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HYDROGEOLOGY AND SEAWATER INTRUSION PRONENESS IN THE METAPONTO PLAIN AQUIFER (BASILICATA, ITALY)

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EXTENDED ABSTRACT

Gli acquiferi costieri, a causa dell'interazione tra i processi idrogeologici continentali e marini, sono particolarmente sensibili ai cambiamenti, sia naturali che antropici. Le falde acquifere costiere rappresentano una preziosa fonte di approvvigionamento, la cui rilevanza è enfatizzata dall'importanza delle zone costiere per la presenza di attività agricole, insediamenti produttivi, abitativi e turistici nonché aree boschive e zone umide ecologicamente di pregio.

Il fenomeno dell'intrusione marina rappresenta il problema idrogeologico più tipico per gli acquiferi costieri. Il conseguente rischio di degrado qualitativo delle acque sotterranee evidenzia l'importanza dell'elaborazione e dell'applicazione di metodi efficienti per la prevenzione e la mitigazione dei processi di salinizzazione, che possono rendere le acque sotterranee inutilizzabili sia a scopo potabile che irriguo. L'intrusione marina interessa molte zone costiere in Europa. Nei paesi dell'area mediterranea, il fenomeno è legato principalmente alle attività antropiche e agli effetti del cambiamento climatico.

La piana costiera di Metaponto (Basilicata) ricade nell'estrema propaggine meridionale della Fossa Bradanica e si estende per circa 40 km lungo la costa ionica lucana. L'area è soggetta ad una crescente espansione turistica e ad un uso intensivo di pratiche zootecniche e agricole. Le risorse idriche sotterranee risultano particolarmente esposte sia al degrado quantitativo, a causa delle condizioni climatiche storicamente sfavorevoli (bassa piovosità e ricarica, temperature e deficit idrico colturale elevati), in peggioramento per il cambiamento climatico e per la crescente domanda idrica, sia al degrado qualitativo causato dall'intrusione salina. Lo scopo di questo lavoro è la caratterizzazione idrogeologica e idrogeochimica dell'acquifero poroso della piana di Metaponto, propedeutica alla valutazione e alla modellazione del fenomeno dell'intrusione salina. Tale valutazione, oltre a migliorare il quadro conoscitivo dell'area investigata, fornirà un efficace supporto per una ottimale gestione e protezione delle acque sotterranee presenti.

In particolare, lo studio idrochimico è stato finalizzato sia a definire le caratteristiche chimiche delle acque sotterranee, sia a valutare la presenza di altri processi rilevanti oltre alla miscelazione, in particolare all'interfaccia tra acqua dolce e acqua salata, come lo scambio cationico. I parametri chimico-fisici di 53 campioni di acque sotterranee sono stati rilevati in sito mediante sonda multiparametrica (conducibilità elettrica a 25°C, temperatura e pH), e sono stati determinati i principali ioni (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-} e HCO_3^-) utilizzando metodi di cromatografia ionica. Le concentrazioni dei principali costituenti sono state riportate nel diagramma di Piper, che ha permesso di rappresentare le facies geochimiche e le tipologie di acque analizzate. Nonostante una dispersione significativa dei punti rappresentativi del chimismo delle acque sotterranee, è possibile riconoscere due principali tipi di acque sotterranee: la facies bicarbonato-alcalina-terrosa (tipica delle acque sotterranee dei depositi marini terrazzati ed alluvionali) e la facies solfato-clorurato alcalina (riferibile ai campioni dei pozzi ubicati nei depositi costieri). L'esame della distribuzione dei principali ioni disciolti nelle acque sotterranee ha evidenziato in alcuni casi l'arricchimento di Ca^{2+} insieme all'impoverimento di ioni Na^+ e K^+, indicativo di una progressiva miscelazione con acqua di mare. L'applicazione del metodo del bilancio idrogeologico inverso, attraverso la stima della piovosità efficace e la definizione delle caratteristiche dei complessi idrogeologici affioranti, ha consentito di calcolare l'infiltrazione efficace, risultata in media annua pari a circa 34 Mm^3.

La concettualizzazione idrogeologica e la caratterizzazione idrochimica delle acque sotterranee hanno rappresentato le principali fasi iniziali dell'approccio proposto, fondamentali per le fasi successive basate sulla simulazione numerica del flusso e dell'intrusione marina. In particolare, la caratterizzazione idrogeologica è finalizzata alla definizione del modello concettuale dell'area, fondamentale per la modellazione delle acque sotterranee, rappresentando un utile strumento in termini di gestione e pianificazione dello sfruttamento della risorsa idrica. La comprensione dei meccanismi che determinano le variazioni di salinità è funzionale alla simulazione di possibili scenari futuri legati alle modifiche qualitative e quantitative delle acque sotterranee.

La ricerca su questo sistema acquifero deve essere continuata e ampliata per migliorare ulteriormente la conoscenza del processo di salinizzazione. In particolare, i rilievi idrogeologici e geognostici *in situ* saranno essenziali per il consolidamento e la validazione del modello numerico.

ABSTRACT

In the Metaponto coastal plain (Basilicata region, southern Italy), the anthropogenic impact, mainly linked to agriculture and tourism, has significantly modified the land use and threatened the groundwater quality over the last century. Five protected sites located near the river mouths are included in the Natura 2000 network thanks to the high ecological value of their flora and fauna. The reduction of the groundwater flow, probably caused by the construction of dams and reservoirs for water storage, threatens the equilibrium of the coastal vegetated areas. Among the effects of groundwater quality modifications, the risk of salinity increase should be considered relevant.

The purpose of this paper is to describe the approach, which is preliminary to the density-driven flow modeling, supporting the implementation of management criteria facing seawater intrusion, climate change, and water demand in future scenarios. The definition of an accurate physically-based model is based on the geological and hydrogeological conceptualization and hydrochemical discussion.

Keywords*: coastal aquifer, seawater intrusion, aquifer conceptualization, numerical modeling, groundwater resources management*

INTRODUCTION

Coastal aquifers, the domains where continental fresh groundwater and seawater meet (POST, 2005), are significantly sensitive to changes induced by both natural causes and human activities. Saltwater intrusion (SWI), which can be defined as the movement of salt water invading freshwater aquifers, affects these areas, making groundwater unsuitable for both drinking and irrigation use, and affecting coastal environments also by changing the soil chemistry, reducing its fertility, and impacting local ecosystems.

The salinization of groundwater affects 16% of the world's land area; SWI is one of the two primary genetic sources of salinization, in terms of the involved global population (Polemio & Zuffianò, 2020). The European Environment Agency (EEA) considers SWI as one of the major threats to coastal freshwater resources in Europe (Scheidleger *et alii*, 2004). Italy is one of the countries most affected by SWI, due to overexploitation and climate change (Barrocu *et alii*, 2003; EEA, 2012; Romanazzi & Polemio, 2013).

The most common causes of SWI are aquifer over utilization and, locally, over pumping, but this phenomenon can be further worsened by the effects of climate change. With the sea levels rise, the saline front, the interface between freshwater and saltwater, can advance landward and further upstream into coastal estuaries. This process can be aggravated by drought and reduced rainfall. The resulting increase in water salinity can threaten the flora and fauna of coastal areas, and damage delicate habitats such as marshes and wetlands. The United Nations reports indicate nearly 2.4 billion people (about 40% of the world's population) live within 100 km of the coast. Furthermore, coastal areas, especially coastal plains, are generally very important from an economic, social, and environmental point of view, due to the presence of agricultural and productive activities, residential and tourism settlements, wooded areas, and wetlands of high ecological value (Vespasiano *et alii*, 2019; Erostate *et alii*, 2020).

The salinization risks of coastal groundwater highlight the importance of the development of innovative and efficient methods for the prevention and mitigation of the salinization process. A significant contribution to a proper policy of groundwater utilization, including monitoring design and planning, can be offered by scenario numerical modeling, to characterize SWI modifications and develop optimal management tools for the sustainable use of these resources (Polemio & Zuffianò, 2020). In the last years, various models have been applied to find solutions to the issues related to this phenomenon, such as maximization of the total pumping rate, minimization of saltwater volume into the aquifer, minimization of drawdown, minimization of pumped water salinity (Singh, 2015). The choice of the numerical code to use depends on a series of factors associated with the definition of the investigated hydrogeological problem and/or the ability of the code to successfully simulate the hydrogeological problem (Kallioras *et alii*, 2010; Polemio *et alii*, 2011). The approaches used for the simulation of SWI can be divided into two main categories: interface models and variable density models (Bakker *et alii*, 2013). In the former, freshwater and seawater are considered as two immiscible fluids of constant density separated by a sharp interface, whereas in the latter (e.g., SEAWAT, Guo & Langevin, 2002), the transition zone between saltwater and freshwater has a finite thickness and the fluid density can vary continuously, so they are more suitable for simulating the density-dependent groundwater flow system.

The paper is part of a Ph.D. in which are involved the University of Basilicata, ENI, and CNR (Italian National Research Council). The main objectives of the research project are the modeling and management of groundwater resources of the Metaponto coastal plain (MCP) (Fig. 1) through the analysis of factors linked both to the intrinsic characteristics of the coastal aquifer (geological and hydrogeological) and external factors, such as excessive withdrawals, and climate change, from recharge modification the sea-level variations.

Among the various Italian coastal aquifers subject to SWI, this area was chosen because, in addition to the effects of climate change, other anthropogenic aspects also play a significant role in facilitating the intrusion process. The plain is intensively cultivated, and groundwater resources are important for economic growth in terms of tourism and agriculture (Polemio *et alii*, 2005). During the 20th century, human influence (i.e.,

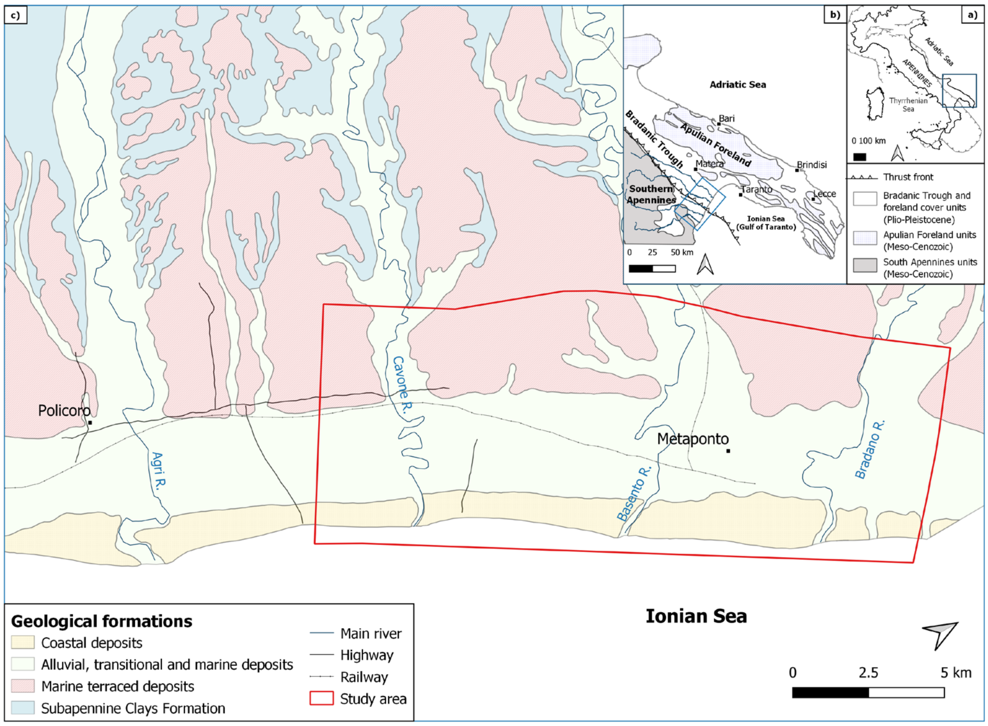

Fig. 1 - Schematic geological map. a) Schematic structural map of Italy and location of b); b) schematic structural map of Southern Italy and location of c); c) schematic geological map of the Metaponto coastal plain and location of the selected study area

development of modern irrigation systems, overexploitation of wells) has led to negative consequences on the natural system in terms of groundwater quality and soil salinization (Satriani *et alii,* 2012; Imbrenda *et alii,* 2018). The land reclamation works of the marshy areas started in the 1930s have helped to lower the water table and, at the same time, the excavation of the drainage channels has facilitated the circulation of saltwater also far from the coast. The modifications of the coastline through the construction of ports and the phenomenon of coastal regression, due to climatic variations and the progressive human changes of the beach, must also be considered. Low rainfall (mean annual value less than 600 mm) and moderate temperature (mean annual value equal to 16.3 °C), typical of a Mediterranean climate, cause low effective rainfall, and, consequently, low aquifer recharge. Polemio *et alii* (2003a) highlighted that SWI seems to involve a stretch of the coastal plain for a width of 1-1.5 km.

The assessment of the vulnerability to SWI requires some preliminary operations, such as the hydrogeological balance and the estimation of active recharge, and the definition of the conceptual hydrogeological model. The present work focused on: the hydrogeological characterization of the porous aquifer of the MCP, the hydrochemical characterization of groundwater, and the estimation of the active recharge using the inverse hydrogeological balance approach (Cotecchia *et alii*, 1990; Civita & De Maio, 2001) based on the GIS-based spatially distributed method (Canora *et alii,* 2018).

The hydrochemical characterization and the hydrogeological conceptualization are the main initial steps of the proposed approach inspiring the next steps based on the numerical groundwater simulation in which different future scenarios, characterizing the combined effects of natural and anthropogenic changes, will be considered up to the definition of the optimal mitigation and adaption actions.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF THE STUDY AREA

The MCP (Fig. 1), stretching 40 km along the Ionian coast of the Basilicata region, is the southernmost and most recent outcropping part of the Bradanic Through, bordering the Apulian foreland to NE and the Apennines Chain to SW. It is composed of regressive filling from Pliocene to the Pleistocene age with marine sediments deeply eroded by five major rivers running perpendicular to the shoreline (Muzzillo *et alii,* 2020). From a geological point of view, four main complexes can be identified, also characteristic from a hydrogeological point of view. They are, from the bottom to the top: the Argille Subappennine (Subapennine Clays) Formation; the Marine terraced deposits; the Alluvial, transitional, and marine deposits; and the Coastal deposits (Fig. 1).

The Argille Subappenine Formation (Late Pliocene? - Middle Pleistocene in age) outcrops in small strips along the slopes of the river valleys. From the hydrogeological point of view, these deposits, consisting of clay and silty clay, can be classified as almost impervious and constitute the aquifer substratum (Polemio *et alii*, 2003a).

The Marine terraced deposits (regressive deposits consisting, from the top downstream towards the coast, of conglomerates, sands, and pebbles in a sandy and/or clayey matrix, of Middle-Upper Pleistocene in age), overlying the Argille Subappenine Formation, outcrop in the upland segments of the study area. The flat-topped surfaces of the terraces are broken off both by the river valleys and by marked morphological steps representing the marine terraced scarps, that run roughly parallel to the present coastline and should represent the ancient coastlines and so the phases of sea level standing (Parea, 1986).

Alluvial, transitional and marine deposits widely outcrop in the coastal plain. Alluvial deposits constitute the valley floor of the major rivers present in the area and of some of their tributaries. Along river valleys, the alluvial deposits are essentially made up of sandy silts and silty-clayey layers, with interspersed sandy strata. In the coastal plain, the alluvial sediments are more distinctly sands, gravels, and silts and overlay buried transitional deposits consisting of sandy, silty, and silty-clayey layers variously distributed in the space. The coastal alluvial sediments show medium hydraulic conductivity (Polemio *et alii,* 2003b).

The Ionian littoral is mainly defined by sandy beaches, becoming gravelly-sandy or sandy with pebbly lens moving towards the Sinni area (Cocco *et alii*, 1975). The beaches are bounded inland both by marshy areas and by coastal dunes, made up of sands, packed and weakly cemented.

Briefly, it is possible to say that the MCP extends orthogonally to the coast from the upper marine terraces to the Ionian littoral.

The spatial distribution of the different formations and geomorphological evolution led to the setting of different boundary conditions for the groundwater flow system. Three different types of aquifers can be distinguished (Polemio *et alii*, 2005). Two of these are inland aquifers constituted by Marine terraced deposits and alluvial deposits of river valleys that anastomose in the coastal plain aquifer, which is the third one. All the aquifers are mainly unconfined, apart from some portions, which are confined. Groundwater flows from the Marine terraced deposits and the river valley alluvial deposits to the coastal plain aquifer. The recharge of the coastal plain aquifer is mainly guaranteed by the discharge from upward aquifers and by the river leakage.

The hydraulic conductivity of the Marine terraced deposits is generally from medium to high, with the highest values of 10^{-3} m/s (Polemio *et alii*, 2003b) corresponding with the sandy and gravelly sediments, and becomes very low for the silty-clayey levels.

The plain deposits have, on a large scale, a medium hydraulic conductivity, assessed as 2.3×10^{-4} and 6.5×10^{-5} m/s for mean and median values, respectively (Polemio *et alii*, 2003b); the hydraulic conductivity can locally change to very low values for the silty-clayey layers.

The plain deposits create a shallow sandy aquifer, which is generally the only one exploited for any kind of practical utilization. The aquifer bottom, which is located below the sea level along a coast strip, increases the proneness to SWI in the test site area, which was selected for the next research steps, up to the numerical modeling and definition of management criteria.

MATERIAL AND METHODS

Data collection

The selection of potential areas most subjected to SWI was been carried out by the data analysis, considering the following parameters: depth to water, saturated aquifer thickness, depth of the shallow aquifer bottom, hydraulic conductivity, and aquifer grain size.

The collection of the historical data series and the analysis thereof have focused on the geological, geochemical, hydrological, and hydrogeological data. The early stage of the study has concerned the geological, hydrogeological, and geotechnical description of the study area as well as the chemical and physical characterization of groundwater. The investigation was conducted on: the existing bibliography, including ISPRA geological maps, geological reports, and publications; hydrogeological data sets, and groundwater chemical and physical descriptions; and maps on a scale ranging from 1:100,000 to 1:10,000.

As many as 1,130 wells have been surveyed in the study area (Polemio *et alii*, 2003a). The location, the geometry, and the depth of the wells have been recorded in the database. Stratigraphic, piezometric, and physical and chemical data are available for some of the wells as the historical series are drawn from various sources. Briefly, stratigraphic and hydrological data are available for 71.9% of the wells, whereas chemical data are available for 13.9% of them. Geotechnical data, which pertain to 5.6% of the wells, have been inferred from the geognostic surveys which had been carried out during road works.

The examined geological and hydrogeological parameters comprise: the depth to the bottom aquifer, generally a clayey layer-inferred from stratigraphic surveys; the piezometric head above sea level, and the well tests. These data were used to assess more additional parameters, such as the depth to water or the unsaturated zone thickness, the hydraulic conductivity, and the type of groundwater flow (phreatic or confined). The data were collected by many institutions such as *Regione Basilicata, Ministero dell'Ambiente, Servizio Idrografico Nazionale, Anas*

S.p.A., Comune di Policoro, Comune di Scanzano Jonico, Ente per lo Sviluppo dell'Irrigazione e la Trasformazione Fondiaria in Puglia, Lucania e Irpinia, and *Consorzio di Bonifica di Bradano e Metaponto* (Polemio *et alii*, 2003a). The wealth of information assembled to characterize the geological and hydrological conceptualization of the MCP was extracted from a vast array of sources and dates to various periods. Hence, huge efforts have been put to make data comparable and overlapping and validate the findings in keeping with the objectives of this research activity. To manage space-related information, a Geographic Information System (GIS) was used, allowing the management and organization of databases containing information relating to all the surveyed wells. Any kind of collected data was georeferenced and implemented in a geodatabase on the QGIS platform. The thematic layers thus created have been and will be gradually updated with new data that will be acquired through on-going surveys.

The study pursues the definition of a reliable conceptual model, representative of the aquifer system. A solid conceptual model can arise from a multidisciplinary approach, which schematizes reality taking into account the numerous factors that contribute to determine the system's behavior and its response to external variations. This phase of the work is necessary to define the hydrostructural and hydrodynamic characteristics of the aquifer system and to understand the mechanisms that regulate the quantity and quality aspects of water resources. Based on such a conceptual model, it is possible to define groundwater modeling, a useful tool also in terms of management and planning the water resources.

Hydrochemical Survey

The hydrochemical study was finalized both to define the groundwater chemical characteristics and the existence of other relevant processes apart from fresh-salt water mixing, especially at the salt/fresh water interface, as the cation exchange processes. The hydrochemical study focused on 53 groundwater samples for which on-site chemical-physical parameters (EC or electrical conductivity at 25 °C, T or temperature (°C) and pH) and main ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-}, and HCO_3^-) were determined. Each sampled well was purged using a flow cell and a multi-parametric probe with EC, T, and pH sensors, withdrawing 3 water-well volumes in low flow conditions. When steady parameter values were observed, the sampling was performed. The main constituents of waters were determined using ion chromatography methods, whereas the total alkalinity values of the samples were determined by titration with 0.1 N HCl. The locations of the sampling points are shown in Fig. 2.

The fraction of seawater (f_{sea}) in the samples was calculated from the concentration of the chloride ions (mmol/L), considered a conservative ion in the mixing process (Appelo & Postma, 2005):

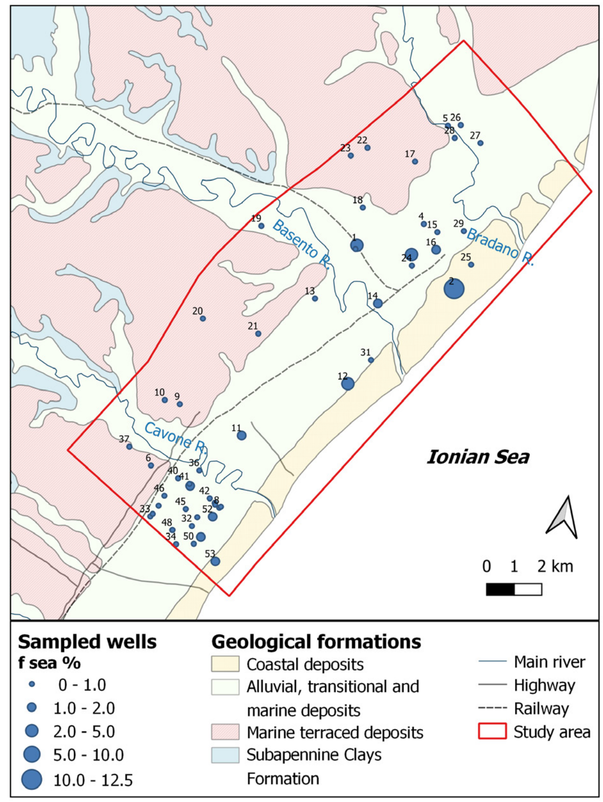

Fig. 2 - Map of the sampled wells

$$f_{sea} = \frac{m_{Cl^-,sample} - m_{Cl^-,fresh}}{m_{Cl^-,sea} - m_{Cl^-,fresh}}$$

As end points, we used the seawater sample and a pure fresh groundwater sample, corresponding to well 43, which showed the lowest chloride concentration (0.45 meq/L).

The expected concentration of the different ions ($m_{i,mix}$), resulting from mixing between fresh water and saltwater, can be calculated by:

$$m_{i,mix} = f_{sea} \times m_{i,sea} + (1 - f_{sea}) \times m_{i,fresh}$$

where $m_{i,sea}$ and $m_{i,fresh}$ are the seawater and freshwater concentrations of the ion *i* (mmol/L), respectively. The enrichment or depletion ($m_{i,react}$) of the ion *i* is then obtained by:

$$m_{i,react} = m_{i,sample} - m_{i,mix}$$

The $m_{i,react}$ may take both positive and negative value, or be equal to zero (only mixing). Positive or negative values of $m_{i,react}$ indicate the presence of geochemical processes that modify the water hydrochemistry in addition to simple mixing (Tab. 4).

Inverse Hydrogeological Water Balance

The assessment of the aquifer recharge is necessary to define the priority protection measures and the sustainable management of groundwater. In the literature, there are several direct and indirect methods for the estimation of groundwater recharge, each with a different degree of approximation depending on the availability of data and space-time scales considered (Simmers, 1988). Direct methods describe the mechanism of water percolation from the soil to the aquifer by simulating water flows and storage at temporal and spatial resolutions based on meteorological, topographical, land cover, and hydrogeological input parameters. Since in most cases not all these data are available, it is necessary to use indirect methods using variables that represent the flow of water through the soil and allow the definition of the relationship between flow and recharge (Scanlon *et alii,* 2002). To evaluate the annual groundwater recharge of the MCP, the inverse hydrogeological water balance approach was applied (Celico, 1988; Cotecchia *et alii*, 1990; Civita, 2005; Canora *et alii,* 2018; Canora & Sdao, 2020). This indirect methodology consists in the calculation of the effective infiltration considering climate data, such as rainfall and temperature, and topographic and hydrogeological parameters, such as the altitude and the characteristics of the hydrogeological complexes present in the basin under consideration (Civita & De Maio, 2001; Civita, 2005). This method implemented in the GIS environment allows to derive the spatial distribution of the infiltration rate (potential recharge of the aquifer) in the hydrogeological basin based on geostructural and hydrogeological data (Canora *et alii*, 2018). In QGIS software, a 5 m-resolution Digital Terrain Model (DTM) of the study area was used, and the location of the thermic and rainfall gauges, located inside or bounding the area, was georeferenced (Tab. 1). Despite the apparent homogeneous distribution of the thermopluviometric stations in the study area, to obtain a better correlation between the precipitation data and the altitude, some stations located in the vicinity of the study area were considered due to the lack of points climate monitoring at the highest altitudes (Tab. 1 and Fig. 3).

Subsequently, daily rainfall and air temperatures series were collected, in the period 2000-2015, from ALSIA (Lucanian Agency for Development and Innovation in Agriculture).

The inverse hydrogeological water balance uses rainfall as the main input variable into the system. The water balance equation provides the average annual assessment of the hydrological variables:

$$P = ET_r + I + R \qquad (1)$$

where: P indicates the rainfall (mm), ET_r is the amount of actual evapotranspiration (mm), I is the effective infiltration (mm) that can be considered as the active recharge, and R is the direct runoff

Station	Lat. N	Long. E	m (a.s.l.)
Bernalda, C.da Pezzagrande	40°26'23"	16°45'45"	49
Metaponto, AASD Pantanello	40°26'24"	16°54'46"	9
Montalbano Jonico, C.da Cozzo del Fico	40°16'53"	16°36'52"	151
Montescaglioso, Fiumicello	40°28'49"	16°43'12"	45
Nova Siri, Agriturismo La Collinetta	40°8'51"	16°35'21"	136
Pisticci, C.da Castelluccio	40°21'53"	16°37'13"	189
Pisticci, Pisticci Scalo	40°24'48"	16°34'40"	49
Policoro, C.da Troyli	40°13'33"	16°37'32"	115
Policoro, Pantano Sottano	40°10'60"	16°41'17"	4
San Giorgio Lucano, Piano delle Rose	40°8'17"	16°21'49"	455
Stigliano, C.da Torre	40°23'35"	16°20'9"	285

Tab. 1 - Thermopluviometric gauges locations (altitude, m. a.s.l.)

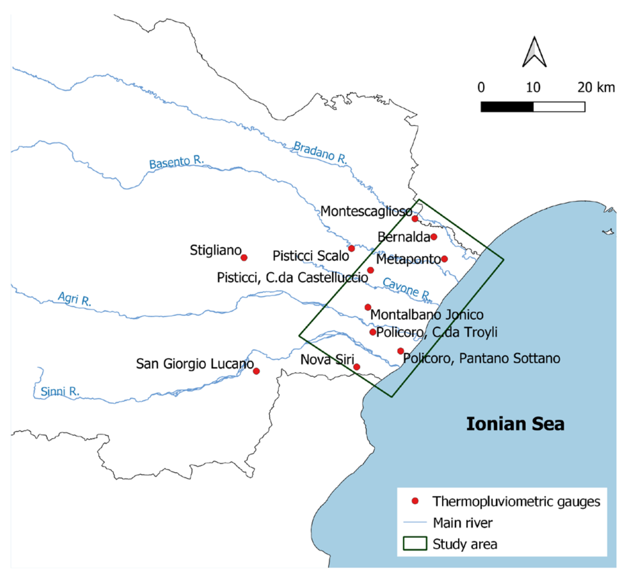

Fig. 3 - Thermopluviometric gauges locations

(mm). Starting from the daily rainfall and temperature data, related to the reference period (2000-2015), the monthly and annual averages of the rainfall and thermic data for each gauge were calculated. The average monthly temperatures were used to calculate for each gauge the corrected mean annual temperature (T_c), also depending on rainfall, by using:

$$T_c = (\sum P_i \, T_i\,) \,/\, (\sum P_i) \qquad (2)$$

where: P_i is the average monthly rainfall (mm) and T_i indicates the temperature (°C) of the i-th month, with i from 1 to 12, counting from January. The spatial distribution of corrected temperature and rainfall across the study area was estimated using the straight-line correlation between the thermic and pluviometric data with the altitude q by the definition of linear regression functions $T_c = f(q)$ and $P = f(q)$:

$$T_c\,(°C) = -\,0.0034 \times q\;(m\;a.s.l.) + 14.727 \quad (r^2 = 0.8582) \qquad (3)$$

$$P\,(mm) = 0.5149 \times q\,(m\ a.s.l.) + 507.22 \quad (r^2 = 0.8711) \quad (4)$$

These functions were used to compute the water balance within the whole study area by using a GIS procedure. The altitude in each cell was derived from the DTM.

The corrected temperature T_c is necessary to estimate the real evapotranspiration. Due to the limited availability of temporal and spatial meteorological datasets, the real evapotranspiration was calculated by applying the empirical Turc's formula (Turc, 1954), based on annual rainfall and air temperature data:

$$ET_r = \frac{P}{\sqrt{0.9 + \left(\frac{P}{300+25T_c+0.05T_c^3}\right)^2}} \quad (5)$$

where: ET_r is the average real annual evapotranspiration (mm), P is the average annual rainfall (mm), and T_c is the corrected average annual temperature (°C). The reliability of Turc's empirical model was confirmed by several studies carried out in the Mediterranean basin and European areas (Turc, 1954; Santoro, 1970; Parajka & Szolgay, 1998; Allocca *et alii,* 2014). The effective rainfall P_e, evaluated for each cell as the difference between mean annual rainfall P (mm) and mean annual real evapotranspiration ET_r (mm), represents the sum of effective infiltration I (mm) and direct runoff R (mm):

$$P_e = P - ET_r = I + R \quad (6)$$

The effective infiltration (the water rate that percolates underground) is related to the infiltration capacity of the geological formations depending on many factors such as outcropping lithologies, soil textures, and land use, expressed by the identification of the appropriate set of potential infiltration coefficients χ (Tab. 2) (Civita, 2005; Canora *et alii,* 2018). The

Geological formation	χ
Alluvial, transitional and marine deposits	0.75
Coastal deposits	0.80
Marine terraced deposits	0.85
Subapennine Clays formation	0.15

Tab. 2 - Values of χ, the potential infiltration coefficient

potential infiltration coefficient was assigned to each geological formation present in the area considering the characteristics of the aquifer system and referring the permeability of the complexes to the literature values (Civita, 2005). The effective infiltration was calculated in each cell by using effective rainfall values and potential infiltration coefficients:

$$I = P_e \times \chi \quad (7)$$

where: I is the mean annual effective infiltration (mm), P_e is the mean annual effective rainfall (mm), and χ is the potential infiltration coefficient (dimensionless).

The direct runoff rate (the flow rate on the topographic surface) was calculated as the difference between the effective rainfall P_e and infiltration I:

$$R = P_e - I \quad (8)$$

RESULTS AND DISCUSSION

Hydrochemical Survey

Table 3 provides a statistical outline, listing the minimum, the maximum, the mean, and the standard deviation values of each chemical parameter.

Value	EC	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	F^-	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-
	µS/cm at 25 °C	-	meq/L								
Minimum	337.00	6.69	0.63	0.07	0.49	0.53	0.01	0.45	0.02	0.07	1.07
Mean	1522.90	7.50	7.59	0.47	3.66	3.84	0.04	6.03	0.31	3.29	6.25
Maximum	8697.34	9.64	73.95	2.17	8.78	12.62	0.12	76.16	1.84	20.05	14.19
SD	1245.17	0.68	10.60	0.48	2.33	2.58	0.03	10.46	0.38	3.95	2.92

Tab. 3 - Descriptive statistics for the physical-chemical parameters of groundwater

The concentrations of the major ions estimated for each sample are plotted in the Piper diagram (Fig. 4), used to show the geochemical facies and water types. Three dominant types of groundwater have been distinguished: the HCO_3-Ca, the SO_4-Cl-Na, and a mixed Ca-Mg-Cl water type. Most of the samples showing an HCO_3-Ca type are representative of groundwater flowing in the Marine terraces and Alluvial deposits, whereas most of the SO_4-Cl-Na type is characteristic for the samples taken in the coastal plain deposits. The peculiarities of each aquifer

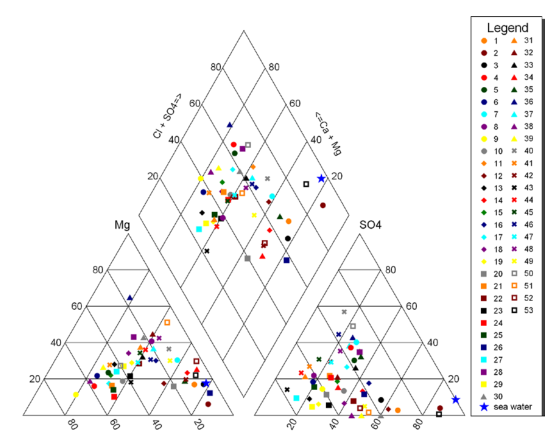

Fig. 4 - Piper diagram of sampled groundwater

domain are reflected in the water type; a significant dispersion is observed in Fig. 4, which means that other processes can be observed.

Apart from the anthropogenic role, which could worsen the groundwater quality along the path from the inland recharge areas to the outflow coastal area (Polemio & Limoni, 2006), we took into account the natural role of ion exchange processes that occur in the coastal aquifers by the effect of SWI or displacement of seawater by freshwater (freshening).

The composition of fresh groundwater in coastal areas is dominated by Ca^{2+} and HCO_3^- ions, which result from calcite dissolution, while in seawater the dominant ions are Na^+ and Cl^-. If groundwater samples of a coastal aquifer show Ca^{2+} surplus, compared to the conservative mixture, it could be due to SWI effects, while a surplus of Na^+ may indicate aquifer freshening (Appelo & Postma, 2005).

As resulted from Tab. 4, where only water samples showing significant changes are listed, the water samples 3, 14, 26, 31, 34, 35, 52 show enrichment of Na^+ and HCO_3^- together with a depletion of Ca^{2+} ions, which are indicative of aquifer. The remaining samples show enrichment of Ca^{2+} together with a depletion of Na^+ and K^+ ions, indicative of a progressive mixing with saline water, due to lateral and/or upconing effects of SWI.

Sample location	f % $_{(sea)}$	Na^+_{react}	K^+_{react}	Ca^{2+}_{react}	Mg^{2+}_{react}	$SO_4^{2-}{}_{react}$	$HCO_3^{2-}{}_{react}$
3	2.22	5.69	-0.13	-1.02	1.91	0.77	4.80
4	0.40	-1.19	-0.22	4.88	0.68	3.12	-0.26
5	0.74	-1.46	-0.26	5.39	2.28	3.66	1.63
6	0.29	-0.76	-0.25	4.27	1.41	1.34	3.38
9	0.33	-1.97	-0.14	5.17	-0.03	0.61	1.94
10	0.81	-0.80	-0.23	4.21	1.28	1.06	3.57
12	2.53	-2.38	1.28	3.70	1.80	-0.54	4.74
13	0.30	-1.17	0.34	2.35	1.80	0.14	3.26
14	1.21	2.43	0.25	-0.58	2.24	1.25	3.23
15	0.60	-1.12	-0.25	4.23	1.62	1.64	2.90
16	1.26	-1.13	0.40	1.43	3.41	2.07	2.47
17	0.79	-0.84	-0.25	6.43	1.49	3.59	3.29
18	0.50	-1.94	-0.21	0.61	1.68	-0.29	0.72
19	0.53	-0.29	-0.01	2.22	2.47	-0.06	4.84
21	0.49	-0.11	-0.27	4.45	0.88	2.08	3.18
22	0.97	-1.40	-0.20	2.07	2.49	0.15	3.06
23	0.71	-0.24	-0.13	3.21	1.64	-0.12	4.93
24	0.11	-0.68	-0.31	0.43	-0.58	0.12	-1.77
25	0.19	-0.30	-0.32	1.62	-0.07	0.41	0.85
26	0.92	1.09	-0.39	-1.87	-0.44	0.51	1.36
28	0.63	-0.71	-0.36	1.57	5.02	3.58	0.13
29	0.27	-1.40	-0.33	0.07	0.44	-0.42	1.71
31	0.07	0.66	-0.31	-0.14	2.07	0.59	0.05
34	0.38	3.16	-0.34	-1.81	1.36	0.49	0.47
35	0.52	1.81	-0.35	-0.98	0.49	2.51	-0.60
41	0.06	-0.91	-0.24	0.30	0.50	0.90	-0.32
47	0.34	-0.30	0.82	1.36	2.16	2.47	1.47
50	0.44	-1.13	0.66	3.02	2.27	6.04	-0.01
52	1.71	2.67	0.28	-1.87	4.25	-0.33	6.61

Tab. 4 - Fresh-saline mixing and effects of cation exchange

Inverse Hydrogeological Water Balance

The aquifer recharge of the study area was carried out by applying the GIS-based distributed inverse hydrogeological water balance method (Celico, 1988; Lerner *et alii*, 1990; Civita & De Maio, 2001; Canora *et alii*, 2018), which provided the distribution of all hydrogeological water balance components in the hydrogeological basin described above (Fig. 5). These values are averaged over the reference period of observations from 2000 to 2015 (Tab. 5).

Variable	mm/y
Rainfall (*P*)	538
Actual evapotranspiration (ET_r)	465
Effective infiltration (*I*)	52
Direct runoff (*R*)	21

Tab. 5 - Annual mean amount of the inverse hydrogeological water balance variables

In the hydrogeological basin, with an extension of about 655 km^2, the mean annual rainfall is about 538 mm. The results of the inverse hydrogeological water balance procedure show that the effective evapotranspiration (equal to 465 mm) provides an effective infiltration rate equal to 52 mm/year, which is equivalent to about 1080 l/s. The mean annual value of direct runoff is equal to 21 mm/year.

The groundwater recharge is about 10% of the total amount of rainfall, a low rate due to the unfavorable climatic conditions and the low hydraulic conductivity of the topsoil (Polemio *et alii*, 2003b; Muzzillo *et alii*, 2020). The spatial distribution of the mean annual effective infiltration shows changing behavior throughout the entire basin due to the different infiltration capacities of the geological formations. In particular, the lowest infiltration values are found in correspondence with the Argille Subappenine Formation, where direct recharge is essentially interdicted by the presence of a surficial silty and clay layer (Polemio *et alii,* 2003b). The main water supply of the aquifer comes from the points at higher altitudes of the Marine terraced deposits, where the highest value of rainfall and infiltration can be found. From inland toward the coastline, direct infiltration tends to decrease, with values below 50 mm/y. The direct natural recharge of the shallow coastal aquifer is extremely low due both to the low actual rainfall and mainly to the low hydraulic conductivity of the topsoil. The recharge is mainly guaranteed by the discharge from the upward aquifers of the Marine terraced deposits and the river leakage.

The aquifer's active recharge amount plays an important role to obtain adequate groundwater resources management, which will be probably strongly conditioned by future climate trends.

CONCLUSIONS

The multidisciplinary approach underlying the research project can be useful for groundwater resources management purposes from both a quality and quantity point of view. An effective conceptualization of the MCP is important for understanding the mechanisms involved in SWI and represents a useful tool to support groundwater management,

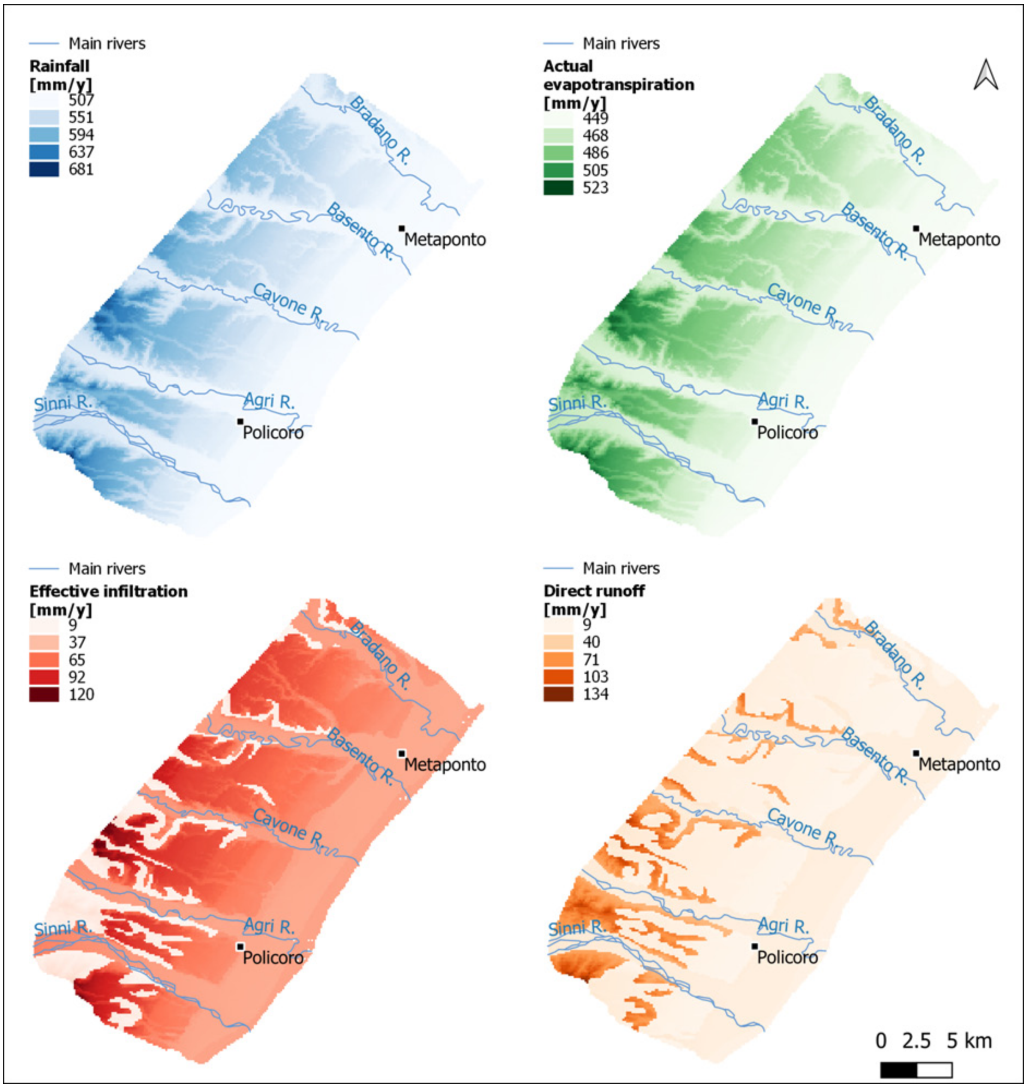

Fig. 5 - Spatial distribution of the annual mean amount of the inverse hydrogeological water balance variables evaluated from 2000 to 2015

simulating possible future scenarios with variations in rainfall, temperature, sea level, and salinity. The proposed approach could be helpful for decision-makers to manage resource utilization while ensuring its availability and quality.

The evaluation of the effective recharge can be useful to identify the priority quantity protection measures for sustainable groundwater planning and management in the study area. The inverse hydrogeological water balance method is relatively simple to apply and its application allowed the estimation of effective infiltration for the entire hydrogeological basin.

According to the hydrochemical analysis of 53 groundwater samples, the ion exchange processes are dominant in this coastal aquifer, showing the effects of SWI and the displacement of seawater by freshwater.

Research on this aquifer system needs to be continued and expanded to improve the knowledge of the salinization process. In particular, the conceptual hydrogeological model of the aquifer must be defined, and in situ activities as hydrogeological and geognostic surveys are essential for the consolidation and validation of the numerical model.

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