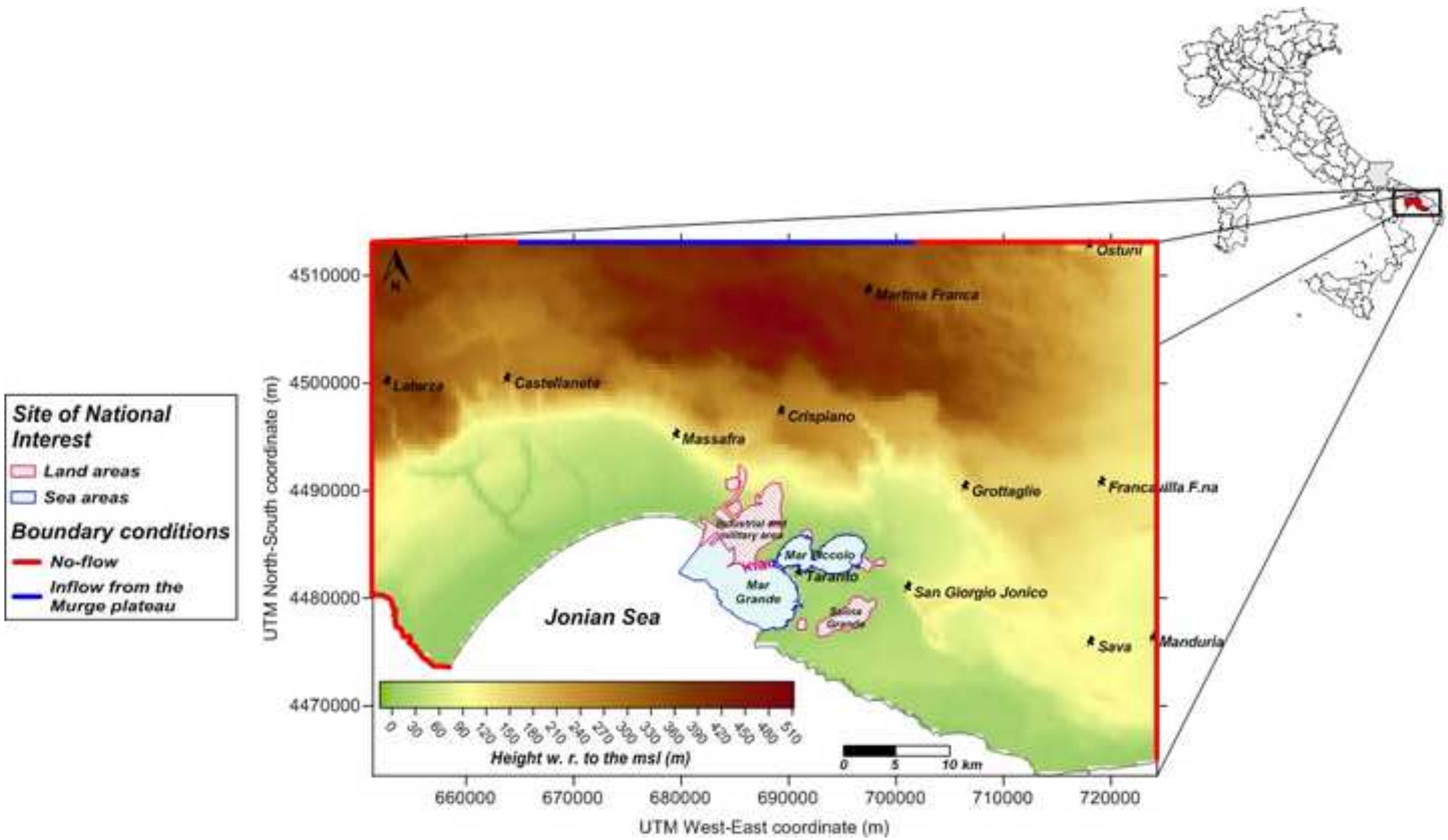

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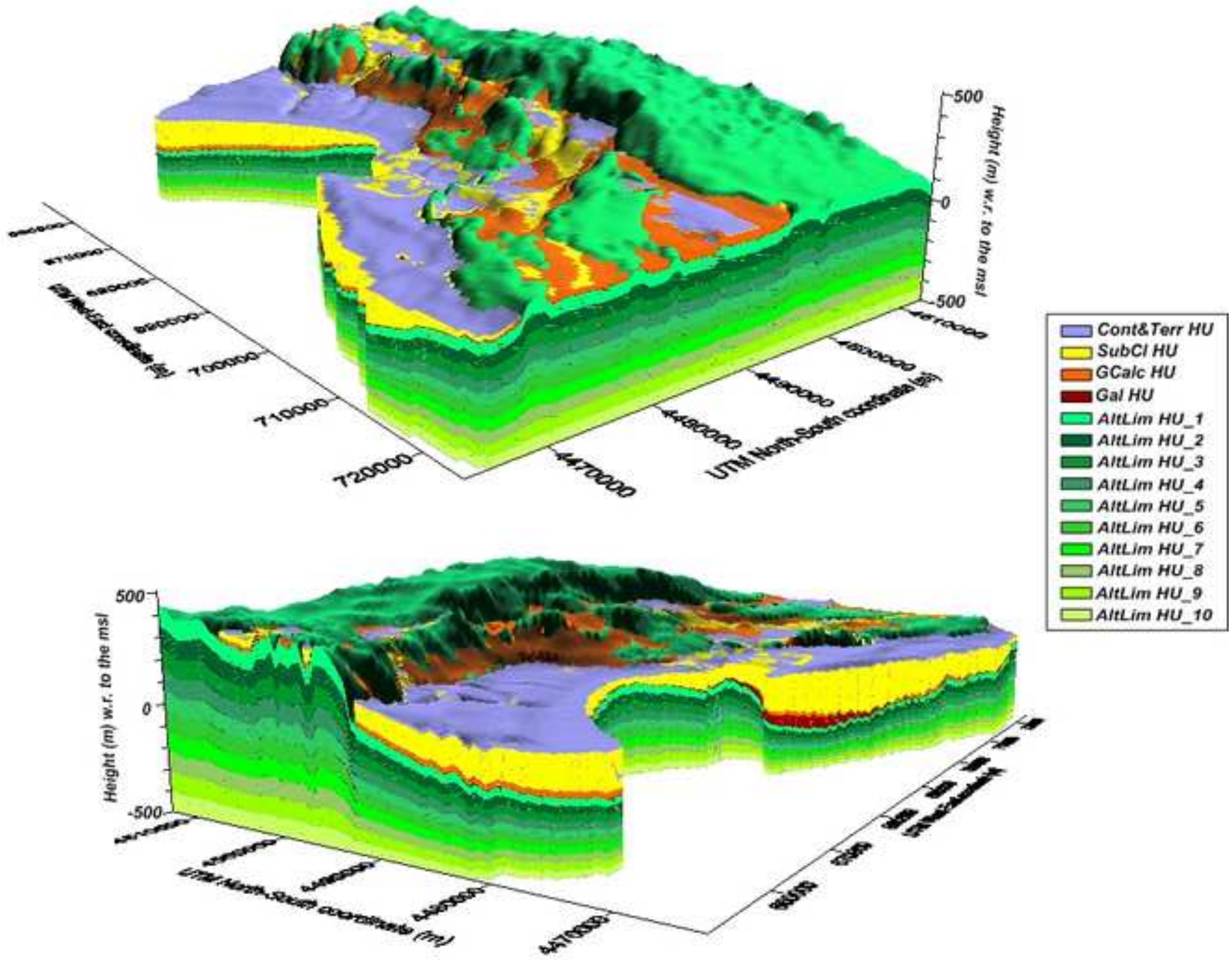

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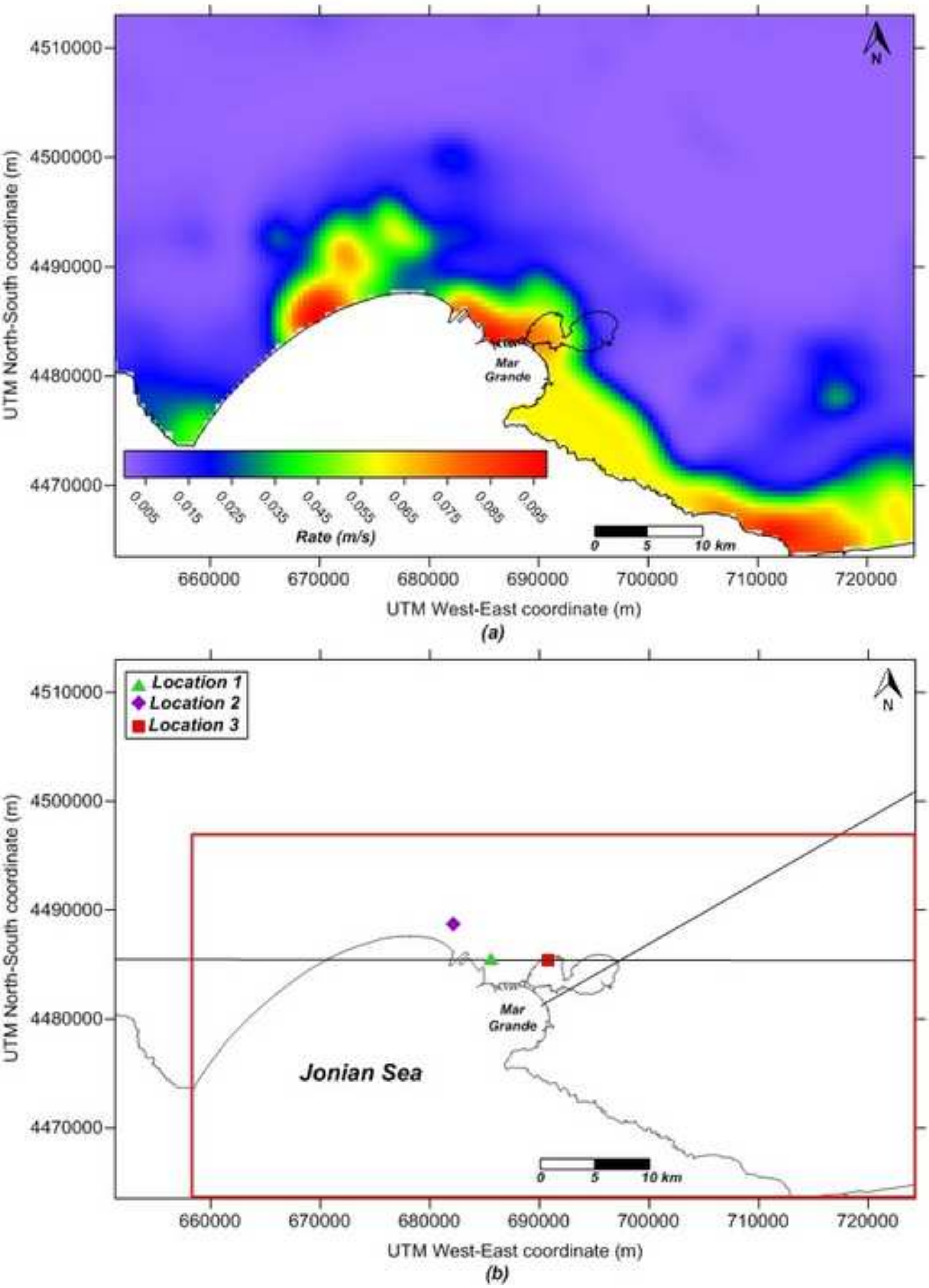

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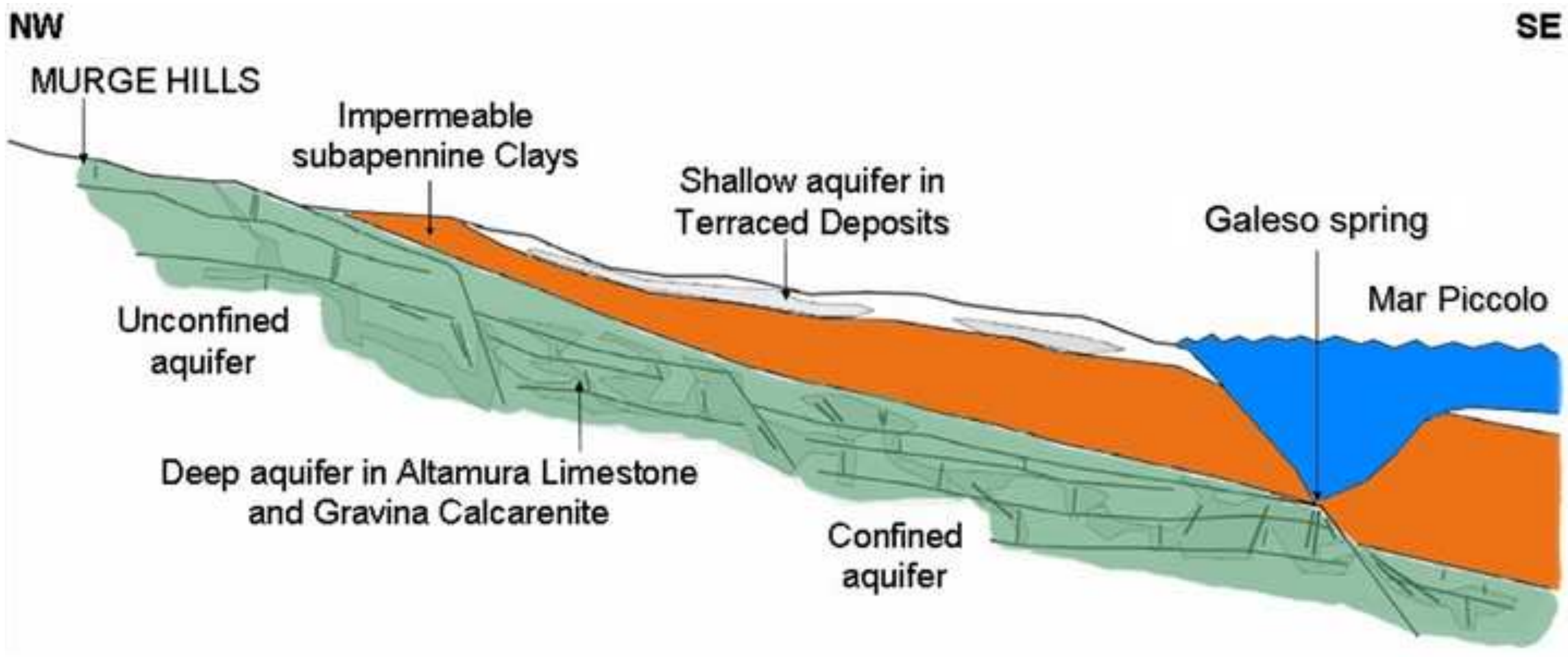

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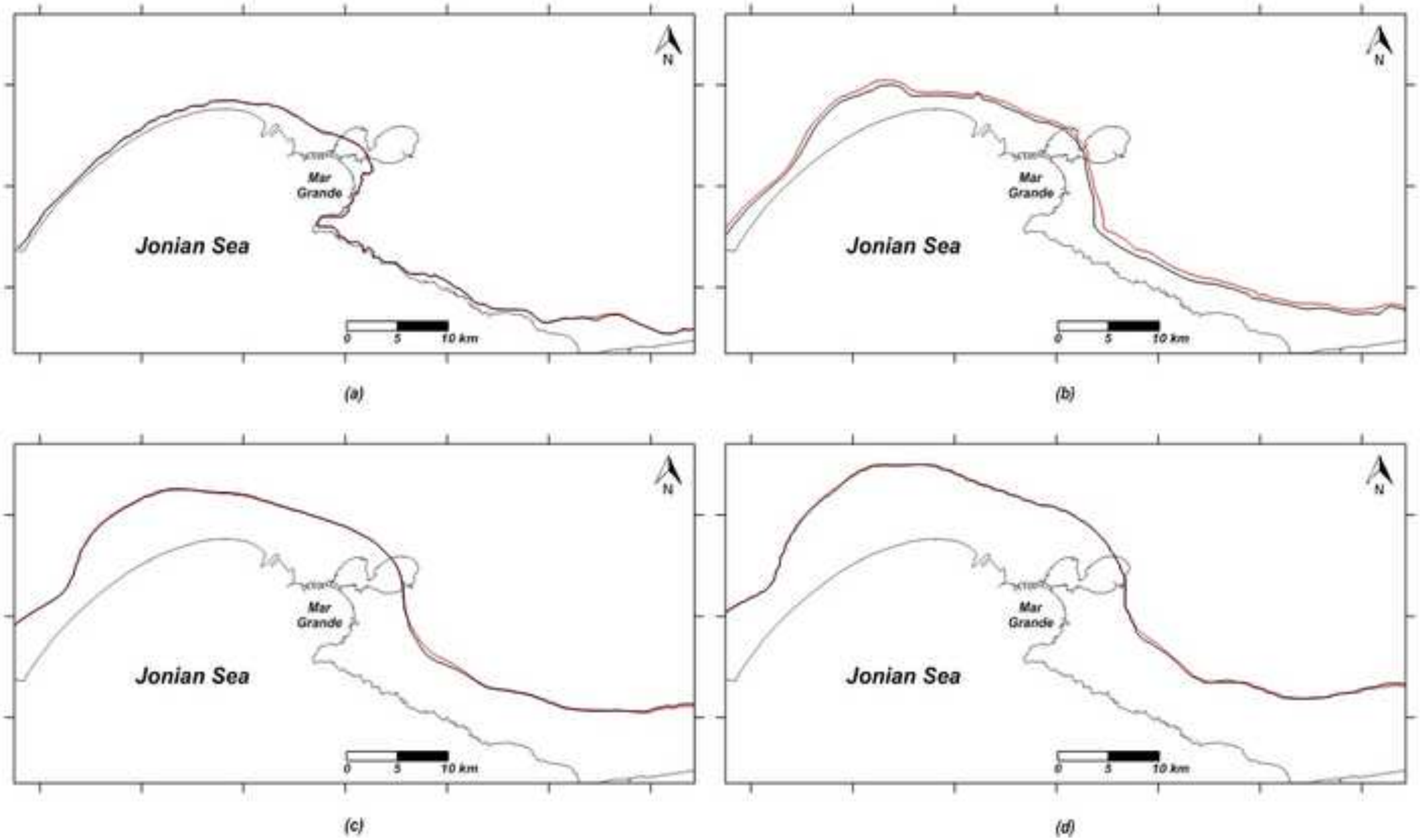

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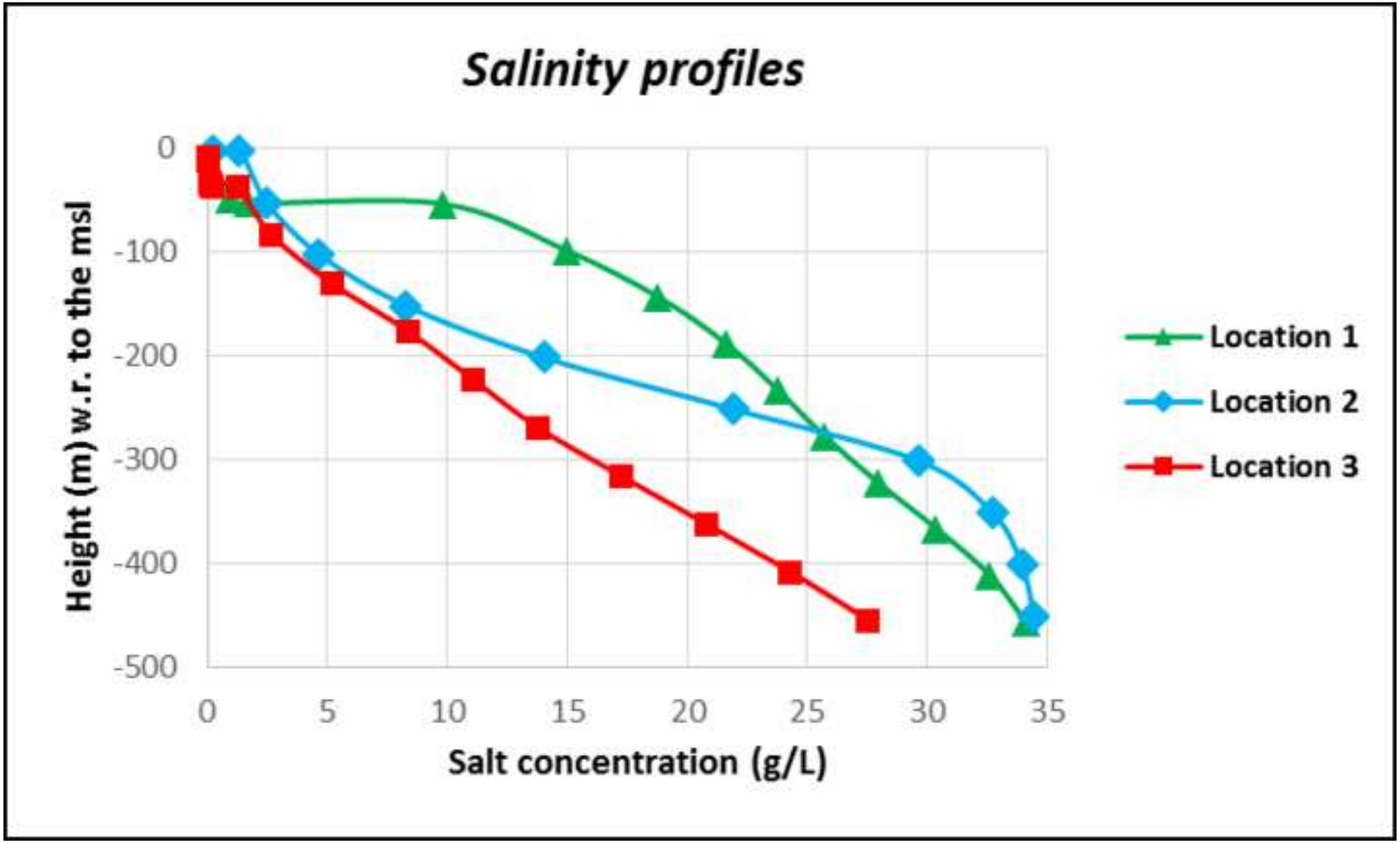

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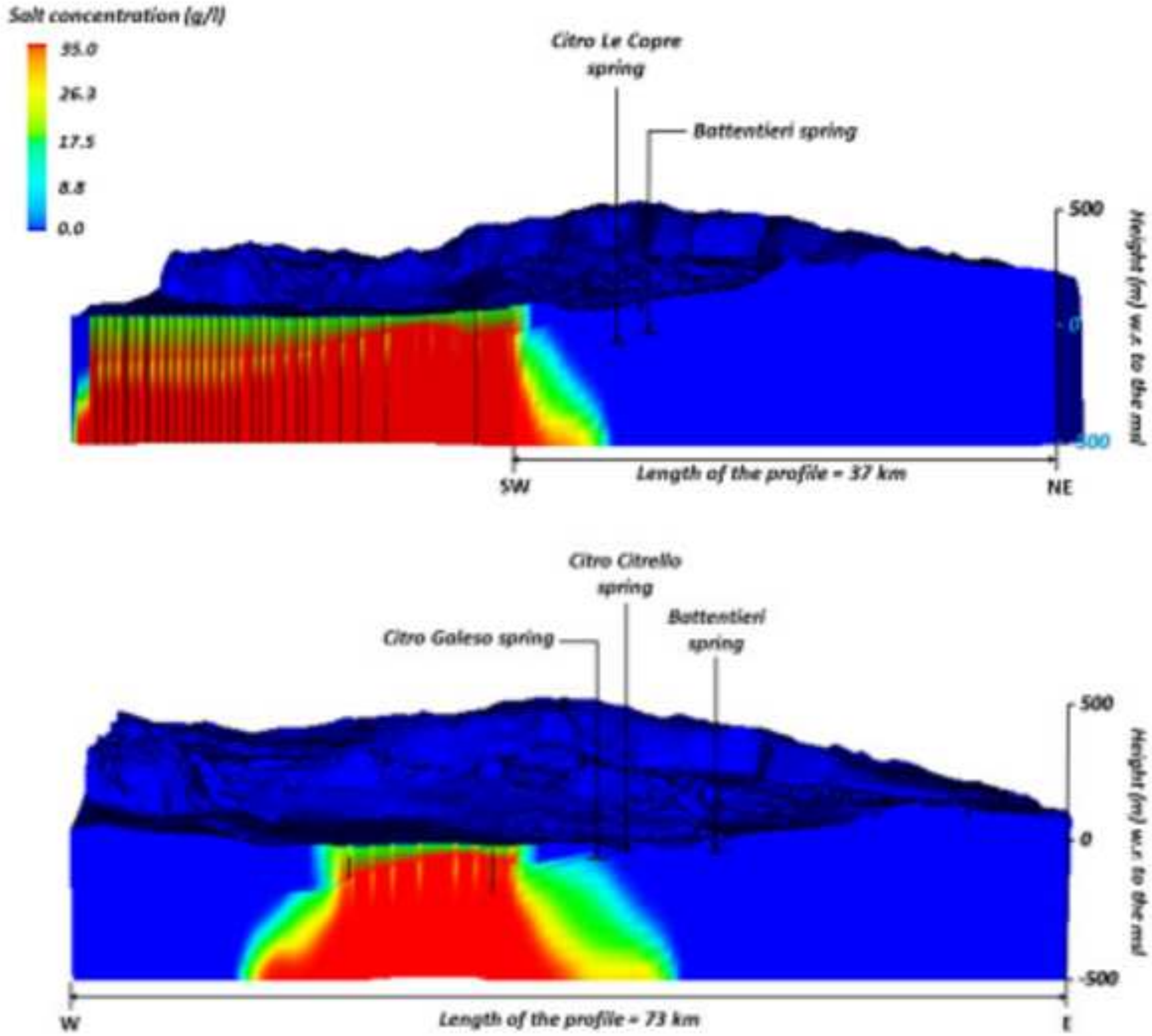

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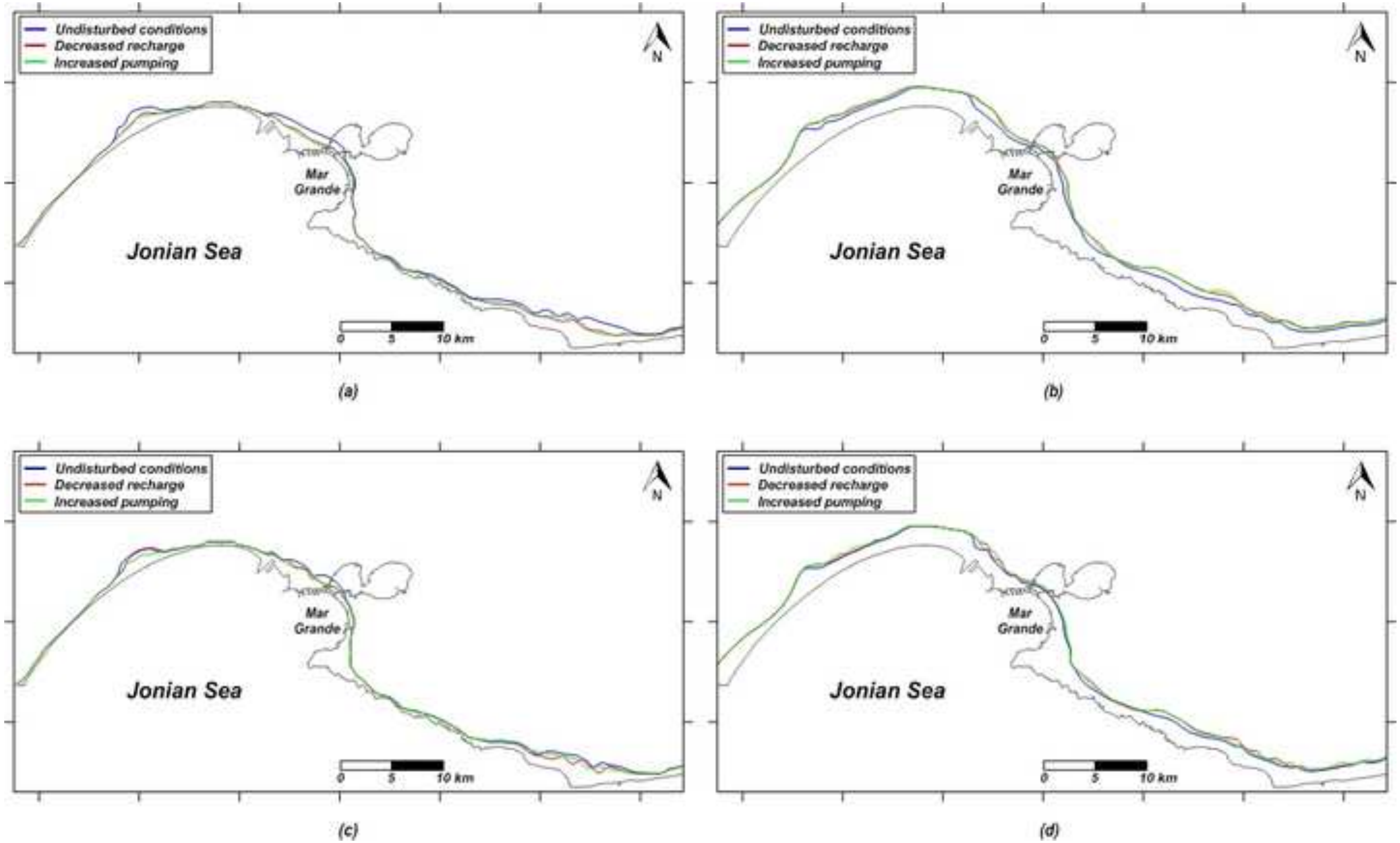

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