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SEAWATER INTRUSION MODELING UNDER CLIMATE AND ANTHROPOGENIC CHANGES IN THE METAPONTO COASTAL AQUIFER (BASILICATA, SOUTHERN ITALY)

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EXTENDED ABSTRACT

Gli acquiferi costieri rappresentano importanti serbatoi di risorse idriche sotterranee, ma allo stesso tempo sono sistemi idrogeologici estremamente vulnerabili ai fenomeni di inquinamento dovuti alla pressione antropica e agli effetti dei cambiamenti climatici (Post, 2005). Il problema idrogeologico più tipico per gli acquiferi costieri è l'intrusione salina. Tale fenomeno rende le acque sotterranee inadatte all'approvvigionamento idrico per usi potabili e irrigui e impatta sugli ecosistemi costieri alterando la chimica del suolo e riducendone la fertilità. Le cause più frequenti sono riconducibili all'eccessivo sfruttamento delle risorse idriche, che può essere aggravato dai cambiamenti climatici; inoltre, l'innalzamento del livello del mare può causare l'avanzamento del fronte salino verso l'interno. Considerando, inoltre, che le aree costiere sono generalmente molto importanti dal punto di vista economico, sociale e ambientale per la presenza di attività agricole e produttive, insediamenti residenziali e turistici, aree boschive e zone umide di elevato valore ecologico, appare evidente che questi sistemi debbano essere protetti (Erostate *et alii*, 2020).

Il fenomeno dell'intrusione salina è diffuso in molte zone costiere dell'Europa (Vanneuville *et alii*, 2012) e l'Italia è tra i Paesi più interessati (Romanazzi *et alii*, 2015).

Il presente studio si propone di modellare l'intrusione salina nell'acquifero costiero della piana di Metaponto (Basilicata, Italia meridionale) analizzando le caratteristiche geologiche, idrogeologiche e idrochimiche del sistema acquifero e fattori esterni come il sovrasfruttamento della risorsa idrica e gli effetti dei cambiamenti climatici. Nell'area di studio, l'approvvigionamento di acque sotterranee è fondamentale per lo sviluppo economico. La piana costiera di Metaponto rappresenta un'area rilevante per l'intera regione grazie alla crescente espansione turistica e a pratiche agricole intensive di pregio. L'impatto antropico gioca un ruolo significativo nel facilitare il processo di intrusione salina. Nell'ultimo secolo, le opere di sistemazione idraulica del Consorzio di Bonifica eseguite nelle aree paludose hanno favorito lo sviluppo della piana. Lo sfruttamento delle acque sotterranee per sostenere le attività agricole, turistiche e industriali, così come gli effetti dei cambiamenti climatici sul processo di ricarica, hanno fortemente impattato sulle condizioni idrogeologiche degli acquiferi dell'intera piana.

Attualmente, le risorse idriche sotterranee sono esposte al degrado quantitativo dovuto alle condizioni climatiche storicamente sfavorevoli, peggiorate dai cambiamenti climatici e dalla crescente domanda di acqua, e al degrado qualitativo causato anche dall'intrusione salina. Il tasso di infiltrazione efficace dell'area è infatti moderato a causa del clima tipicamente mediterraneo, caratterizzato da alte temperature e precipitazioni scarse concentrate soprattutto in inverno.

Sulla base dei risultati di analisi condotte nell'area, come le indagini idrogeologiche e idrochimiche, e della valutazione della vulnerabilità intrinseca all'intrusione salina, in questo lavoro sono state effettuate simulazioni numeriche per la parte di piana costiera più suscettibile all'intrusione. I dati geologici, idrogeologici, idrologici, climatici e idrochimici raccolti ed elaborati sono stati utilizzati per definire il modello concettuale dell'acquifero, sulla base del quale sono state implementate le successive simulazioni numeriche del flusso delle acque sotterranee e la modellazione del fenomeno di intrusione, in condizioni stazionarie e transitorie, con il software Visual MODFLOW Flex 7.0 (© 2021 by Waterloo Hydrogeologic). È stato sviluppato un modello numerico tridimensionale del flusso delle acque sotterranee e sono state simulate le variazioni della falda e della salinità in diversi scenari considerando gli effetti del tasso di emungimento e l'impatto dei cambiamenti climatici sulla ricarica dell'acquifero. I risultati evidenziano che lo scenario relativo agli effetti del cambiamento climatico sulla valutazione della ricarica diretta, non apporta modifiche significative al fenomeno di intrusione. Al contrario, elevati tassi di emungimento sembrano influenzare la progressione verso le aree interne dell'acqua salmastra: l'intrusione salina è potenzialmente non trascurabile in futuro, in caso di sfruttamento dei pozzi. I risultati della modellazione numerica presentati in questo studio possono essere utili per supportare la protezione della qualità e della quantità delle acque sotterranee e fornire indicazioni per l'implementazione di criteri e strategie di gestione che affrontino i cambiamenti climatici e le variazioni della domanda idrica.

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ABSTRACT

The Metaponto coastal plain, located in the Basilicata region (southern Italy), is a relevant area for economic development due to the touristic and intensive agricultural sectors. In the 20th century, the land reclamation works, irrigation systems, and wells exploitation to support agriculture and industry strongly impacted the hydrogeological system, intensifying the potential seawater intrusion (SWI) that must be considered relevant in this coastal aquifer. The effective infiltration rate of the area is moderate due to the Mediterranean climate conditions, characterized by high temperatures and scarce precipitation concentrated mainly in winter. The present study aims to evaluate and model the SWI process in the most prone area of the Metaponto coastal plain. Groundwater flow and variable-density transport, under steady-state and transient conditions, were simulated with MODFLOW and SEAWAT codes integrated into Visual MODFLOW Flex 7.0 software. The pumping rate effects and the impact of climate change on the aquifer recharge were considered in different scenario simulations. The results highlighted that the SWI is potentially not negligible in the future under exploitation and may impact the groundwater SWI level risk. The numerical modeling outcomes presented in this work can be used for the effective management of the Metaponto coastal plain groundwater resources.

Keywords: *coastal aquifer, seawater intrusion, flow and transport numerical modeling.*

INTRODUCTION

This study aimed to model in the Metaponto coastal aquifer (Basilicata, southern Italy) the SWI by analysing the geological, hydrogeological, and hydrochemical features of the aquifer system and external factors such as excessive withdrawals and climate change causing recharge modification. Groundwater supplies are crucial for the economic growth in the Metaponto coastal plain, an important area for the Basilicata region due to the marked agricultural land use and the residential and tourist settlements, woods, and wetlands (Canora *et alii*, 2022).

Since the 1950s, the Irrigation and Land Development Authority hydraulic arrangement and land reclamation projects have aided the development of the whole plain. Groundwater exploitation, intensive agriculture and industry, as well as the effects of climate change, have significantly altered the plain hydrogeological conditions. Different anthropogenic impacts play a significant role in facilitating the SWI process in addition to the effects of climate change. In the last century, the land reclamation works of the marshy areas started in the 1930s, the more recent irrigation systems and the groundwater overexploitation finalized to the intensive agriculture, the tourism development and industrial activity modified the hydrogeological conditions of the aquifers in the whole plain. In particular, the land use changes threatened groundwater availability and quality in the area and intensified the aquifer pollution risk, also magnifying soil salinization and SWI risks.

Based on the outcomes of different studies conducted in the study area, such as hydrogeological and hydrochemical investigations and the intrinsic vulnerability assessment to SWI (Muzzillo *et alii*, 2021a; Muzzillo *et alii*, 2021b; Muzzillo *et alii*, 2022), numerical simulations were carried out in this work for the portion of the coastal plain more susceptible to SWI. The geological, hydrogeological, hydrological, climatic, and hydrochemical data collected and processed were employed to define an accurate conceptual model of the aquifer, which was the first step for the following numerical simulations of groundwater flow and the modeling of the SWI phenomenon.

In recent decades, the use of computational codes has become considerably widespread. Among the numerous numerical models available, the most widely used are MODFLOW (McDonald & Harbaugh, 1984), SUTRA (Voss, 1984), FEFLOW (Diersch, 1996), MT3DMS (Zheng & Wang, 1999), and SEAWAT (Guo & Langevin, 2002). The Visual MODFLOW (VMOD) Flex 7.0 software (© 2021 by Waterloo Hydrogeologic), which includes the MODFLOW and SEAWAT codes, was used. Groundwater flow was simulated under steady-state natural conditions and transient conditions.

According to the latest studies on climate change, the Mediterranean region appears to be subject to higher warming than the global average, and will become drier due to the decreased precipitation and increased evapotranspiration (IPCC, 2022). Based on all these effects, in this study different scenario simulations considered the climate and anthropogenic impacts (in terms of pumping) on groundwater resources. SWI is potentially not negligible in the future under groundwater exploitation that could impact coastal groundwater.

STUDY AREA

Geographic location and climate conditions

The Metaponto coastal plain, located in the southern sector of the Basilicata region (Italy), extends from the Sinni to the Bradano Rivers, in the SW-NE direction for about 40 km along the Ionian coast and in the SE-NW direction from the shore up to about 9 km inland (Fig. 1).

The study area morphology is constituted by smooth marine terraces interrupted by the surface drainage network of the river valleys and downward by plains close to the sea. The mean elevation is about 20 m a.s.l., and the slope is about 5%.

The Mediterranean climate characterizes the study area, with dry summers and mild, wet winters. The rainfall rates are scarce and concentrated in winter, with the highest detected in November and December, whereas the lowest occur in July and August. The

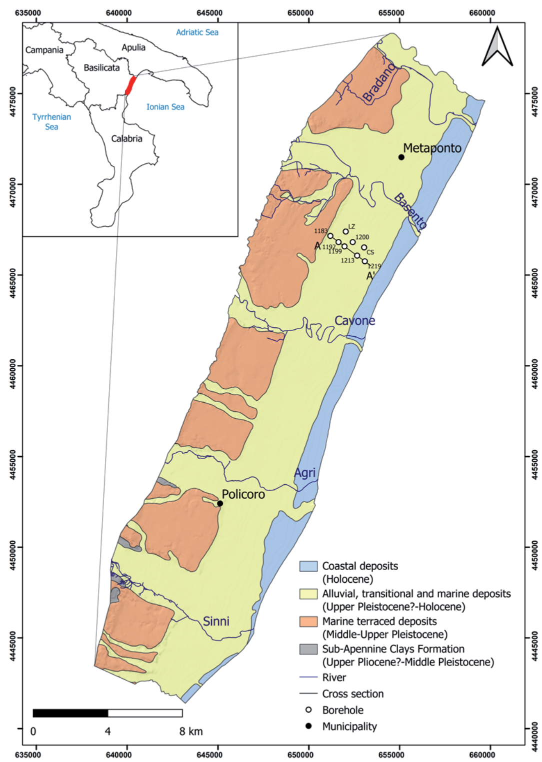

Fig. 1 - Geological map of the Metaponto coastal plain (modified from Canora *et alii, 2022; Geological Map of Italy at 1:100,000 scale and 1:50,000 scale).*

highest temperatures are recorded in the summer, July and August, with a maximum of about 27 °C, whereas the lowest temperatures are observed in winter, with a minimum of about 9 °C in January.

Geological setting

From a geological point of view, the Metaponto coastal plain belongs to the sedimentary succession of the Bradanic Foredeep lying between the Apennine Chain eastern front and the Apulia Foreland western sector (Pescatore *et alii*, 2009). The Bradanic Foredeep has undergone a progressive emersion stage since the Middle Pleistocene (Ciaranfi *et alii*, 1983; Doglioni *et alii*, 1996; Corrado *et alii*, 2017) due to the interaction between a moderate tectonic uplift (Westaway & Bridgland, 2007) and Quaternary eustatic sea-level changes (Pescatore *et alii*, 2009). The Bradanic Foredeep is constituted, from bottom to top, by the Sub-Apennine Clays Formation (Upper Pliocene?-Middle Pleistocene) (Vezzani, 1967; Parea, 1986). This formation passes upwards to the Terraced Marine Deposits (Middle-Upper Pleistocene) and the alluvial and coastal deposits (Upper Pleistocene?-Holocene) (Pescatore *et alii*, 2009; Tropeano *et alii*, 2002; Sabato *et alii*, 2018).

The surface and subsurface structure of the study area, characterized by the presence of marine terraces, coastal plains, and paleo-riverbeds, is the result of evolutionary processes of sedimentation, erosion, and sea level variations due to the action of marine and fluvial morphological agents.

The geomorphological evolution of the study area is identifiable by the presence, from 380 m a.s.l. to 10-15 m a.s.l., of a staircase of marine terraces (Brückner, 1980; Caputo *et alii*, 2010; Sauer *et alii*, 2010; Gioia *et alii*, 2020). The staircase of marine terraces characterizes the inland areas, cut through by the Bradano, Basento, Cavone, Agri, and Sinni Rivers that follow an orthogonal trend to the Ionian coast from the NE to the SW. Due to the particular morphology of the territory, the rivers caused flooding and marsh areas in the peri-coastal environment.

The marine terraced deposits (Middle-Upper Pleistocene), composed of thin gravel and medium-fine sands, unconformably overlie the marine silty clays of the Sub-Apennine Clays Formation (Upper Pliocene?-Middle Pleistocene) (Tropeano *et alii*, 2002), which outcrop in limited portions of the study area along the deeper incisions of the fluvial network (Pescatore *et alii*, 2009; Tropeano *et alii*, 2013). The river incisions of the Sinni, Agri, Cavone, Basento, and Bradano Rivers (from SW to NE) cut across the flat surfaces of the marine terraces, which have a trend similar to the current shoreline and depict the ancient coastlines of the various sea level standing stages (Parea, 1986). The alluvial, transitional, and marine deposits (Upper Pleistocene?-Holocene), widely present in the coastal plain, overlay the marine grey-blue silty clays (Pescatore *et alii*, 2009). Alluvial deposits, found primarily along river valleys and on flood plains, are characterized by silty-clayey and sandy silt layers with interspersed sandy layers. The transitional and marine deposits are characterized by gravel, sand, and silt layers of the deltaic and beach depositional environment, unevenly distributed mainly in the coastal plains and prograded up to the current coastal deposits (Pescatore *et alii*, 2009; Tropeano *et alii*, 2013; Sabato *et alii*, 2018).

The coastal deposits define the sandy beaches, which turn sandy or gravelly sandy, with pebbly lenses towards the Sinni River (Cocco *et alii*, 1975). Inland, coastal dunes and wetlands, consisting of compact and weakly cemented sand, delimit beaches (Fig. 1).

The Metaponto coastal plain lithostratigraphic setting consists of different stratigraphic units (Canora *et alii*, 2022) (Fig. 2). The shelf-transition clayey, clayey-silty, and clayey-sandy deposits, with local intercalations of discontinuous gravel levels (Middle Pleistocene), reaches about 120 m below sea level in correspondence with the paleo river valleys (Tropeano *et alii*, 2013), mainly filled by estuarine deposits (Pescatore *et alii*, 2009) (Fig. 2). The second unit is made up of fluvial and/or deltaic sandy-gravelly deposits with local clayey and clayey-silty deposits that belong to marine terraced deposits (Upper Pleistocene) (Fig. 2).

The buried and outcropping coastal prisms of Metaponto, which include alluvial, transitional, and marine deposits, are constituted by the last two lithostratigraphic units (Fig. 2). During low-stand of sea level, these units have filled the ancient river valleys, deep between 30 and 40 m below the present sea level. These deposits, laterally discontinuous, lie by an erosion surface on the substrate and the sandy-gravelly deposits. The upper unit is constituted by the outcropping deposits of the coastal prisms (Upper Pleistocene-Holocene). The incised paleo valleys were filled with these medium-to-fine sand, gravelly, and silty deposits of a continental-to-transitional environment during a low-stand of relative sea level, and later aggradation formed the present-day Metaponto coastal area.

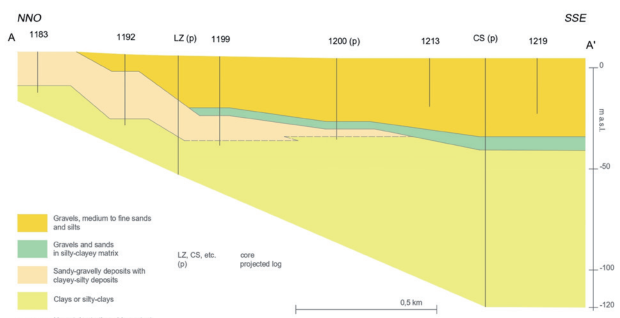

Fig. 2 - Simplified cross section AA' (see Fig. 1) of the stratigraphic units present in the area (adapted from SABATO *et alii, 2018 and Geological Map of Italy at 1:50,000 scale)*

Hydrogeological characterization

The complex geological and stratigraphic setting of the Metaponto coastal plain characterizes its distinctive hydrogeological structure.

The geomorphological evolution and the deep and surface distribution of the several formations determined peculiar boundary conditions of the groundwater flow. Grey-blue clays represent the bottom of the aquifer system, characterized by very low hydraulic conductivity (POLEMIO *et alii*, 2003). Different aquifers, mostly unconfined, can be distinguished (MUZZILLO *et alii*, 2021b). They are located in the marine terraced deposits, in the alluvial deposits of river valleys, and in the coastal plain. The continuity of the aquifer in the marine terraced deposits, with medium to high hydraulic conductivity, is interrupted by the river valleys (POLEMIO *et alii*, 2003). The alluvial paleo river valleys aquifers are very deep, with limited lateral extension and medium hydraulic conductivity. The shallow coastal plain aquifer has medium-low relative hydraulic conductivity compared to the other aquifers. The shallow coastal aquifer corresponds to the intermediate most permeable sandy thickness, characterized by a varied particle-size distribution contained among silty clayey impermeable strata of different extents and thicknesses (POLEMIO *et alii*, 2003). The aquifer permeable layers are thicker than 10 m, and generally, their thickness increases from the inland toward the shore. The pumping tests on a large scale referred to the entire plain allowed to determine the mean and median values of the hydraulic conductivity of the plain deposits, which are $2.28 \cdot 10^{-4}$ and $6.53 \cdot 10^{-5}$ m/s, respectively (POLEMIO *et alii*, 2003; MUZZILLO *et alii*, 2021b). Although the hydraulic conductivity decreases from inland to the coast, its reduction near the shore might not be enough to reduce the risk of SWI.

The coastal aquifer bottom is made up of the silty clay formation, which deepens toward the coastline and has an irregular surface with local depressions. Since the aquifer bottom gradually decreases from the Sinni to the Bradano River in the SW-NE direction and dips below sea level close to the shore, SWI may be allowed along the coast in the north-eastern direction, depending on the local hydrodynamic conditions.

Due to climatic conditions, the effective infiltration rate of about 52 mm/year is modest (MUZZILLO *et alii*, 2021a). The recharge of the coastal aquifer system is mostly guaranteed by the discharge from the upward marine terraces' aquifer and river leakage. The water table spatial trend confirms the upstream groundwater recharge of the coastal aquifer. The groundwater equipotential lines of the coastal deposits, almost parallel to the shoreline, highlight the groundwater preferential flow directions, directed orthogonally from the marine terraces to the Ionian coast. To assess the potential groundwater recharge (*i.e.*, effective infiltration) of the Metaponto coastal plain aquifer system, the estimation of the hydrological budget components was conducted through the inverse hydrogeological water balance approach over the reference period of observations 2000-2015 (CIVITA, 2005; CANORA *et alii*, 2018). It provided a mean annual rainfall rate of 538 mm/year, an actual evapotranspiration rate of 465 mm/year determined using Turc's formula (TURC, 1954), an effective infiltration rate of 52 mm/year, and a direct runoff rate of 21 mm/year (MUZZILLO *et alii*, 2021a).

The water resources demand is higher in summer when agricultural requests and the tourist population increase.

MATERIAL AND METHODS

Data, conceptual and numerical model

The first stage of the study concerned the geological and hydrogeological characterization of the entire Metaponto coastal plain. The investigation was conducted on the existing bibliography, available data sets, and in situ measurements. The collected data were derived from different sources and dates to various periods. They were georeferenced and implemented in a geodatabase on Geographic Information System (GIS), using QGIS software to elaborate and manage space-related thematic layers.

The study area was selected considering the results of the groundwater's hydrochemical characterization (MUZZILLO *et alii*, 2021a) and the SWI vulnerability assessment (MUZZILLO *et alii*, 2022). These previous studies showed that the area most potentially subjected and prone to the SWI risk is characterized by the highest concentration values of total dissolved solids (TDS) detected in specific groundwater analyzed samples. The

TDS chemical concentrations come from the PRISMAS Project related to the Metaponto coastal plain for the Basilicata Region (Martinelli & Marchetti, 2000). The study site considered as the model domain runs along the coast for about 11.6 km, from Cavone to Bradano Rivers, and extends inland for about 3.6 km, covering a surface of about 42 km^2 (Fig. 3).

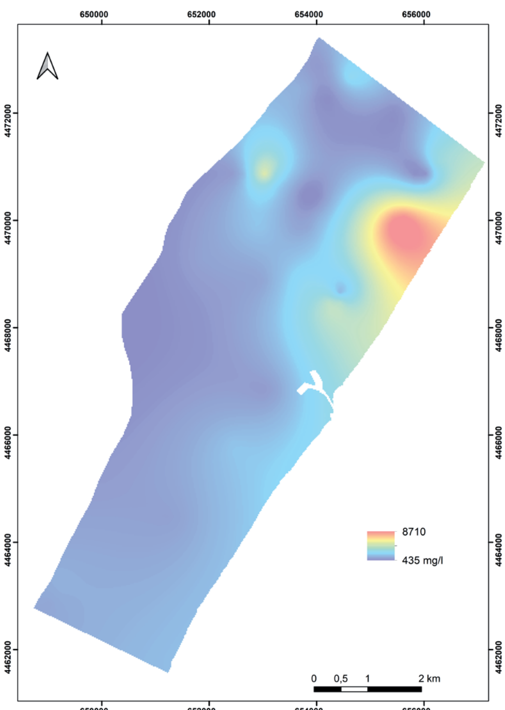

Fig. 3 - Study site and spatial distribution of the monitored TDS concentrations (mg/l)

Spatial data, such as the Digital Terrain Model (DTM) and hydrographic network, were uploaded in QGIS from the Regional Spatial Data Infrastructure (Regione Basilicata, 2023). The hydraulic heads, hydraulic conductivity, and TDS data were implemented in the geodatabase.

Among the available numerical hydrogeological models, Visual MODFLOW (VMOD) Flex is a powerful software package that provides the tools for building three-dimensional groundwater conceptual and numerical models. VMOD Graphical User Interface (GUI) enables the creation of groundwater models graphically on-screen using raw GIS data objects easily imported, such as DXF, TXT, and SHP files. MODFLOW code (McDonald & Harbaugh, 1984) was considered to simulate groundwater flow. SEAWAT (Guo & Langevin, 2002), included in VMOD Flex to simulate SWI, was developed for three-dimensional, transient, variable-density groundwater flow and multi-species solute transport in porous media. SEAWAT was selected as the numerical engine for the simulation, and the saturated (variable density) flow type was specified.

Model calibration under steady state and transient conditions was performed using PEST (Doherty, 1994) in VMOD Flex. The reliable conceptual model representative of the aquifer system under study was defined starting from geological and hydrogeological data. The area selected for the numerical modeling includes coastal deposits and alluvial, transitional, and marine deposits. The surface representing the trend of the Sub-Apennine Clays Formation, which is the aquifer confining unit, was implemented (Fig. 4).

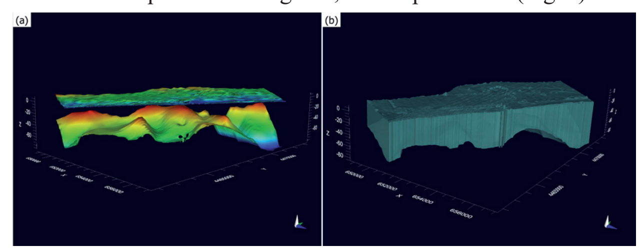

Fig. 4 - 3D view of the surfaces implemented into VMOD Flex for subsurface geological model definition: (a) DTM and top of the Sub-Apennine Clays Formation; (b) thickness trend of the modeled aquifer

The definition of the clay surface trend, representing the confining unit of the aquifer system, was carried out from stratigraphic wells data and previously published lithostratigraphic findings on the Metaponto coastal plain subsurface (Pescatore *et alii*, 2009; Tropeano *et alii*, 2013). The construction of the conceptual model also required the assignment of the hydraulic conductivity values: in the horizontal/x-direction (Kx) and the horizontal/y-direction (Ky) equal to $6.53 \cdot 10^{-5}$ m/s, and the vertical/z-direction (Kz) 10^{-6} m/s (Polemio *et alii*, 2003). The active domain have 1018 active cells (Muzzillo, 2023). The 5 m resolution DTM was used to define the surface morphology of the model. Groundwater flow simulation under steady-state and transient conditions was performed considering a single saturated layer.

RESULTS AND DISCUSSION

Steady-state groundwater flow simulation

The definition of suitable boundary conditions is necessary to implement the numerical model and simulate groundwater flow and transport under different situations to understand the hydrodynamic system's behaviour and response to external factors. The boundary conditions assigned under steady-state flow conditions are described below.

Cells at the lateral edges of the modeling domain were defined as inactive (no flow).

The Constant Head boundary condition was applied along the shoreline to simulate the sea (assigning a head equal to zero) and along the upper edge of the modeling domain (4 m head) derived by reconstructing the water table surface trend.

The River boundary condition conceptualizes the surface water characteristics and is used to model the influence of a surface water body on the groundwater flow system. It was given to Basento River cells up to the Mercuragno hydrometric station. For the Recharge boundary condition, the average recharge rate of 27 mm/year, estimated with the inverse hydrogeological water balance considering the reference period 1925-1979, was assigned to the entire domain. The model calibration was performed through the PEST procedure. The hydraulic head values of seven observation wells data were used to compare to the simulated values (MUZZILLO, 2023).

Horizontal conductivity Kx was selected as the parameter to include in the PEST run, and the values $1{,}29\cdot10^{-5}$ m/s and $1{,}7\cdot10^{-4}$ m/s were entered as the minimum and maximum of Kx, respectively. The hydraulic conductivities assigned to pilot points, a total of 35 (MUZZILLO, 2023), were used to characterize the spatial distribution of the hydraulic conductivity by the spatial interpolation Kriging algorithm (WEBSTER & OLIVER, 2007).

The comparison between simulated and observed hydraulic heads validates the selected boundary conditions (Tab. 1).

Well	Measured head (m)	Simulated head (m)	Residual (m)
54	1.52	2.81	-1.29
72	2.63	3.21	-0.58
73	2.60	2.88	-0.28
123	3.77	4.00	-0.23
129	1.00	2.34	-1.34
142	0.55	0.92	-0.37
143	1.20	2.22	-1.02

Tab. 1 - Observed and simulated hydraulic head values with residuals under steady-state conditions after the calibration

The modified Kx hydraulic conductivity obtained after the PEST run was used as input for a new simulation.

Groundwater flow simulation under steady-state conditions confirms the spatial trend of the water table.

Transient state calibration and validation

The only boundary condition defined for groundwater flow modeling under transient conditions, different from the steady-state, was the Constant Head at the study site top edge. The simulation was carried out in transient conditions considering the starting and ending hydraulic heads of the network wells monitored from the winter of 1997 (W97) to the winter of 1999 (W99) (PRISMAS Project, MARTINELLI & MARCHETTI, 2000), considering the end time of 730 days. Results of the first run are shown in Fig. 5 for each time step referred to the four seasons.

Specific storage Ss and yield Sy parameters, equal to $1\cdot10^{-5}$ m^{-1} and 0.2, respectively, were included in the PEST run for the simulation calibration in transient conditions. The analysis of the observed and simulated wells' hydraulic heads data confirms that they are comparable. In particular, the maximum residual was 1.25 m for well PI6 in the 1998 spring observation (Fig. 6, Tab. 2).

The modified Ss and Sy parameters obtained after the PEST run were used as inputs for a new simulation.

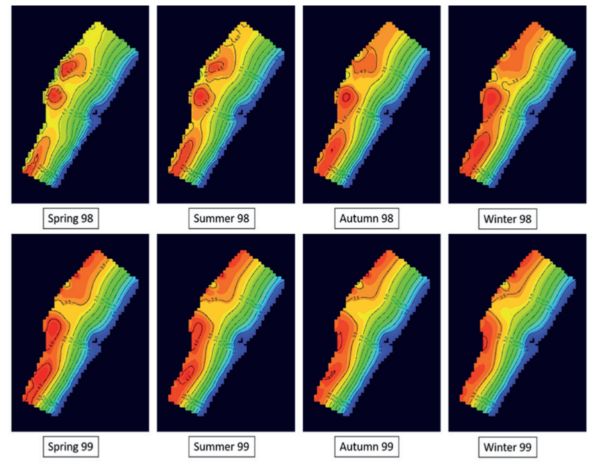

Fig. 5 - Hydraulic head trend in transient conditions before calibration (modified from MUZZILLO, 2023)

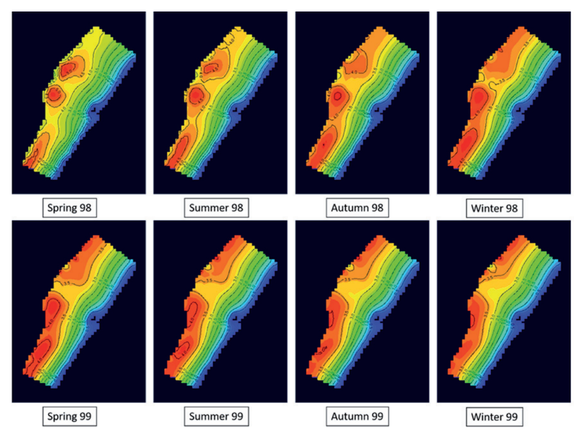

Fig. 6 - Observed and simulated hydraulic head values under transient conditions after the calibration (modified from MUZZILLO, 2023)

Well	Observation	Measured head (m)	Simulated head (m)	Residual (m)
PI6	Spring 98	2.36	3.61	-1.25
PI9	Spring 98	4.29	3.85	0.44
BE4	Autumn 98	1.70	1.43	0.27
PI6	Winter 99	3.00	2.68	0.32
PI9	Winter 99	4.80	3.85	0.95

Tab. 2 - Observed and simulated hydraulic head values with residuals under transient conditions after the calibration (modified from MUZZILLO, 2023)

Transient state solute transport modeling and validation

The transient solute transport simulation was performed by implementing TDS concentration (expressed in mg/l) as the expression factor of SWI. The domain was vertically discretized with a mesh organized into ten layers (each of about 5 m thickness).

The TDS concentration map, elaborated from available data measured in the study site, was implemented in the numerical code assigning the Initial Concentration property in the domain (Fig. 3), except for cells of the coastline, where the Constant

Concentration boundary condition was applied. The Ionian Sea salinity (in terms of TDS) of 39.500 mg/l (Grauel & Bernasconi, 2010) was assigned to these cells.

A TDS concentration of 575 mg/l was assigned to cells of the Basento River derived from measured electrical conductivities (expressed in μS/cm at 20 °C) (Regione Basilicata, 2016).

Effect of climate change and pumping rates

The climatic parameters were considered to take into account the effects of climate change on groundwater resources in the study area. Several authors (Giorgi & Lionello, 2008; Romanazzi *et alii*, 2015), starting from the analysis of the precipitation and temperature trends in the Ionian region, hypothesized climate change predictions for the period 2001-2020, defining an average temperature rise of 0.9 °C and a precipitation decrease of 3.9% compared to 1960-1980. The effective infiltration (already extremely low at 27 mm/year) dropped to zero due to the significant increase in the actual evapotranspiration rate. The simulation results by changing the infiltration parameter showed no significant modifications to the SWI phenomenon.

Further numerical modeling, considering the exploitation of the groundwater resources due to the numerous human activities that perturbate the coastal plain environment, was carried out by simulating two hypothetical groundwater pumping scenarios conducted in four wells in the study site. Three of these wells (BE4, PI6, PI9) were used for the simulation calibration under transient conditions, whereas the 2579 was chosen from the Basilicata Region's inventory of surveyed and authorized wells. The Pumping Well boundary condition was selected to simulate the two pumping rates considered. The first one of 10 l/s represents the average pumped discharge of the surveyed wells in the coastal plain inventory. The second one of 100 l/s was chosen to consider a significant exploitation rate. The pumping rates were kept active and constant throughout the first two time steps, corresponding to the spring and summer, when the potential water demand can increase.

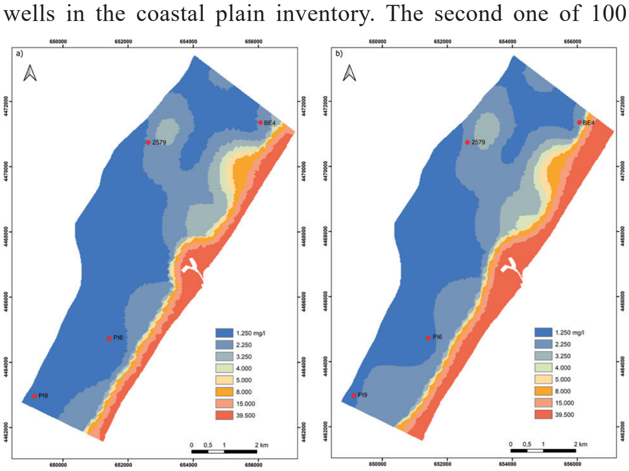

Fig. 7 - Spatial distribution of the TDS concentrations in the first layer with pumping boundary condition in four wells (red dots) for the time steps corresponding to the spring-summer period of the two years, considering a 10 l/s (a) and 100 l/s (b) pumping rates

The outcomes of the first scenario simulation highlight significant variations in correspondence of the pumping from the wells located in the portions of the aquifer more prone to the SWI due to the proximity to the sea (Fig. 7a). Considering the second scenario, more evident inward progression in TDS concentrations can be observed (Fig. 7b). The simulated TDS concentration trend is representative of the potential phenomenon of groundwater salinization and groundwater SWI risk level.

CONCLUSIONS

The hydrogeological characterization of the Metaponto coastal aquifer system was crucial for understanding the mechanisms involved in SWI.

Numerical modeling with the MODFLOW and SEAWAT codes within the VMOD Flex 7.0 software (© 2021 by Waterloo Hydrogeologic) enabled reasonably accurate simulation of the aquifer system dynamic behaviour and can be a helpful tool for groundwater management and planning.

In this work, based on the conceptual hydrogeological model of the coastal aquifer, a three-dimensional numerical model of groundwater flow was developed, and changes in water table and salinity were simulated, allowing the hydrogeological and hydrodynamic characteristics of the aquifer system to be defined and the flow and transport mechanisms governing groundwater resources to be understood.

Considering the climate change scenario on direct recharge assessment, no significant changes to the SWI phenomenon result. On the contrary, higher groundwater pumping discharges appear to influence the inland progression of brackish water.

Finally, to better address the SWI phenomenon in the Metaponto coastal aquifer system, the results achieved in this study can help define adequate groundwater management and planning proposals aiming to preserve from the SWI risk the groundwater resources with a view to sustainability. The outcomes can also provide effective support for groundwater quality and quantity protection and optimal indications for implementing management criteria and strategies addressing climate change and variations in water demand.

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REFERENCES

Brückner H. (1980) - *Marine Terrassen in Süditalien. Eine quartärmorphologische Studie über das Küstentiefland von Metapont.* Düsseldorfer Geographische Schriften, **14**: 1-235.

Canora F., Musto M.A. & Sdao F. (2018) - *Groundwater recharge assessment in the carbonate aquifer system of the Lauria Mounts (southern Italy) by GIS-based distributed hydrogeological balance method.* In Computational Science and Its Applications; ICCSA 2018, Lecture Notes in Computer Science, Springer, Cham, Switzerland, 10961: 166-181.

Canora F., Muzzillo R. & Sdao F. (2022) - *Groundwater Vulnerability Assessment in the Metaponto Coastal Plain (Basilicata, Italy).* Water, **14**: 1851. https://doi.org/10.3390/w14121851

Caputo R., Bianca M. & D'onofrio R. (2010) - *Ionian marine terraces of southern Italy: Insights into the Quaternary tectonic evolution of the area.* Tectonics, **29**(4): TC4005. https://doi.org/10.1029/2009TC002625

Ciaranfi N., Ghisetti F., Guida M., Iaccarino G., Lambiase S., Pieri P., Rapisardi L., Richetti G., Torre M., Tortorici L. & Vezzani L. (1983) - *Carta Neotettonica dell'Italia meridionale.* Prog. Fin. Geodinamica Pubbl., **251**: 1-62.

Civita M. (2005*) - Idrogeologia Applicata e Ambientale.* CEA: Milano, Italy: 794 pp.

Cocco E., Cravero E., Di Geronimo S., Mezzadri G., Parea G.C., Pescatore T., Valloni R. & Vinci A. (1975) - *Lineamenti geomorfologici e sedimentologici del litorale alto ionico (Golfo di Taranto).* Boll. Soc. Geol. Ital., **94**: 993-1051.

Corrado G., Leo P.D., Giannandrea P. & Schiattarella M. (2017) - *Constraints on the dispersal of Mt. Vulture pyroclastic products: Implications to mid-Pleistocene climate conditions in the foredeep domain of southern Italy.* Geomorphologie, **23**(2). https://doi.org/10.4000/geomorphologie.11731

Diersch H.-J.G. (1996) - *Interactive, graphics-based finite-element simulation system FEFLOW for modeling groundwater flow, contaminant mass and heat transport processes.* User's Manual Version 4.5. WASY Institute for Water Resources Planning and Systems Research Ltd., Berlin, Germany.

Doglioni C., Tropeano M., Mongelli F. & Pieri P. (1996) - *Middle-late Pleistocene uplift of Puglia: an anomaly in the Apenninic foreland.* Memorie Società Geologica Italiana, **51**: 101-117.

Doherty J. (1994) - *PEST: Model-Independent Parameter Estimation.* Watermark Computing.

Erostate M., Huneau F., Garel E., Ghiotti S., Vystavna Y., Garrido M. & Pasqualini V. (2020) - *Groundwater dependent ecosystems in coastal Mediterranean regions: Characterization, challenges and management for their protection.* Water Res., **172**: 115461.

Geological Survey of Italy (1976) - *Geological Map of Italy, Sheets Matera n. 201, Montalbano J. n. 212, 1:100,000 scale.* Ispra - Land Protection And Georesources Department: Rome, Italy, 1976.

Geological Survey of Italy (2018) - *Geological Map of Italy, Sheet Policoro n. 508, 1:50,000 scale.* Ispra - Land Protection And Georesources Department: Rome, Italy, 2018.

Gioia D., Bavusi M., Di Leo P., Giammatteo T. & Schiattarella M. (2020) - *Geoarchaeology and geomorphology of the Metaponto area, Ionian coastal belt,* Italy. J. Maps, **16**: 117-125.

Giorgi F. & Lionello P. (2008) - *Climate change projections for the Mediterranean region.* Global and Planetary Change, **63**: 90-104.

Grauel A. & Bernasconi S. (2010) - *Core-top calibration of δ18O and δ13C of G. ruber (white) and U. mediterranea along the southern Adriatic coast of Italy.* Marine Micropaleontology, **77**: 175-186.

Guo W. & Langevin C.D. (2002) - *User's Guide to SEAWAT: A Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow.* Techniques of Water-Resources Investigations, Chapter A7, 77, U.S. Geological Survey, Tallahassee, Florida.

IPCC (2022) - *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.

Martinelli A. & Marchetti G. (2000) - *PROGETTO PRISMAS: Sintesi dei risultati.* Convegno nazionale Progetto Interregionale PRISMAS, Perugia, Italy, 9 novembre 2000.

McDonald M.G. & Harbaugh A.W. (1984) - *A Modular Three-Dimensional Finite Difference Groundwater Flow Model.* U.S. Geological Survey Open-File Report: 83-875.

Muzzillo R. (2023) - *Hydrogeology and numerical modeling of coastal groundwater resources focusing on salinization risk in the Metaponto plain (Basilicata, southern Italy).* PhD thesis, University of Basilicata, Potenza, Italy, 9 January 2023. https://hdl.handle.net/11563/162866

Muzzillo R., Canora F., Polemio M. & Sdao F. *(2022) - Seawater intrusion vulnerability assessment by GALDIT method in the Metaponto coastal aquifer (Basilicata, Italy).* Italian Journal of Engineering Geology and Environment, **1**: 32-41.

Muzzillo R., Zuffianò L.E., Canora F., De Giorgio G., Limoni P. P., Polemio M. & Sdao F. (2021A) - *Hydrogeology and seawater intrusion proneness in the Metaponto plain aquifer (Basilicata, Italy).* Italian Journal of Engineering Geology and Environment, Special Issue **1**: 139-149. https://doi.org/10.4408/IJEGE.2021-01.S-13

Muzzillo R., Zuffianò L.E., Rizzo E., Canora F., Capozzoli L., Giampaolo V., De Giorgio G., Sdao F. & Polemio M. (2021B) - *Seawater Intrusion Proneness and Geophysical Investigations in the Metaponto Coastal Plain (Basilicata, Italy).* Water, **13**(1): 53.

Parea G. C. (1986) - *I terrazzi marini tardo-pleistocenici del fronte della catena appenninica in relazione alla geologia dell'avanfossa adriatica (The Late Pleistocene marine terraces in front of the Apennines in relation to the geology of Adriatic Foredeep).* Memorie Società Geologica Italiana, **35**: 913-936.

Pescatore T., Pieri P., Sabato L., Senatore M.R., Gallicchio S., Boscaino M., Cilumbriello, A., Quarantiello R. & Capretto G. (2009) - *Stratigrafia dei depositi pleistocenico-olocenici dell'area costiera di Metaponto compresa fra Marina di Ginosa ed il Torrente Cavone (Italia meridionale):* Carta geologica in scala 1:25,000. Il Quat., **22**: 307-324.

Polemio M., Limoni P. P., Mitolo D. & Santaloia F. (2003) - *Characterisation Of The Ionian-Lucanian Coastal Plain Aquifer (Italy).* Boletin Geologico Y Minero, **114**(2): 225-236.

Post V.E.A. (2005) - *Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead?* Hydrogeology Journal, **13**: 120-123.

Regione Basilicata (2016) - *Piano Regionale di Tutela delle Acque, Delibera Giunta Regione Basilicata n. 252 del 16/03/2016.*

Regione Basilicata (2023) - *Regional Spatial Data Infrastructure (RSDI).* Available online: https://rsdi.regione.basilicata.it/ (accessed on 20 July 2023).

Romanazzi A., Gentile F. & Polemio M. (2015) - *Modelling and management of a Mediterranean karstic coastal aquifer under the effects of seawater intrusion and climate change.* Environ. Earth Sci., **74**: 115-128.

Sabato L., Cilumbriello A. & Tropeano M., Con Contributi Di: Bertini A., Gallicchio S., Maiorano P., Pieri P. & Spilotro G. (2018) - *Note illustrative della Carta Geologica d'Italia alla scala 1:50.000, Foglio Geologico 508 Policoro.* ISPRA, Serv. Geol. d'It., Ed. System Cart: 204 pp. https://www.isprambiente.gov.it/Media/carg/note_illustrative/508_Policoro.pdf

Sauer D., Wagner S., Bruckner H., Scarciglia F., Mastronuzzi G. & Stahr K. (2010) - *Soil development on marine terraces near Metaponto (Gulf of Taranto, southern Italy).* Quaternary International, **222**(1-2): 48-63.

Tropeano M., Cilumbriello A., Sabato L., Gallicchio S., Grippa A., Longhitano S.G., Bianca M., Gallipoli M.R., Mucciarelli M. & Spilotro G. (2013) - *Surface and subsurface of the Metaponto coastal plain (Gulf of Taranto-Southern Italy): Present-day- vs. LGM landscape.* Geomorphology, **203**: 115-131.

Tropeano M., Sabato L. & Pieri P. (2002) - *The Quaternary «Post-turbidite» sedimentation in the South-Apennines Foredeep (Bradanic Trough-Southern Italy).* Boll. Soc. Geol. Ital., **1**: 449-454.

Turc L. (1954) - *Calcul du bilan de l'eau. Évaluation en fonction des précipitations et des températures.* IAHS Publ., **37**: 88-200.

Vanneuville W., Werner B., Kjeldsen T.R., Miller J., Kossida M., Tekidou A., Kakava A. & Crouzet P. (2012) - *Water Resources in Europe in the Context of Vulnerability: EEA 2012 State of Water Assessment.* European Environment Agency (EEA): Copenhagen, Denmark; EEA Report Volume 11/2012, 96.

Vezzani L. (1967) - *I depositi plio-pleistocenici del litorale ionico della Lucania.* Atti Acc. Gioenia Sci. Nat. in Catania s. VI, **18**: 159-180.

Voss C. (1984) - *Finite Element Simulation Model for Saturated-Unsaturated Fluid Density-Dependent Groundwater Flow with Energy Transport or Chemically Reactive Single-Species Solute Transport.* U.S. Geological Survey, Reston, VA, USA.

Webster R. & Oliver M.A. (2007) - *Geostatistics for Environmental Scientists.* John Wiley & Sons: Chichester, UK: 330 pp.

Westaway R. & Bridgland D. (2007) - *Late Cenozoic uplift of southern Italy deduced from fluvial and marine sediments: Coupling between surface processes and lower-crustal flow.* Quat. Int., **175**: 86-124.

Zheng C. & Wang P.P. (1999) - *MT3DMS: Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems. Documentation and User's Guide.* United State Army Corps of Engineers, Vicksburg, MI, USA.

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