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SEAWATER INTRUSION VULNERABILITY ASSESSMENT BY GALDIT METHOD IN THE METAPONTO COASTAL AQUIFER (BASILICATA, ITALY)

Rosalba MUZZILLO[(*)], Filomena CANORA[(*)], Maurizio POLEMIO[(**)] & Francesco SDAO[(*)]

[(*)]Università degli Studi della Basilicata - Scuola di Ingegneria - 85100 Potenza (Italy)
[(**)]CNR-IRPI, National Research Council - Research Institute for Hydrogeological Protection - 70126 Bari (Italy)
Corresponding author: filomena.canora@unibas.it

EXTENDED ABSTRACT

Gran parte degli acquiferi costieri ricadenti in aree densamente popolate sono interessati dal fenomeno dell'intrusione salina, ormai riconosciuto come un problema concreto dal punto di vista ambientale, economico e sociale (Scheidleger *et alii*, 2004). Nelle regioni del Mediterraneo questi acquiferi costituiscono importanti serbatoi di risorse idriche destinate ad uso potabile, ma nello stesso tempo risultano essere sistemi idrogeologici estremamente vulnerabili, perché minacciati dai fenomeni di inquinamento dovuti alla pressione antropica e al fenomeno dell'intrusione salina, dal sovrasfruttamento della risorsa e dagli effetti dei cambiamenti climatici. La conoscenza dettagliata di tali sistemi acquiferi, la valutazione della vulnerabilità e del rischio al fenomeno di intrusione salina contribuiscono ad una più efficace gestione e protezione delle risorse idriche sotterranee.

L'obiettivo di questo studio è stato quello di valutare la vulnerabilità delle acque sotterranee all'intrusione salina, nell'acquifero costiero della piana di Metaponto (regione Basilicata, Italia meridionale) attraverso l'applicazione del metodo GALDIT, condotta con l'ausilio del sistema informativo geografico open source QGIS.

La piana costiera di Metaponto rappresenta un'area importante per l'intera regione sia per la sua spiccata vocazione agricola che per gli insediamenti abitativi, le strutture turistiche, le aree boschive e le zone umide. L'area di studio si estende per circa 40 km in direzione SO-NE dal fiume Sinni al fiume Bradano, e in direzione SE-NO dalla costa fino a circa 9 km verso l'interno. La piana, notevolmente antropizzata, è soggetta ad una crescente espansione turistica e a pratiche agricole intensive di pregio. L'assetto superficiale e sub-superficiale dell'area oggetto di studio, caratterizzato dalla presenza di terrazzi marini, piane costiere e paleoalvei, è il risultato di processi evolutivi di sedimentazione, erosione e variazioni del livello del mare dovuti all'azione degli agenti morfologici marini e fluviali. Da un punto di vista geologico, l'area appartiene alla successione sedimentaria della Fossa Bradanica, costituita, dal basso verso l'alto, dalla Formazione delle Argille Subappennine (Pliocene superiore?-Pleistocene medio) (Vezzani, 1967; Parea, 1986), passanti verso l'alto ai Depositi Marini Terrazzati (Pleistocene medio-superiore) e ai Depositi Alluvionali e Costieri (Pleistocene superiore?-Olocene), in discordanza sulle Argille Subappennine (Tropeano *et alii*, 2002; Pescatore *et alii*, 2009; Cilumbriello *et alii*, 2010; Sabato *et alii*, 2018). L'idrogeologia della piana è caratterizzata dalla presenza di un complesso sistema acquifero costiero, all'interno del quale si incontrano acque continentali e acque marine (Post, 2005). Le indagini condotte e i diversi dati raccolti hanno permesso una ricostruzione dell'assetto geolitologico ed idrogeologico dei diversi acquiferi presenti nell'area di studio e la definizione dei caratteri chimico-fisici delle acque sotterranee (Cilumbriello *et alii*, 2010; Muzzillo *et alii*, 2021a; Muzzillo *et alii*, 2021b). In particolare, le caratteristiche idrochimiche e la distribuzione spaziale della conducibilità elettrica delle acque sotterranee evidenziano che l'acquifero costiero è parzialmente interessato dal fenomeno dell'intrusione marina (Polemio *et alii*, 2002; Muzzillo *et alii*, 2021a; Muzzillo *et alii*, 2021b). Tale fenomeno è principalmente correlabile allo sfruttamento della falda idrica dovuto alle diverse attività antropiche e alle pratiche agricole, nonché agli attuali effetti del cambiamento climatico sulle risorse idriche sotterranee, in particolare, relativi al decremento della ricarica e all'innalzamento medio del livello del mare. Il metodo GALDIT è un metodo parametrico a punteggi e pesi (Chachadi *et alii*, 2003; Lobo Ferreira *et alii*, 2005), in cui i punteggi attribuiti a ciascun parametro vengono moltiplicati per una stringa di pesi che amplifica in varia misura l'importanza dei parametri stessi. Esso è specifico per la valutazione della vulnerabilità all'intrusione salina degli Acquiferi Costieri (Chachadi & Lobo Ferreira, 2001; Chachadi & Lobo Ferreira, 2005; Lobo Ferreira *et alii*, 2005; Polemio & Zuffianò, 2020) che, prendendo in considerazione i fattori intrinseci dell'acquifero quali: tipologia dell'acquifero (G), conducibilità idraulica dell'acquifero (A), quota della falda (L), distanza dalla linea di costa (D), impatto dell'intrusione marina nell'area (I) e spessore dell'acquifero (T), consente la determinazione e la zonazione dell'indice di vulnerabilità. La carta prodotta presenta tre classi ed evidenzia che l'alta vulnerabilità all'intrusione salina è stata rilevata lungo la fascia costiera, entro 500 m dalla costa, e copre circa il 7% dell'area investigata, con un'estensione di circa 20 km^2. Il 22.65% dell'area è caratterizzato da una moderata vulnerabilità, estendendosi mediamente fino a 4 km in corrispondenza dei fiumi Agri e Cavone, e con un'ampiezza di circa 7 km nell'area compresa tra i fiumi Basento e Bradano, dove lo spessore della falda risulta essere maggiore di 10 m, e in cui si riscontrano i più alti valori di conducibilità elettrica delle acque sotterranee. La bassa vulnerabilità copre la maggior parte dell'area di studio (70.40%), qui la quota piezometrica è più alta e la conducibilità elettrica delle acque sotterranee ha i valori più bassi. Dalla zonazione della vulnerabilità emerge che la propensione all'intrusione salina si accentua da SO verso NE, allargandosi dalla costa verso l'interno.

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ABSTRACT

The groundwater vulnerability assessment to seawater intrusion (SWI), applying the GIS-based overlay-index GALDIT method, is provided for the Metaponto coastal aquifer (Basilicata region, southern Italy). The method is based on six conditioning parameters: groundwater occurrence (G), aquifer hydraulic conductivity (A), groundwater level (L), distance from the shore (D), impact of the existing status of SWI (I), and aquifer thickness (T).

Three vulnerability classes were detected: low, moderate, and high, covering 70.40%, 22.65%, and 6.95% of the study area, respectively. The highest class is located close to the coastal sector due to the proximity to the sea, the greater thickness of the aquifer, and the shallow freshwater-seawater interface.

To evaluate the sensitivity of the method on the predictive analysis and the influence of the single parameter and weight on the final vulnerability, the sensitivity analysis was carried out. The single-parameter analysis indicated that the factors such as groundwater table above sea level (a.s.l.), aquifer type, and impact of SWI have the greatest influence on the vulnerability.

The application leads to the vulnerability mapping to SWI in the coastal plain that results to be a promising tool for decision-making finalized to properly manage groundwater.

***Keywords**: coastal aquifer, seawater intrusion, groundwater vulnerability, GALDIT method, Metaponto plain*

INTRODUCTION

Water supply has become a growingly crucial problem because of water scarcity. Coastal aquifer systems supply large fresh water amounts to millions of people all over the world (Post & Abarca, 2010).

In recent decades, human population growth has dramatically affected coastal areas in terms of groundwater overexploitation because of increasing demands for agricultural, industrial activities, and human consumption (Jackson *et alii*, 2001).

In coastal aquifers, seawater intrusion (SWI) has become one of the most serious threats imposed on groundwater quality (Polemio & Zuffianò, 2020). Indeed, this phenomenon alters groundwater chemistry with significant environmental and economic consequences determining impacts on agricultural systems and access to drinking groundwater. In these systems, extremely sensitive to changes caused by both natural and human activities, the flowing freshwater is in dynamic balance with salt water. The severity of SWI, beyond mankind's pressures, is determined by the hydrogeological characteristics of the aquifers that condition the vulnerability level, other factors can be recognized in the climate change effects and sea-level rise. The salinization of the coastal aquifers strongly affects the groundwater quality and consequently the availability of freshwater, damages ecosystems, and affects human health (Patel & Shah, 2008).

The phenomenon of SWI is mainly correlated to overpumping due to the different anthropic activities and agricultural practices, as well as to the current effects of climate change on groundwater resources. The impacts of climate change manifest in the reduced rainfall and recharge modification and the sea-level variations, which cause the advance landward of the freshwater-saltwater interface and further upstream into coastal estuaries (Costall *et alii*, 2020; Psomas *et alii,* 2021).

Groundwater vulnerability assessment to SWI represents an utmost importance tool to develop and propose the most appropriate and cost-effective groundwater management and protection strategies, for groundwater salinization prevention to make more resilient coastal aquifers and ecosystems.

Lobo Ferreira & Cabral (1991) defined groundwater vulnerability to SWI as "the sensitivity of groundwater quality to an imposed groundwater pumping or sea-level rise or both in the coastal belt, which is determined by the intrinsic characteristics of the aquifer". The intrusion of seawater into coastal groundwater highlights the importance of developing innovative and effective methods to prevent and mitigate the process of salinization.

Different researchers for assessing the vulnerability to SWI in coastal aquifers, several approaches, models, and methods have applied (Praveena & Aris, 2009; Younes A. & Fahs M., 2014; Kazakis *et alii*, 2018; Mavriou *et alii,* 2019; Moazamnia *et alii*, 2020).

The worldwide-applied overlay-index method for assessing groundwater vulnerability to SWI is GALDIT (Kura *et alii*, 2015; Trabelsi *et alii*, 2016; Luoma *et alii*, 2017; Kim *et alii*, 2021). Chachadi & Lobo Ferreira (2001) developed the GALDIT method for vulnerability assessment of coastal aquifers to SWI. GALDIT is the acronym for selected vulnerability indicators such as Groundwater occurrence, Aquifer hydraulic conductivity, water Level above sea level, Distance from the coastline, Impact status of existing seawater intrusion, and aquifer Thickness (meaning saturated thickness).

It is a numerical ranking system, based on six hydrogeological, topographic and morphological parameters with appropriately assigned ratings and weights (Chachadi & Lobo Ferreira, 2001; Chachadi & Lobo Ferreira, 2005; Lobo Ferreira *et alii*, 2005).

The overlay-index methods have been greatly enhanced due to the Geographic Information Systems (GIS) application, able to store, elaborate, and represent a wide amount of georeferenced data to assess groundwater vulnerability.

The main aim of this study was the assessment of the groundwater vulnerability to SWI, using a GIS-based application of the overlay-index GALDIT method in the Metaponto coastal aquifer system (Basilicata, southern Italy), finalized to a more detailed understanding of the hydrogeological conditions to develop effective managing plans to face the groundwater salinization process. The Metaponto coastal plain is an important economic and environmental area of the region, due to the presence

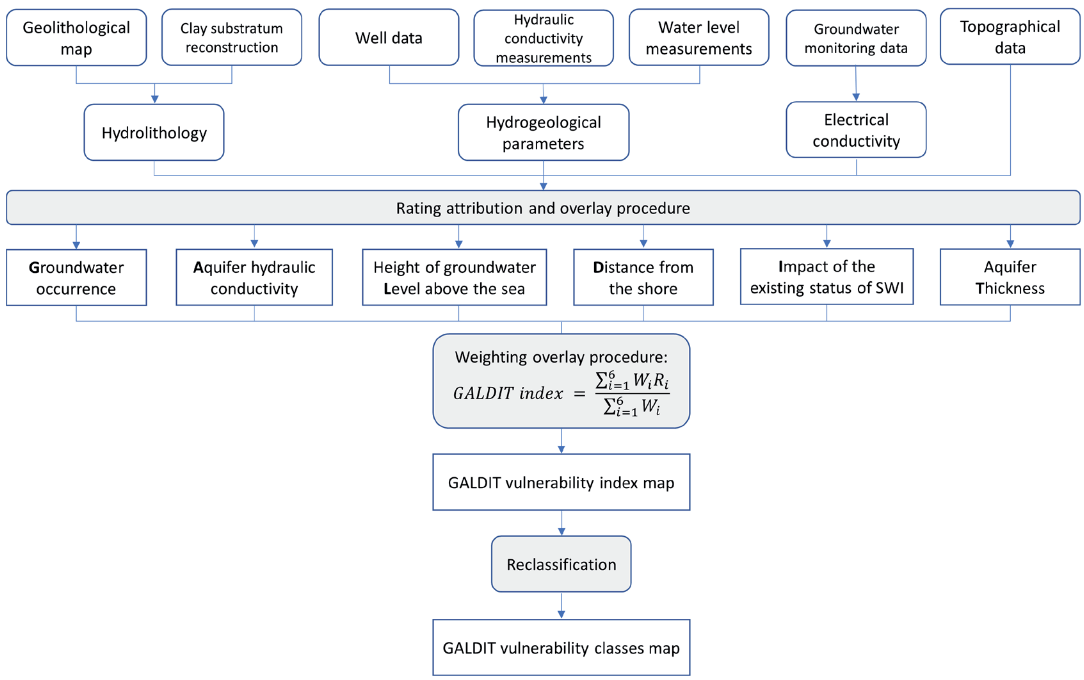

Fig. 1 - Flowchart of the GALDIT method

of agricultural and productive activities, residential and tourism settlements, wooded areas, and wetlands with high ecological value (Canora *et alii,* 2022). In the entire coastal plain, complex land reclamation of the marshy areas was conducted, starting from the middle of the last century, to modify the plain into an area of agricultural vocation with crops of great value. Extensive planning and territorial interventions relating to a significant tourist expansion have led to the construction of touristic villages close to the coastal area and marinas in correspondence with the main river mouths. The above-mentioned land-use modifications of the plain and the progressive human pressures have deeply changed the study area and the aquifer system causing the occurrence of seawater in freshwater.

The resulting increase in groundwater salinity is mainly due to excessive withdrawals and climate change, with the decrease of rainfall and increase in temperature trends (Polemio & Casarano, 2004; Polemio *et alii*, 2004) and seems to involve mainly a stretch of the coastal plain for a width of 1-1.5 km trends (Polemio *et alii*, 2003a). This can threaten wide areas inland compromising the ecosystem's health of the coastal areas, and damage the delicate habitats such as wetlands and marshes.

METHODOLOGY

Application of the GALDIT method

As part of the relevant issue of SWI in the Metaponto coastal aquifer, the GALDIT method was applied (Chachadi & Lobo Ferreira, 2001; Chachadi & Lobo Ferreira, 2005; Lobo Ferreira *et alii*, 2005), aimed at assessing the intrinsic vulnerability of groundwater. It takes into account the geological and hydrogeological conditions of a specific site regardless of the pollutant characteristics (Ducci & Sellerino, 2013; Medici *et alii*, 2021). This approach involves, before the actual application, the creation of a geodatabase and the processing of the collected data in a Geographic Information System (GIS). The development of GIS permitted the storage, elaboration, representation, and analysis of a huge quantity of georeferenced data over large spatial scales (Jha *et alii*, 2007). In this study, the use of QGIS software (version 3.16.4) made it easier to process and overlay the data required by the GALDIT method. The developed approach is low-cost, needs low computational time, and provides reliable outcomes.

GALDIT is an overlay-index method based on six hydrogeological, topographic, and geomorphological parameters that influence the SWI phenomenon: groundwater occurrence (G), aquifer hydraulic conductivity (A), the height of groundwater level above the sea (L), distance from the shore (D), the impact of the existing status of SWI (I), and aquifer thickness (T) (Fig. 1).

These conditioning factors of the aquifer give a time-independent evaluation of its vulnerability to SWI. The relationship used for the calculation of the GALDIT index is expressed as follows:

$$GALDIT\ index = \frac{\sum_{i=1}^{6} R_i W_i}{\sum_{i=1}^{6} W_i} \quad (1)$$

where R_i is the rating and W_i is the relative weight assigned to each parameter, respectively. The range, rating, and weight of the parameters depend on the local aquifer characteristics. The dataset was implemented in QGIS with information collected from the Regional Spatial Database and monitoring hydrogeological data of 42 wells. The study area was discretized with a 5 m resolution grid. In each cell, each factor was assigned a score depending on the proposed classification and the influence on the vulnerability, ranging from 2.5 (lowest vulnerability) to 10 (highest vulnerability). To produce the final vulnerability index, the chosen scores were multiplied by the weights string. Following the procedure, the weight 1 is assigned to Groundwater occurrence and Impact of the existing status of SWI parameters, to Aquifer thickness the defined weight is equal to 2, the weight 3 is attributed to Aquifer hydraulic conductivity parameter, whereas to the last two parameters Height of the groundwater level above the sea and Distance from the shore is assigned the highest weight, equal to 4, that represents the heaviest impact on vulnerability (Tab. 1). The six products thus obtained are added together and the result is then divided by the sum of the weights, equal to 15. The GALDIT index has a minimum value of 2.5 and a maximum value of 10.

The increase in the GALDIT index values indicates that the aquifer vulnerability to SWI also increases. The GALDIT index is classified into three classes: low (<5), moderate (from 5 to 7.5), and high (>7.5).

GALDIT parameters	Range	Rating	Weight
G – Groundwater occurrence	Bounded	2.5	1
	Leaky confined	5	
	Unconfined	7.5	
	Confined	10	
A – Aquifer hydraulic conductivity (m/day)	<5	2.5	3
	5-10	5	
	10-40	7.5	
	>40	10	
L – Height of the groundwater level above the sea (m)	>2	2.5	4
	1.5-2	5	
	1-1.5	7.5	
	<1	10	
D – Distance from the shore (m)	>1000	2.5	4
	750-1000	5	
	500-750	7.5	
	<500	10	
I – Impact of the existing status of seawater intrusion (μS/cm)	<1000	2.5	1
	1000-2000	5	
	2000-3000	7.5	
	>3000	10	
T – Aquifer thickness (m)	<5	2.5	2
	5-7.5	5	
	7.5-10	7.5	
	>10	10	

Tab. 1 - Ranges, ratings, and weights of GALDIT parameters

Sensitivity analysis

To overcome the limits of subjectivity in the ratings and weights attribution of the index methods such as GALDIT, the single-parameter sensitivity analysis was performed (Napolitano & Fabbri, 1996). This analysis helps to evaluate and understand the influence of the input parameters on the result by providing significant information on the impact of the weights assigned to the related factors. The following equation was used to obtain the effective weight W for each parameter P:

$$W = \frac{P_r P_w}{V} \cdot 100 \quad (2)$$

where P_r and P_w are the rating and weight, respectively, and V is the vulnerability index computed with Equation (1).

Furthermore, the sensitivity analysis based on map removal was carried out (Lodwick *et alii*, 1990). The purpose was to determine whether all parameters are actually required for the calculation of the GALDIT index or if one or more of them can be removed without significantly affecting the result. One parameter at a time was removed, and in each cell, the sensitivity measurement S was expressed as a variation index by the following equation:

$$S = \left(\frac{\left| \frac{V}{N} - \frac{V'}{n} \right|}{V} \right) \cdot 100 \quad (3)$$

where V is the unperturbed vulnerability index computed with all the N parameters, and V' is the perturbed vulnerability index calculated with fewer n input factors. By calculating the average variation index of all cells for each parameter, it is possible to understand which parameter can have a negligible effect on the result if it is not included.

STUDY AREA

The Metaponto coastal plain, covering an area of about 280 km^2, is located along the Ionian Coast on the southern side of the Basilicata region (Fig. 2). The coastal area is characterized by the presence of numerous inhabited and tourist villages and the primary economic activity is agriculture. The mean elevation and slope of the coastal area are about 20 m a.s.l. and 5%, respectively.

Bradano, Basento, Cavone, Agri, and Sinni rivers with the almost orthogonal trend to the Ionian coast constitute the hydrographic network of the Metaponto coastal plain, from NE to SW.

The main climatic characteristics of the study area are typical of the Mediterranean climate, with mild wet winters and dry summers. The highest rates of rainfall are detected during November and December, whereas the lowest rates occur during July and August. The highest monthly mean temperatures are recorded during the summer period in July and August with a value of 26.9 °C, whereas the lowest temperatures are observed in winter, with a minimum temperature in January of 9.3 °C.

The hydrological balance, elaborated in the reference period from 2000 to 2015, gives 538 mm as rainfall, 465 mm as actual evapotranspiration determined following Turc's formula (TURC, 1954), and the rate of 52 mm/year as effective infiltration, which is equivalent to about 1080 l/s, as mean annual values in the study area. The mean annual value of direct runoff is equal to 21 mm/year (MUZZILLO *et alii*, 2021a).

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

GEOLOGICAL SETTING

The Metaponto coastal plain is located along the Ionian coastal belt of the Basilicata region (southern Italy). Geologically, it corresponds to the southernmost and more recent outcropping sector of the Bradanic foredeep (MIGLIORINI, 1937; PESCATORE *et alii*, 2009) (Fig. 2). It has undergone a progressive stage of emersion 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 R. & BRIDGLAND D., 2007) and Quaternary eustatic sea-level changes (PESCATORE *et alii*, 2009).

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; CILUMBRIELLO *et alii*, 2010; SAUER *et alii*, 2010; GIOIA *et alii*, 2020).

Middle-Upper Pleistocene marine terraced deposits consist of thin gravel and medium-fine sands that unconformably overlie marine silty clays of the sub-Apennine Clays Formation (Upper Pliocene?-Middle Pleistocene) (TROPEANO *et alii*, 2002), outcropping in limited portions of the study area.

The Alluvial, transitional and marine deposits (Upper Pleistocene?-Holocene) are extensively present in the coastal plain. Silty-clayey and sandy silts layers, with interspersed sandy layers, constitute the alluvial deposits, mainly present along the river valleys and on flood plains. Gravel, sand, and silt layers of the delta and beach depositional environment, of the coastal plains and prograded up to the present Coastal Deposits, characterize the transitional and marine deposits (PESCATORE *et alii*, 2009; CILUMBRIELLO *et alii*, 2010; TROPEANO *et alii,* 2013; SABATO *et alii*, 2018). The Coastal Deposits, related to the recent sedimentary processes, are characterized by a low-gradient sandy beach, limited landward by several meters-thick dunes, striking mainly parallel to the shoreline (PESCATORE *et alii*, 2009; GIOIA *et alii*, 2020) (Fig. 2).

HYDROGEOLOGICAL CHARACTERIZATION

The hydrogeological characteristics of the Metaponto aquifer system reflect its geological and geomorphological setting. The aquifers are located in the marine terraced deposits, in the alluvial deposits of river valleys, and in the coastal plain.

The continuity of the aquifer that lies in the marine terraced deposits, showing medium to high hydraulic conductivity, is cut by the Ionian river valleys (POLEMIO *et alii*, 2003).

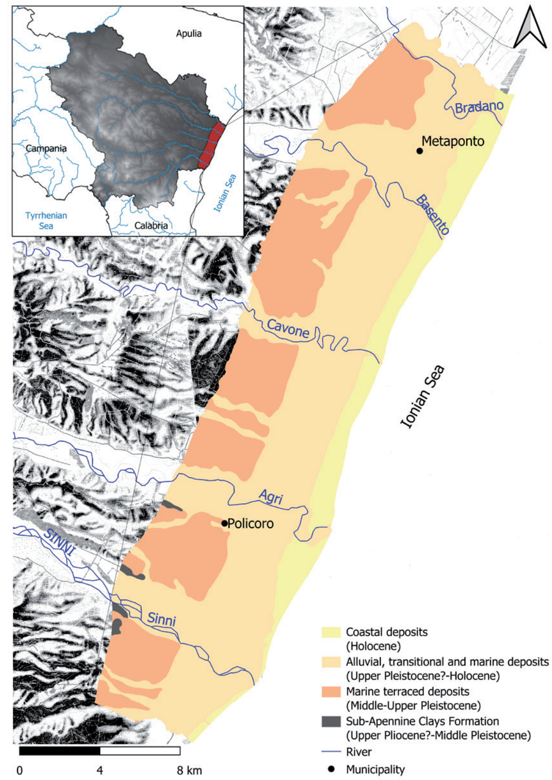

Fig. 2 - Schematic geological map of the Metaponto coastal plain (adapted from Geological Map of Italy 1:100.000 scale and 1:50.000 scale).

The aquifers of the alluvial paleo river valleys are very deep with limited lateral extension and show medium hydraulic conductivity.

The coastal plain aquifer, limited in-depth, has related medium-low hydraulic conductivity with respect to the previous ones; its importance is due to the continuity across the plain.

The mean and median hydraulic conductivity values of the plain deposits are 2.28 x 10^{-4} and 6.53 x 10^{-5} m/s, respectively, determined from pumping tests on a large scale referred to the entire plain (POLEMIO *et alii*, 2003). From inland to the shore, the hydraulic conductivity decreases, but its reduction in the proximity of the coast may not be sufficient to mitigate SWI risk.

The shallow coastal aquifer corresponds to the intermediate most permeable sandy thickness, characterized by a variable particle-size distribution confined within silty clayey impermeable levels of varying extents and thicknesses (POLEMIO *et alii*, 2003). The thickness of the permeable layers of the aquifer is greater than 10 m and generally tends to increase from the inland toward the coast. The silty clay formation constitutes the bottom of the coastal aquifer; it deepens towards the shore with an irregular surface, characterized by local depressions. The aquifer bottom gradually decreases from the Sinni to the Bradano rivers, in the SW-NE direction, and in the proximity of the coastline, it drops below sea level, potentially allowing SWI, along the coast in the northeastern direction, depending on the local hydrodynamic conditions (Polemio *et alii*, 2002).

The effective infiltration amount of about 52 mm/y, considered as recharge of the coastal aquifer system, is modest due to the climate conditions of the area (Muzzillo *et alii*, 2021a). The aquifer recharge is mostly guaranteed by the discharge from the marine terraces aquifer, and by river leakage. The spatial trend of the groundwater surface confirms the upstream groundwater recharge of the coastal aquifer (Fig. 3). The water table contour lines, nearly parallel to the coastline, allow identifying the preferential flow directions of the groundwater, oriented orthogonally to these lines, moving from the terraces to the coast.

According to the hydrogeochemical analysis, SWI affects groundwater quality, with higher effects closer to the coast (Muzzillo *et alii*, 2021b).

The main groundwater chemical characteristics can be traced back to two main types of groundwater: the bicarbonate-alkaline-earthy one (typical of the groundwater flowing in the marine terraces and alluvial deposits) and the sulfate-chlorinated-alkaline type (referable to wells located in coastal deposits).

The examination of the distribution of the main dissolved ions in groundwater showed in some cases the enrichment of Ca^{2+} together with the depletion of Na^{+} and K^{+} ions, indicative of a progressive mixing with seawater, potentially due to lateral and/or up-coning effects of SWI. According to the hydrochemical analysis of the groundwater samples, the ion exchange processes are dominant in this coastal aquifer, demonstrating the impacts of SWI and seawater displacement by freshwater (Muzzillo *et alii*, 2021a).

The trend of the fraction of seawater increased moving from inland to the shore, indicating the significance of SWI. These data suggested that the fresh-saline mixing was not negligible so far from the coast, confirming the negative role of the paleo valley on the groundwater salinization risk. The whole study area is vulnerable to SWI, not just the portion closest to the coast (Muzzillo *et alii*, 2021a).

RESULTS AND DISCUSSION

By applying the GALDIT method, the groundwater vulnerability assessment to SWI has been carried out.

The collected data and the thematic layers were implemented, elaborated, and represented in the QGIS environment. All GALDIT parameters according to the methodology above described (Fig. 1) were evaluated, rated, and weighted (Tab. 1). The spatial distribution of the GALDIT parameters was elaborated using the Kriging interpolation technique (Fig. 4).

G – Groundwater occurrence is related to confined and unconfined conditions of the aquifer and can influence the

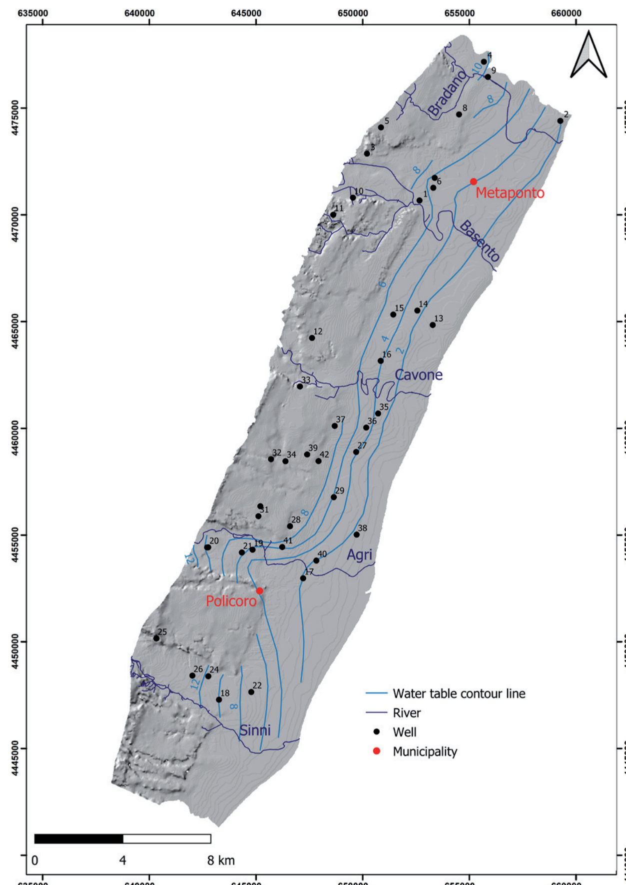

Fig. 3 - Simplified water table map of the Metaponto coastal plain

extent of SWI. The confined aquifer rating is higher (more vulnerable) because, during pumping, the depression cone is commonly larger than the unconfined aquifer. A large portion of the investigated aquifer system occurs in unconfined conditions, so it was given a rating of 7.5 (Tab. 1) (Fig. 4-a).

A – High hydraulic conductivity implies an increase in the magnitude of seawater front movement and consequently higher vulnerability to SWI. For the study area, the hydraulic conductivity values were derived from several pumping tests conducted in the study area over the previous twenty years (Polemio *et alii*, 2003). The hydraulic conductivity thematic layer was elaborated using these values. The study area's hydraulic conductivity varies from 10^{-5} to 10^{-3} m/s. The hydraulic conductivity expressed in m/day, with rating that ranges from 2.5 to 10, is shown in Table 1 (Fig. 4-b).

L – Groundwater table above sea level is a crucial factor in determining the extent of SWI due to its control of the hydraulic pressure to drive the seawater's front back. As the height of the water above sea level increases, the possibility of undergoing the intrusion phenomenon decreases. This parameter was derived

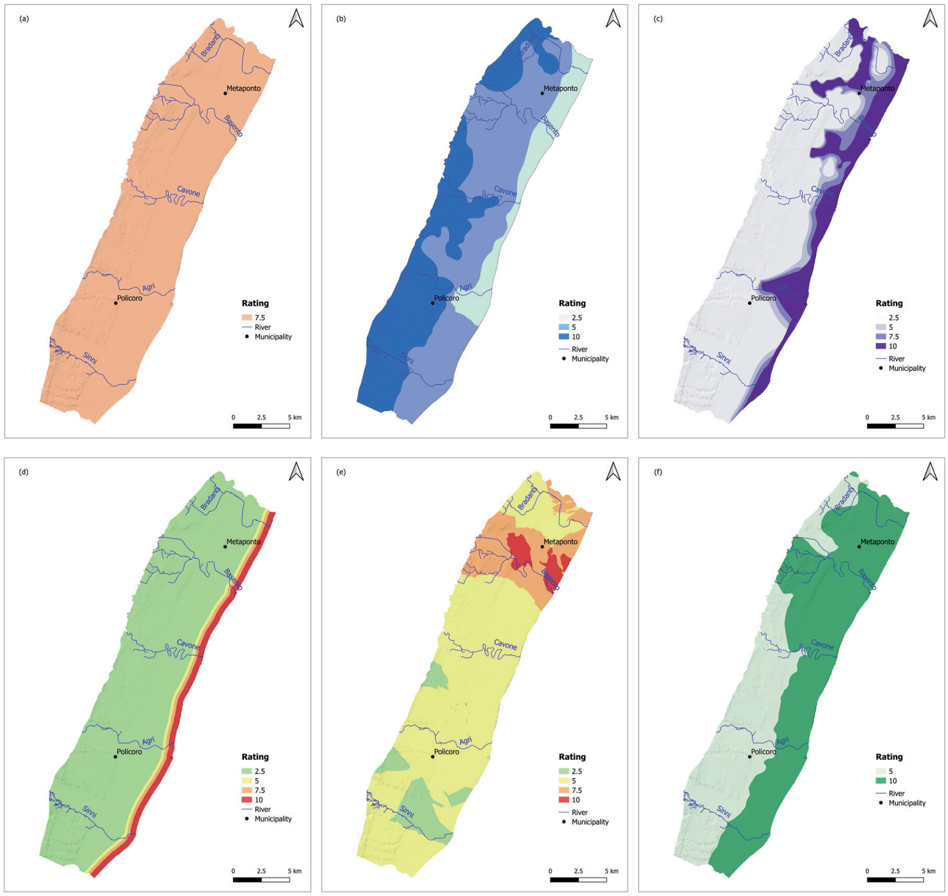

Fig. 4 - Thematic layers of the GALDIT parameters: (a) groundwater occurrence; (b) aquifer hydraulic conductivity; (c) groundwater table above sea level; (d) distance from shore; (e) impact of the existing seawater intrusion; (f) aquifer thickness

from measurements taken at 42 monitoring wells in the study area, used for agricultural and household consumption (Fig. 3). The height of groundwater level above the sea raster was rated following the four classes given in Table 1. The maximum impact of SWI is observed in the proximity of the coast and the impact decreases moving inland (Fig. 4-c).

D – The influence of SWI commonly decreases moving inland from the shore, the greatest influence is along the coast. Chachadi & Lobo Ferreira (2005) indicated the perpendicular distance inland from the coast and the height of the groundwater level above sea level as the factors with the highest influence on potential SWI, assigning them the maximum weight equal to 4. The distance from the shore was calculated using the four buffer zones tool of QGIS (500 m, 750 m, 1000 m, >1000 m) (Fig. 4-d).

I – To consider the effect of the existing SWI, firstly, Chachadi & Lobo Ferreira (2001) proposed using the groundwater $Cl^-/(HCO_3^- + CO_3^{2-})$ ratio. Then, Dörfliger *et alii* (2011) presented groundwater electrical conductivity as an alternative indicator of groundwater salinity, and this parameter has been used in literature for the computation of the GALDIT index (Luoma *et alii*, 2017; Chang *et alii*, 2019). In this study, the rates attributed to the I parameter by Chang *et alii* (2019) were used. The impact of the current status of SWI was expressed in terms of measured groundwater electrical conductivity (Tab. 1) (Fig. 4-e).

T – The extent and magnitude of SWI are heavily influenced by the aquifer thickness or saturated thickness, where the aquifer is unconfined. Aquifer with high thickness values is more prone to SWI than aquifer with lower thickness. In this study, the aquifer thickness was defined with respect to the top of the sub-Apennine Clays Formation, which represents the bottom of the aquifer. The thickness of the coastal aquifer is generally higher than 10 m and increases from inland to the coast (Polemio *et alii*, 2003) (Tab. 1) (Fig. 4-f).

By the GIS-based procedure, the final vulnerability index to SWI was elaborated by Equation (1).

The GALDIT index ranges from 3.3 to 8.5. The final map, showing the spatial distribution of the vulnerability to SWI, was obtained by reclassifying the GALDIT index defined in the study area.

Three vulnerability classes are depicted: low (GALDIT index <5), moderate (5-7.5), and high (>7.5) (Fig. 5). The results of the GALDIT application produced findings in accordance with the hydrogeological characteristic of the investigated area. Low vulnerability covers the majority of the study area (70.40%), in areas more than 1000 m away from the coast, where both the groundwater level above the sea and the groundwater electrical conductivity have the lowest values. The 22.65% of the area is characterized by a moderate vulnerability, extending on average up to 4 km in correspondence with Agri and Cavone rivers, and up to about 7 km in the area between Basento and Bradano rivers, where the aquifer thickness is greater than 10 m and the highest values of electrical conductivity, greater than 2000 µS/cm, have been measured. High vulnerability class to SWI was detected along the coastal strip, at a distance within 500 m from the coastline, and covers 6.95% of the investigated territory, with an extent of about 20 km^2. On the coastline, this result is primarily due to the proximity both of the detected area from the shore, and the freshwater-seawater interface. Another highly impacting factor on the final result is the aquifer thickness, which shows the highest value along the coast. As highlighted below, this phenomenon seems to be accentuated from SW towards NE, moving along the coast since the top of the grey-blue clay formation gently slopes from the Sinni to the Bradano rivers.

The statistics of the single-parameter sensitivity analysis were computed for each parameter (Tab. 2). The original theoretical weight provided by the GALDIT method, the theoretical weight normalized to 100, the average effective weight calculated over the entire study area, the standard deviation, and the minimum and maximum values are shown (Tab. 2). The analysis highlights that for almost every factor, the theoretical weights are lower than the effective ones. The Distance from the shore and the Impact of the existing status of SWI parameters showed the highest and lowest differences (in absolute value terms) between the effective and theoretical weights, respectively. The Aquifer hydraulic conductivity, with an average weight of 26.63%, has the greatest influence on the final vulnerability index. On the contrary, the Impact of the existing status of SWI has the lowest effective weight, equal to 6.90%, confirming the lowest value of the theoretical one (6.67%).

Parameter	Theoretical weight	Theoretical weight (%)	Average effective weight (%)	Standard deviation (%)	Minimum value (%)	Maximur value (%
G	1	6.67	9.84	1.72	5.88	15.00
A	3	20.00	26.63	12.23	6.00	42.86
L	4	26.67	20.67	9.94	10.26	50.00
D	4	26.67	15.71	5.73	8.51	42.11
I	1	6.67	6.90	2.02	2.00	16.00
T	2	13.33	20.25	6.46	9.30	33.33

Tab. 2 - Statistical summary of the GALDIT single-parameter sensitivity analysis

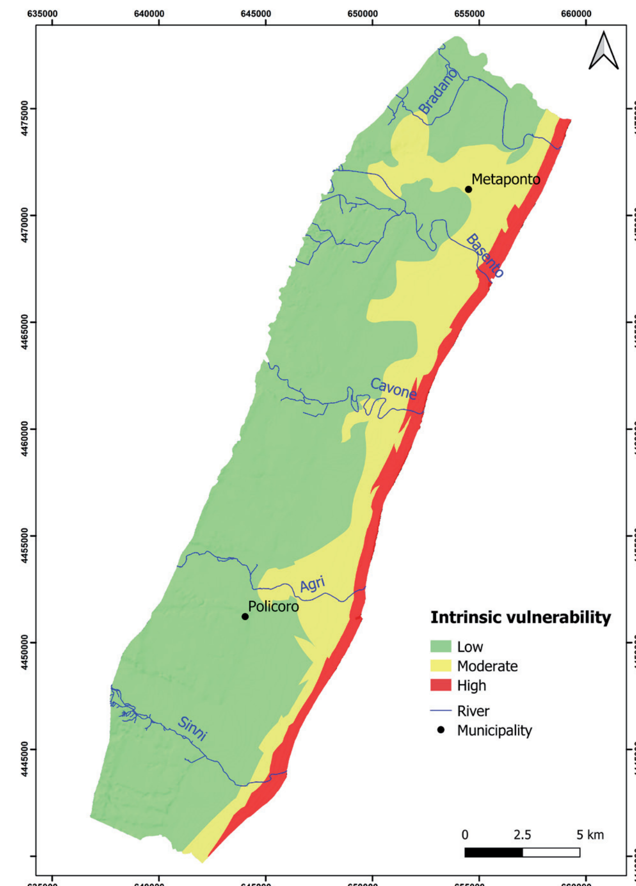

Fig. 5 - Map of the groundwater vulnerability to seawater intrusion

The statistical overview of the variation index obtained from the map removal sensitivity analysis was provided (Tab. 3). The removal of the Distance from the shore parameter, with a mean value of 6.32%, has the highest variation index. In descending order, Groundwater Level above the sea, Impact of the existing status of SWI, Aquifer hydraulic conductivity, and Groundwater occurrence are the other factors showing lower values (Tab. 3). Aquifer thickness showed the lowest mean value, with a variation index of 1.93%.

Variation index (%)	Variable removed					
	G	A	L	D	I	T
Mean	2.65	3.10	5.09	6.32	3.28	1.93
Minimum	1.55	0.23	0.04	0.22	1.33	0.04
Maximum	3.50	6.83	7.81	8.28	4.33	4.26
Standard deviation	0.37	1.59	2.47	1.55	0.43	1.23

Tab. 3 - Statistical summary of the GALDIT map removal sensitivity analysis

The assessment of groundwater vulnerability to SWI represents a significant step to preventing and controlling the degradation process of the resources. Indeed, the identification of areas more subject to SWI is useful and important for water resources managers that can define opportune and proper prevention actions, such as monitoring of the SWI phenomenon, engineering planning, regulatory or legislative approaches.

CONCLUSIONS

In the present paper, the overlay-index GALDIT method was applied for assessing the groundwater vulnerability to seawater intrusion (SWI) of the Metaponto coastal aquifer (Basilicata, southern Italy). The study area presents a growing population and tourist expansion and intensive agricultural practices. Groundwater resources are particularly exposed to quantitative and qualitative degradation, due to unfavourable climate conditions worsened by climate change, the growing water demand, and the contamination caused by anthropogenic activities and the SWI process.

The groundwater vulnerability assessment to SWI of the study area can support authorities and stakeholders in planning effective policies and strategies to protect coastal groundwater resources, including groundwater monitoring. The obtained intrinsic vulnerability map showed highly vulnerable areas in the proximity of the shoreline, occurring roughly parallel to the coast, within the first 500 m. The width of the coastal strip most vulnerable to SWI increases in the NE direction, reaching its maximum extension in the sector between the Basento and Bradano rivers. Higher vulnerability to SWI was detected where the aquifer bottom deepens below sea level.

To investigate the contribution of single parameters to the vulnerability index, sensitivity analysis was performed. According to its outcomes, the hydrogeological and topographical parameters such as the aquifer hydraulic conductivity and the distance from the shore have the greatest impact on groundwater vulnerability across the examined aquifer.

Qualitative degradation is a real risk that threatens the groundwater resources of the Metaponto aquifer. The SWI phenomenon can reduce the availability of good-quality groundwater in areas close to the coast.

The groundwater vulnerability map can be a useful tool for addressing coastal groundwater management to the protection from the SWI threat. The identification of the areas with potential high vulnerability can help to develop appropriate coastal groundwater strategies to face SWI in this area. Additional investigations concerning groundwater monitoring and numerical modeling applications should be carried out to simulate the dynamic behaviour of the aquifer system under natural and anthropic driving forces to produce effective and helpful predictive outcomes finalized to the understanding of SWI phenomenon severity.

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