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Multidisciplinary investigations of a karst reservoir for managed aquifer recharge applications on the island of Vis (Croatia)

Studio multidisciplinare per analizzare la ricarica in condizioni controllate dell'acquifero carsico dell'isola di Vis (Croazia)

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Riassunto

La ricarica dell'acquifero in condizioni controllate (MAR) è una metodologia attraverso la quale è possibile immagazzinare nel sottosuolo l'acqua superficiale in eccesso per una sua estrazione successiva o per scopi ambientali Questo approccio viene generalmente utilizzato in acquiferi non consolidati, mentre la sua applicazione in acquiferi carsici è scarsa. Questa ricerca presenta i primi risultati di uno studio di fattibilità di MAR nell'isola di Vis, una piccola isola carsica situata nel mare Adriatico. Condizioni geologiche ed idrogeologiche favorevoli permettono la formazione di una risorsa sotterranea idropotabile rendendo l'isola autonoma dal punto di vista idrico. L'acquifero carsico più importante, sfruttato nel campo pozzi di Korita, è protetto dall'ingressione di acqua marina da numerose barriere idrogeologiche. Tuttavia, il cambiamento climatico e l'elevata pressione antropica riconducibile all'intenso turismo nell'isola rappresentano una minaccia per la futura disponibilità di acqua potabile. In questo lavoro sono state condotte analisi multidisciplinari di campo ed in laboratorio per dettagliare l'assetto geologico ed idrogeologico dell'isola e le caratteristiche della sua risorsa idrica. Le analisi di campo comprendono il monitoraggio delle acque sotterranee ed il loro campionamento, indagini geofisiche (i.e., tomografia elettrica), e misure strutturali. Le analisi di laboratorio comprendono la misura dei cationi ed degli anioni principali e dell'attività di trizio. Nonostante la scarsa precipitazione durante il periodo di osservazione (settembre 2019 - dicembre 2020), la risorsa idrica nel campo pozzi di Korita ha mostrato parametri fisico-chimici stabili, una buona capacità di immagazzinamento ed una buona riserva a lungo termine. Le indagini geofisiche hanno evidenziato una struttura abbastanza omogenea delle rocce carbonatiche nel sottosuolo, mentre le analisi strutturali hanno indicato la presenza di fratture E-O aperte e carsificate che possono costituire delle vie di flusso preferenziale nell'acquifero carbonatico. L'approccio di MAR proposto in questo lavoro combina un bacino di accumulo e la ricarica diretta nell'acquifero mediante i pozzi esistenti. La risorsa idrica potenziale sarebbe costituita dall'acqua piovana e di ruscellamento raccolte mediante un bacino di accumulo in disuso situato a valle di un vecchio canale artificiale che scorreva attraverso la zona di Korita.

Abstract

Managed aquifer recharge (MAR) refers to a suite of methods by which excess surface water or non-conventional water is stored underground for subsequent recovery or environmental purposes. MAR solutions have been largely used in unconsolidated aquifers, while their application in karst aquifers is rare. This research presents the first results of a MAR viability study on the island of Vis, a small karstic island in the Adriatic Sea. Favorable geological and hydrogeological conditions enable the formation of karst aquifers, making the island autonomous in terms of water supply. The island's main aquifer, exploited in the Korita well field, is protected from seawater intrusion by several hydrogeological barriers. However, climate change and high seasonal pressures related to tourism pose a threat to the future availability of freshwater. Multidisciplinary field and laboratory investigations were carried out to detail the geological and hydrogeological setting of the island and its groundwater resource. Field analyses consisted of groundwater monitoring and sampling, geophysical investigations (i.e., electrical resistivity tomography), and structural measurements. Laboratory analyses included measurements of principal cations and anions and tritium activity. Despite low precipitation during the observation period (September 2019 - December 2020), the groundwater resource at the Korita site showed stable trends of physico-chemical parameters with a good storage potential and a long-term reserve. Geophysical investigations evidenced a relatively homogeneous sequence of the rock mass at a larger scale, while structural analyses indicated the occurrence of E-W karstified and open fractures that could represent a preferential flow path in the carbonate aquifer. A MAR solution for the Vis island was proposed combining an infiltration pond scheme with the direct injection of the accumulated waters into the aquifer using available wells. The potential water source could be represented by the runoff collected in an old artificial channel and the associated pond system in Korita.

Introduction

Sustainable management of groundwater resources in karstic aquifers is one of the key environmental challenges in the Mediterranean region (e.g., Cosgrove and Loucks 2015; García-Ruiz et al. 2011; Sapiano 2020). Karstic groundwater is one of the most important freshwater resource, and it is estimated that 10 to 25% of the global population depends on it (Ford and Williams 2007; Stevanović 2019). In the Mediterranean region, the percentage goes up to 50% (Hartmann et al. 2014), emphasizing its strategic importance and irreplaceability. The intensive karstification of the carbonate rock mass causes distinctive heterogeneity and anisotropy of aquifer's hydraulic properties posing a significant challenge for investigation, utilization, and management of groundwater resources (Worthington 2014). Climate change, overexploitation, improper land use or its modifications, and seawater intrusion are the most common drivers of groundwater resources' degradation (e.g., Giorgi 2006; Rosenzweig et al. 2007; Werner et al. 2013). In particular, the Mediterranean region is often regarded as a hot spot of climate change with a predicted temperature increase of 3.5-5.5 °C until 2100 (Bonacci et al. 2020; Branković et al. 2013) and an increase in precipitation variability with a negative influence on water balance (Aguilera and Murillo 2008; Touhami et al. 2015). The environmental challenges in the Mediterranean region are fostered by the rising anthropic pressure and the high population density with the local population (approximately 160 million people with approximately 10 million inhabitants in the islands; European Environment Agency 2015) drastically increasing during the tourist season (e.g., Leduc et al. 2017; Mongelli et al. 2019).

In Croatia, karstified carbonate rocks cover approximately half of the territory being the bedrock along the coast and its hinterland (HGI-CGS 2009; Velić and Vlahović 2009; Vlahović et al. 2005). The Croatian coast is one of the most indented coastlines in the world, consisting of 79 islands and 525 islets (Duplančić Leder et al. 2004). Merely a few of them have a completely autonomous water supply from karstic aquifers or freshwater lakes (e.g., Vis, Cres), whereas the majority are connected to the water supply system of the mainland. Furthermore, some islands have composite water supply solutions, such as small desalination plants for salinized water from brackish lakes (e.g., Borović et al. 2019). The most significant problem regarding the water supply on Croatian islands is represented by seawater intrusions into aquifers (e.g., Lukač Reberski et al. 2020; Plantak et al. 2021; Terzić et al. 2008). This problem is mostly inherent due to: (i) their small surface area resulting in small catchments and aquifers, (ii) intense fracturing and karstification with a karst base level below the present sea-level resulting in high permeability of the rock mass and preferential seawater intrusion through karstic conduits, and (iii) relatively low precipitation and high evapotranspiration. Anthropic pressures and overexploitation significantly add up to this problem (e.g., Alfrrah and Walraevens 2018; Gaaloul et al. 2012; Meybeck et al. 2003). Despite the relatively low population, the majority of Croatian islands experiences extreme seasonality in water demand due to intensive summer tourism, which coincides with the dry season. Efficient and integrated water management is needed to mitigate these problems increasing the groundwater quantity and improving its quality.

Vis, a small and remote island in the middle of the Adriatic Sea (Fig. 1), maintained an efficient and autonomous water supply system for decades. Currently, the system satisfies the freshwater demand of the local population, but occasional reductions can occur during the dry season due to very low precipitation and high water demand for tourism purposes. The need for alternative water management solutions yielded managed aquifer recharge (MAR) as an option for increasing the safety and resilience of the island's groundwater resources. MAR refers to a suite of methods by which excess surface water is intentionally stored underground for later recovery. MAR operations are generally done to mitigate declining groundwater tables, to improve water quality, or for other environmental benefits (Dillon et al. 2019; Fernández Escalante et al. 2020). On a global scale, MAR methods have been successfully used, but their application in the karstic environment is still marginal (e.g., Daher et al. 2011; Massaad 2000; Rolf 2017; Vanderzalm et al. 2002; Xanke 2017). The most common hydrogeological challenges for the implementation of MAR solutions in karst include: (i) poor knowledge of the aquifer geometry, (ii) high variability of hydraulic conductivity and porosity fields resulting in unpredictable flow paths, and (iii) complex geochemical water-rock interactions adding on the spatial complexity of karstic features.

Several comprehensive methodological approaches for assessing MAR viability were developed (e.g., Daher et al. 2011; DEEPWATER-CE 2020; Hayat et al. 2021; Lobo Ferreira and Leitão 2014; NRMMC-EPHC-NHMRC 2009; Rolf 2017; San-Sebastián-Sauto et al. 2018). The site characterization (e.g., climatological, morphological, geological, hydrogeological, and geochemical reconstructions) commonly represents the first phase of MAR solution planning. In this paper, we present the initial results of a multidisciplinary research to determine the MAR viability on the island of Vis. To detail the hydrogeological setting of the karstic aquifer and the physical and chemical characteristics of the groundwater, hydrogeological, geochemical, geophysical, and structural investigations were conducted. Firstly, the geological, hydrogeological, and climatological settings of the study area will be described. Then, an overview of the utilized data and methods will be provided, followed by the results and their interpretation in the context of the investigated topic.

Data and methods

Geographical setting and climate

The island of Vis is located in the central part of the Adriatic Sea (Fig. 1), approximately 50 and 120 km from the Croatian and Italian mainlands, respectively. The relief consists of three hilly terrains separated by two predominantly E-W valleys, locally hosting karst poljes. The highest peak is Hum

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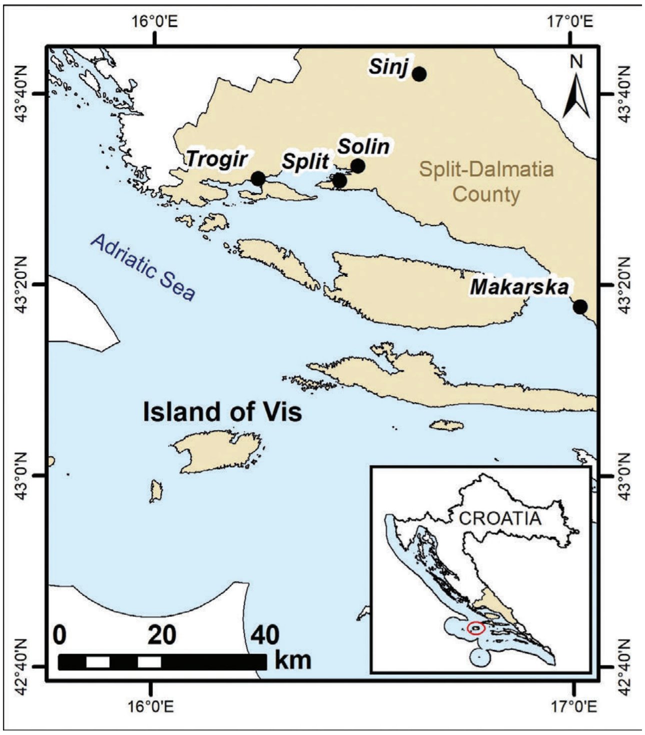

Fig. 1 - Location map of the study area.

Fig. 1 - Ubicazione dell'area di studio.

(587 m a.s.l.), located in the western part of the island. The local population consists of approximately 3,300 inhabitants mostly living in the cities of Vis and Komiža (Fig. 2). The island is well known in terms of summer tourism when the number of visitors surpasses the local population up to ten times.

The climate of the island can be classified as a Mediterranean climate with dry and hot summers (Filipčič 1998). Due to the island's position in the open sea, there is a strong maritime influence reflected in the mitigation of climate extremes and air temperature variations (Bonacci et al. 2020, 2021). In the period from 1991 to 2019, the mean annual air temperature was 17.1 °C and the mean annual precipitation was 775 mm. The precipitation is highly seasonal, with the peak in the colder part of the year (October-March). The evapotranspiration, calculated using Turc's method (Turc 1954), is approximately 65% resulting in annual effective precipitation of approximately 270 mm since surface runoff is negligible and only occurs during long-term rainfall or storms. Effective infiltration between 40 and 65% is common in the Dinaric karst (e.g., Bonacci 2001).

Geological and hydrogeological settings

The island of Vis belongs to the geotectonic unit of the External Dinarides, an area characterized by deep and irregular karstification. It exhibits a composite and peculiar structural fabric (Korbar et al. 2012) affecting its hydrogeological setting. The main lithological units are: (i) Cretaceous limestones and dolomites, (ii) the volcanic-sedimentary-evaporite (VSE) complex of Komiža bay (Middle to Upper Triassic) in the western part of the island, consisting of gypsum, dolomite-gypsum breccias, karst debris, andesites, volcanic agglomerates, siltites, marls, and tuffites, and (iii) Quaternary deposits, represented by the terra rossa cover in karst poljes, and locally colluvial deposits and aeolian sands.

Vis is crosscut by three main subvertical fault systems striking NE-SW to E-W (Fig. 2a). The NE-SW striking fault in the northern part of the island (Oključna fault) and the E-W striking fault in the S (Podšpilje-Rukavac fault) constitute the northern and southern boundaries of the Komiža diapir (VSE complex), and both diverge towards the E defining a radial pattern. The fault system with the strongest morphological expression and associated with the most productive wells (Korita well field) is the Komiža-Vis fault system, striking approximately N70°. Overall, the onshore structure of Vis is an open anticline with an axial plane striking E-W and hinge dipping towards the E. The anticline is bounded to the N and S by the Oključna and Podšpilje-Rukavac faults, respectively.

Terzić (2004) and Terzić et al. (2022) provided a detailed description of the hydrogeological setting of the Vis island and assessed its freshwater resources. The main conclusions were:

- the most significant water-bearing hydrostratigraphic units are represented by moderate permeability laminated and well-bedded limestones with dolomitic beds/interbeds and by high permeability limestones (Fig. 2a). Conversely, low permeability units are: (i) well-bedded dolomites, and (ii) the VSE complex. Locally, low permeability terra rossa sediments from karst poljes infill the underlying rock mass, decreasing its hydraulic conductivity;
- the transmissivity in the Korita well field is from 9×10^{-4} to 2.3×10^{-3} m^2/s, with the results of pumping tests pointing to a homogeneous flow through a densely fractured rock mass rather than conduit flow;
- tracer test evidenced two distinctive catchments (Korita and Pizdica), with the zonal groundwater divide following the relief E of the Komiža bay and including the Hum ridge (Fig. 2b). The precipitation infiltrates and flows east- and westward from the groundwater divide through the moderate to high permeability carbonates. In the E, the groundwater forms the water resource exploited in Korita, which is also partially recharged by the precipitation from the relief in the vicinity of Vis city. In the W, the groundwater flow is stopped by the low permeability VSE complex and it is locally discharged along the coast (Pizdica spring). Small scale catchments develop along the northern and southern coasts resulting in diffused discharges to sea through highly karstified limestones, with the periodical occurrence of vruljas (submerged springs);
- the two most significant hydrogeological barriers that prevent seawater intrusions into the Korita aquifer are represented by the low permeability VSE complex from the W, and by rock mass with reduced permeability below karst poljes in the S. Therefore, the highest risk of seawater intrusion is from the E, along the Komiža-Vis fault zone. Conversely, the Pizdica water resource and

the small scale water resources along the coast are prone to seawater intrusion. The mixing ratio with seawater strongly depends on the permeability of the rock mass.

The Vis water supply system consists of five wells (BO1 to BO5) drilled in the Korita well field, two wells (K1 and B1) in the Komiža hinterland, and the Pizdica spring (Fig. 2). The maximum pumping capacity at Korita is 42 l/s, and the groundwater is pumped from the approximate depth of 110 to 140 m. Groundwater levels vary between 10-20 m a.s.l. depending on the well location and pumping quantity (Terzić et al. 2022). Groundwater quality is excellent since hydrogeological barriers protect it from seawater intrusion. However, the Komiža-Vis fault and its high permeable damage zone could represent a potential seawater flow path posing a great risk for resource management. The wells and the Pizdica spring in the western part of the island provide a total of approximately 5 l/s. Their water quality is variable and mostly depends on the different interactions with the seawater and the bedrock.

Approximately 450,000 m^3 of freshwater is abstracted annually with a variable flow rate depending on the high tourist season. During high season, a fivefold increase in demand exerts stresses on freshwater resources and several reductions for consumers occurred in the last two decades.

Numerous less productive springs and wells on the island are not utilized for drinking water supply. Despite their low yield, they were investigated and sampled since they could represent a possible local water resource during droughts or high exploitation periods (Fig. 2a).

Hydrogeological and hydrochemical investigations

Hydrogeological and geochemical investigations were conducted monthly from September 2019 to December 2020 and consisted of in-situ monitoring and groundwater sampling. Groundwater samples were taken from wells and springs (Fig. 2a) and stored in 200 mL pre-rinsed polyethylene bottles that prevent evaporation and were kept refrigerated at 16 °C. Samples were taken from: (i) deep wells BO2, BO5, K1, B1, DP1, and V1, (ii) shallow dug wells AB (Austrijski bunar) and DRV (Dragevode), and (iii) springs Gusarica, Kamenica, and Pizdica. Electrical conductivity (EC), pH, dissolved oxygen content, and water temperature were measured in-situ using a WTW multi-parameter probe (Multi 3630 IDS SET G; WTW 2021). Laboratory investigations were performed in the Hydrochemical Laboratory of the Department of Hydrogeology and Engineering Geology at the Croatian Geological Survey in Zagreb, Croatia. Principal ion composition (Cl^-, SO_4^{2-}, NO_3^-, Ca_2^+, Mg_2^+, Na^+, K^+) was

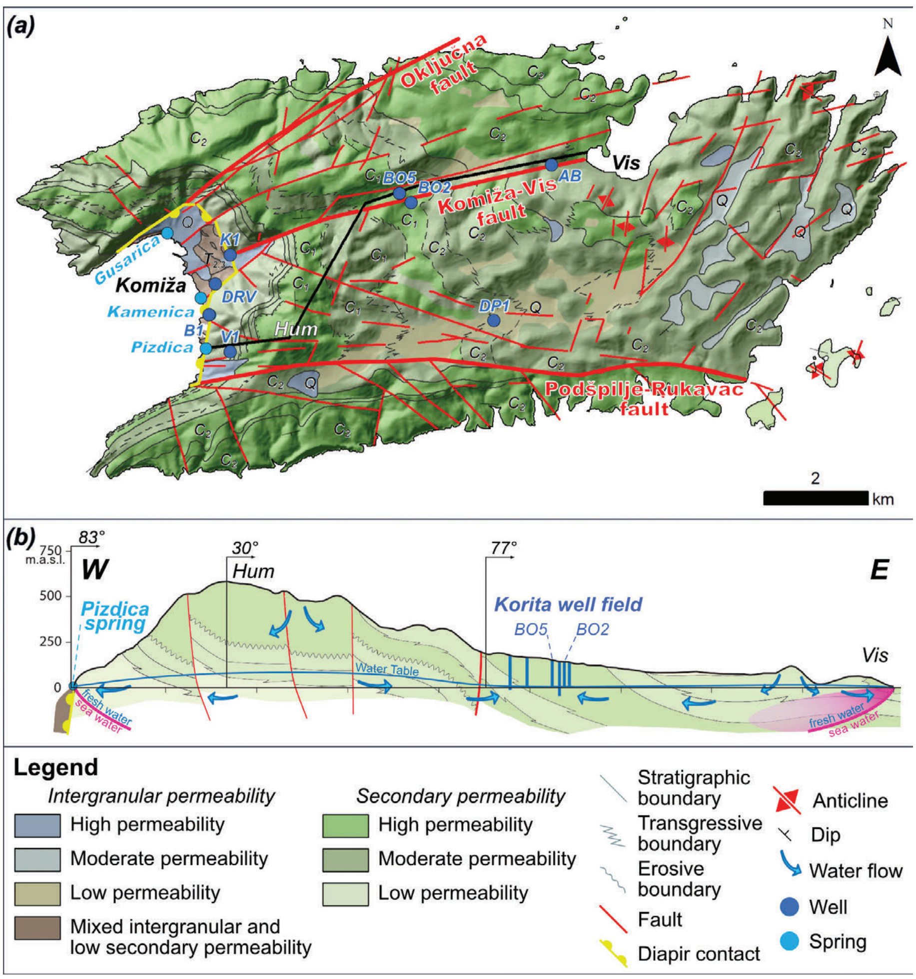

Fig. 2 - Hydrogeological map of the island of Vis with sampling locations (a) and schematic hydrogeological cross-section (b). The age of the lithostratigraphic units is also reported ($T_{2,3}$: Middle to Upper Triassic; C_1: Lower Cretaceous; C_2: Upper Cretaceous; Q: Quaternary). (modified after Korbar et al. 2012 and Terzić et al. 2022)

Fig. 2 - Carta idrogeologica dell'isola di Vis con pozzi e sorgenti campionati in questo lavoro (a) e sezione idrogeologica schematica (b). La carta idrogeologica riporta anche l'età delle unità litostratigrafiche ($T_{2,3}$: Triassico medio – superiore; C_1: Cretaceo inferiore; C_2: Cretaceo superiore; Q: Quaternario). (modificato da Korbar et al. 2012 e Terzić et al. 2022).

analyzed by ion chromatography on DIONEX ICS-6000 DP (Thermo Scientific 2018). The concentration of bicarbonate ions was determined in-situ by volumetric titration (HACH digital titrator) with 1.6 N H_2SO_4 to pH 4.5. Furthermore, the Laboratory for Low-level Radioactivities of Ruđer Bošković Institute in Zagreb conducted the determination of ^3H activity concentration by the method of electrolytic enrichment using the liquid scintillation counter Quantulus 1220 (Krajcar Bronić et al. 2020).

Electrical resistivity tomography (ERT)

Electrical resistivity tomography (ERT) survey was conducted in June 2020 to assess the soil-rock interface and the rock mass quality and to delineate the depth of the groundwater table. A 2D-ERT was carried out using the POLARES 2.0 electrical imaging system (P.A.S.I. s.r.l 2022), which uses a sinusoidal alternate current of adjustable frequency. This system was connected to 32 stainless steel electrodes, which were laid out in a straight line with a constant spacing of 10 m via a multi-core cable. Surveys were conducted using the Wenner–Schlumberger array at a frequency of 1.79 Hz and a maximum phase of 20° between the voltage signal and the current signal. During the field measurements, the frequency was lowered until the number of incorrect measurements was below 10%. The RES2DINV resistivity inversion software (Loke 2011) was used to automatically invert the apparent resistivity data from the field into two-dimensional resistivity subsurface models.

Structural-geological investigations

Since fluid flow in carbonate aquifers is generally dominated by fractures and karstic conduits, it is fundamental to study the geometrical attributes of fractures. High-resolution structural measurements, including orientation, kinematics, and crosscutting relationships, were performed. Orientations of deformation structures were plotted using the Daisy 3 software (Salvini 2004) in stereographic projections (Wulff lower hemisphere stereonet).

Results

Hydrogeological and hydrochemical investigations

Hydrochemical facies of the groundwater enable the determination of the relationship between the chemical properties of water, rock lithology, and local groundwater flow. The chemical composition of the groundwater is graphically represented on the Piper diagram (Fig. 3).

The sampling period was characterized by low rainfall, with the cumulative precipitation being 824 mm from September 2019 to December 2020 and a peak of 200 mm in December 2020. Despite the prolonged dry season and the decline in water levels, the principal ion composition showed relative stability at the analyzed wells and springs (Fig. 3). The groundwater in BO2, BO5, DRV, DP1, B1, and K1 showed a Ca-HCO_3 hydrochemical facies, which is the most common chemical footprint of groundwater in carbonate aquifers. Increasing chlorides at BO2 and BO5 were observed when the wells were pumped at maximum capacity. At the coastal well B1, increased chlorides were caused by the mixing of freshwater and seawater. Coastal springs Kamenica and Gusarica displayed a mixture of Ca-HCO_3 and mixed (Ca-Mg-Cl-SO_4) types due to the increasing SO_4 content resulting from the dissolution of gypsum in the VSE complex. The shallow coastal well AB had mixed (Ca-Mg-Cl-SO_4) hydrofacies with high chloride as a result of seawater

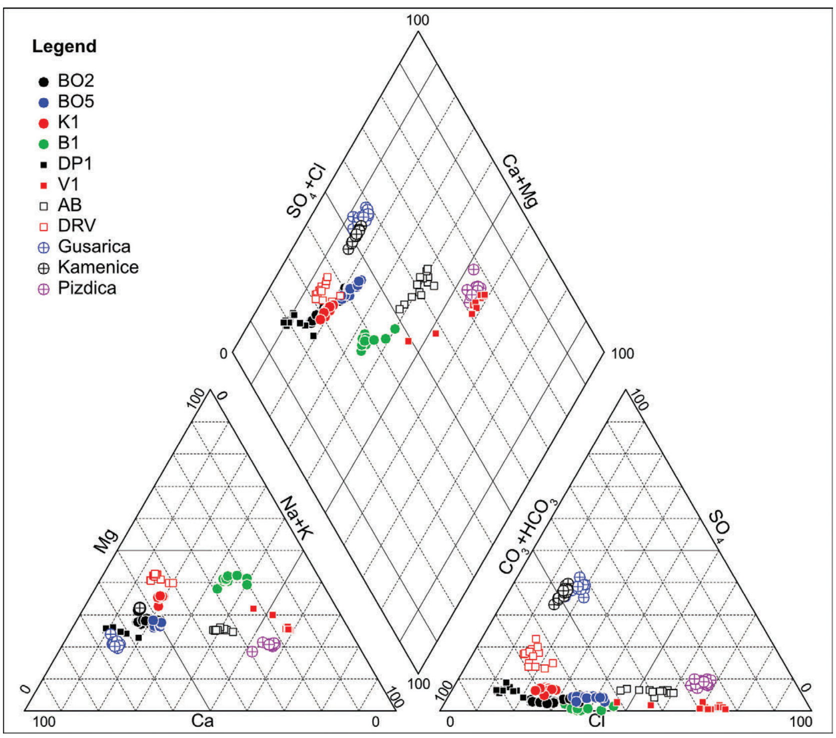

Fig. 3 - Piper diagram of groundwater samples from the island of Vis (September 2019 - December 2020).

Fig. 3 - Diagramma di Piper delle acque sotterranee campionate nell'isola di Vis (settembre 2019 - dicembre 2020).

interaction. V1 well and Pizdica spring displayed Na-Cl facies due to their proximity to the sea and significant mixing of freshwater with seawater. Despite their hydrochemical facies, these waters show relatively high Mg and HCO_3 contents pointing to a water-rock interaction with dolomites.

Time series of in-situ measurements of electrical conductivity, groundwater temperature, and pH in BO2, BO5, K1, and B1 wells and Pizdica (Fig. 4) were further investigated since they are the main water supply sites and have the highest potential for MAR implementation due to existing infrastructure.

EC values displayed relatively stable trends throughout the analyzed period with different amplitudes (Fig. 4a). Peak values occurred in August and September, however, seasonal oscillations were dampened by the prolonged dry season and very low recharge of the aquifer. Despite their vicinity, different EC values in BO2 and BO5 reflect different depths of their well screens, with BO5 being 15 m deeper, as well as variations in pumping rates. Despite a discontinuous time series due to pump malfunctions or intermittent usage, K1 and B1 showed static EC values. Similarly, EC values were mostly static at the brackish spring of Pizdica. The spring was used mostly during the summer season, but a significant increase in EC values was not detected due to the buffer effect of the spring accumulation pond and the relatively low pumping rate (Qmax=3.3 l/s).

Groundwater temperature varies throughout the year following the air temperature (Fig. 4b), with higher values in summer and lower values in winter. Such oscillations were not observed in Pizdica except for a slight temperature increase in August and October 2020. Mean groundwater temperatures are in concordance with the mean annual air temperature on the island of Vis, which varies between 16 °C and 18 °C. The differences in temperatures are caused by variations in catchment size, elevation, recharge/discharge dynamics, and the depths of the saturated zone. Due to the low precipitation in the analyzed period, its effect on the groundwater temperature can be neglected.

The groundwater pH was neutral to weak alkaline (Fig. 4c). BO2, BO5, K1, and Pizdica had similar values and amplitudes, while B1 had higher base values as well as amplitude.

Analyses of ^3H activity were performed on samples from BO2, Pizdica, and K1 during the hydrological minimum of September 2020. The results (in TU) were 1.68 ± 0.72, 2.3 ± 1.0, and 2.3 ± 1.1 for BO2, K1, and Pizdica, respectively. These waters can be classified as a mixture of sub-modern and modern water (0.8-4 TU; Motzer 2007). The lower TU in BO2 possibly indicates a shift towards older groundwater reflecting the exploitation of a deeper resource.

Electrical resistivity tomography (ERT)

ERT survey was conducted in the karst polje Dol, as it represents the lower part of Korita catchment where subsurface and groundwater data are rather scarce or missing. The profile (Fig. 5) was 320 m long and its western-most part is located 1.3 km NE from BO2 (Fig. 2a).

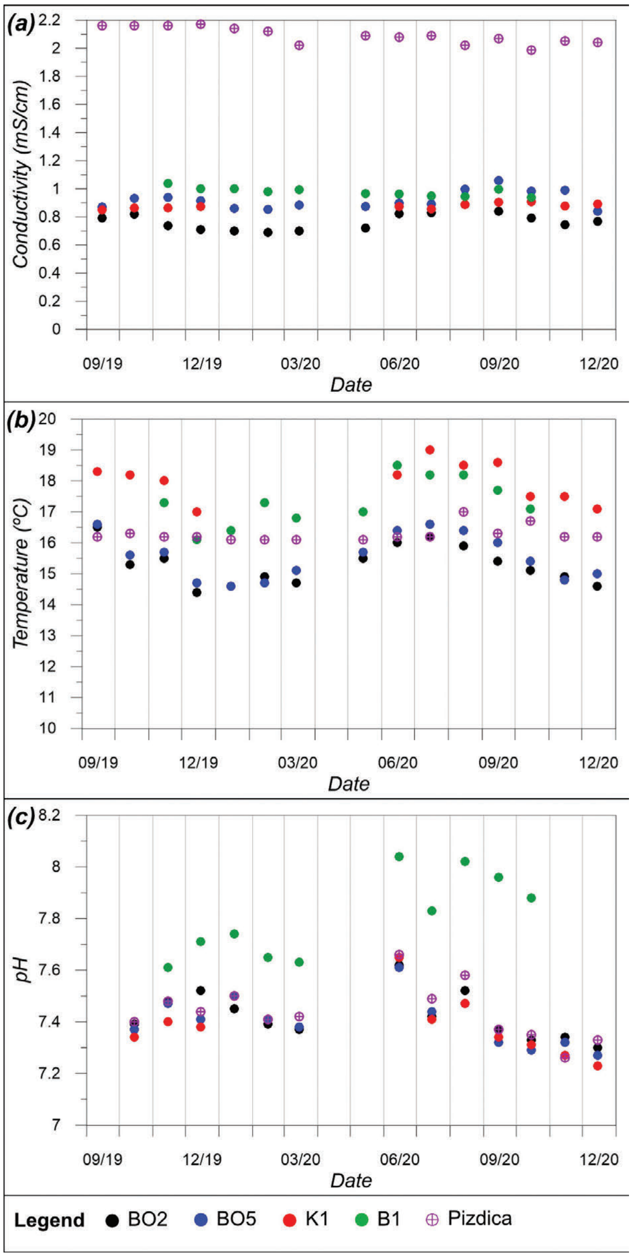

Fig. 4 - . Time series of (a) electrical conductivity, (b) groundwater temperature, and (c) pH. Some data are missing due to the random well closure and to the COVID-19 lockdown in April 2020.

Fig. 4 - Serie temporali della (a) conducibilità elettrica, (b) temperatura, e (c) pH delle acque sotterranee. La mancanza di alcuni dati è riconducile a malfunzionamenti temporanei delle pompe installate nei pozzi ed al lock-down causato dalla pandemia di COVID-19 (aprile 2020).

The results showed a low resistivity zone (15-110 Ωm) interpreted as topsoil (i.e., terra rossa) above a high resistivity bedrock. Clayey materials tend to hold more moisture and have a higher concentration of ions that conduct electricity, resulting in resistivity lower than 100 Ωm (Telford et al. 1990). The distribution of higher and lower resistivity zones in the topsoil coincides with agricultural activities. In particular, the lowest values (15-50 Ωm) were observed in correspondence with a vineyard where an irrigation system is installed. The resistivity increased with depth. The high

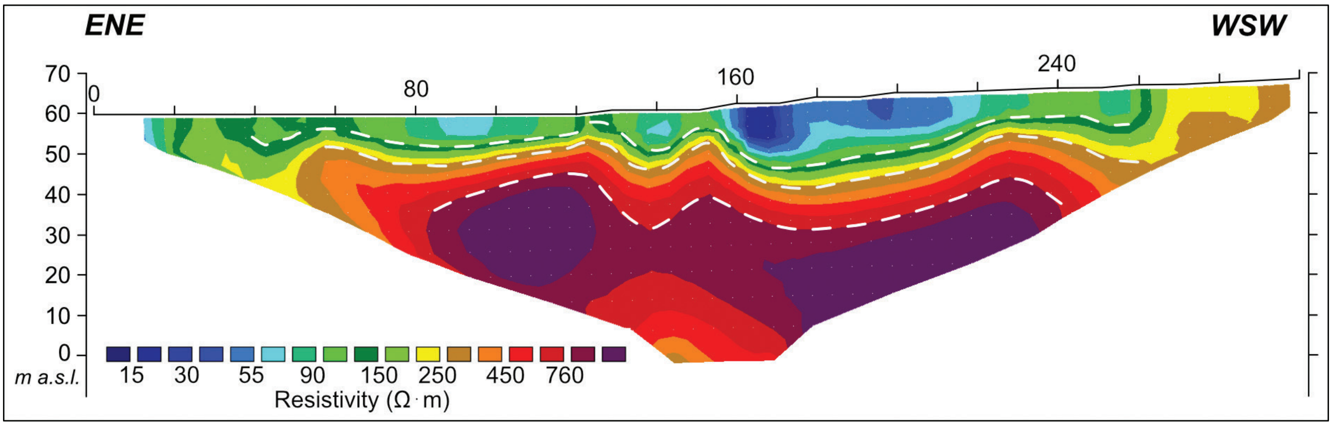

Fig. 5 - ERT profile in Dol polje. Interfaces between the topsoil (low resistivity), lower and upper weathering zones (moderate resistivity), and compact carbonates (high resistivity) are highlighted by white dashed lines.

Fig. 5 - Profilo geoelettrico effettuato nel polje di Dol. L'interfaccia fra il suolo (bassa resistività), la zona di degradazione meteorica (resistività moderata), e l'ammasso roccioso compatto (resistività elevata) è marcata dalla linea bianca tratteggiata.

resistivity bedrock was divided in an upper weathering zone (110-250 Ωm), where open discontinuities with weathered walls are infilled with clay and rock fragments. Values of electrical resistivity between 250-700 Ωm were interpreted as the lower weathering zone, where discontinuities have small apertures and moderate to negligible infilling. Resistivity values higher than 700 Ωm were interpreted as compact carbonates. Carbonates show a significantly higher resistivity than clayey soil because of lower porosity. In the middle section of the profile, at a depth of 0-20 m a.s.l., an anomaly with a resistivity of 300-500 Ωm was observed, indicating a potential groundwater target.

Structural-geological investigations

Structural-geological investigations were performed in 15 sites along the Komiža-Vis road and around the Korita well field, where the Komiža-Vis fault system is observed in tectonized Cretaceous carbonates (Fig. 6).

The collected dataset was dominated by high-angle (mostly >60°) deformation structures, namely faults, fractures, veins, and stylolites. In sites 3 to 15 along the Komiža-Vis fault (Fig. 6), the deformation pattern is constituted by a set of sinistral strike-slip fault planes striking roughly N70°, i.e. subparallel to the fault system, and associated with NE-SW veins and roughly NW-SE striking pressure solution planes, coherent with sinistral shear sense. A subsidiary set of sinistral, N40° striking fault planes, splaying from the E-W striking fault planes, was in turn associated with N-S veins. Moving away from the Komiža-Vis fault zone towards the S (sites 8 and 14), fault planes and associated veins were organized in two orthogonal sets: N100°-110° and N10°-20°. Fault cores of pluridecametric fault segments are composed of chaotic breccias infiltrated by terra rossa, while minor faults splay in their damage zones showing crackle breccia pockets and abundant striae and clear to reddish calcite slickenlines. The same type of calcite occurs in the described vein sets. Fractures, which include both joints and other deformation elements overprinted by abundant meteoric dissolution, were found in all the aforementioned orientations.

Sites 1 and 2 are hosted in the dolostones close to the Komiža diapir contact and showed slightly different deformation structures. Site 1 shows a principal sinistral strike-slip fault plane, striking N80°, and associated veins. This fault plane was abutted by mutually crosscutting dextral NE-SW, sinistral NW-SE fault planes, and N-S cleavage planes. Fault cores of principal faults in dolostones were characterized by intense cataclasis and dolomite cementation, which occurs also in the associated veins and constitutes slickenlines of the subsidiary fault planes. Site 2 showed bedding dipping 45° to the ENE and slickenlines indicating extensional, sinistral, and dextral kinematics. Here, four fault sets were observed: (i) N-S bedding-orthogonal extensional faults, (ii) high angle, N70° striking, mostly sinistral faults, (iii) subvertical NW-SE trending, sinistral faults, and (iv) NE-SW faults and fractures, filled by terra rossa. In this latter area, complex transtensional kinematics are the result of the interaction of the diapir contact and the Komiža-Vis fault.

Discussion and conclusions

The present study describes a multidisciplinary approach (i.e., hydrogeology, geochemistry, geophysics, structural geology) for the assessment of the Managed Aquifer Recharge (MAR) potential on the island of Vis. A detailed characterization of the pilot site is a common prerequisite in several workflows for MAR implementation (e.g., Daher et al. 2011; DEEPWATER-CE 2020; Lobo Ferreira and Leitão 2014; NRMMC-EPHC-NHMRC 2009; Rolf 2017; San-Sebastián-Sauto et al. 2018).

Hydrogeological and hydrochemical analyses were used to establish trends and dynamics of the groundwater resource. The water exploited in the Korita well field displayed long-term stability (i.e., ion composition, EC, pH) despite very low precipitation during the monitoring time, with a slight increase in chloride and EC in the warmer period (Figs. 3 and 4). These variations suggested relatively large groundwater reserves with a good resilience towards seasonal over-pumping

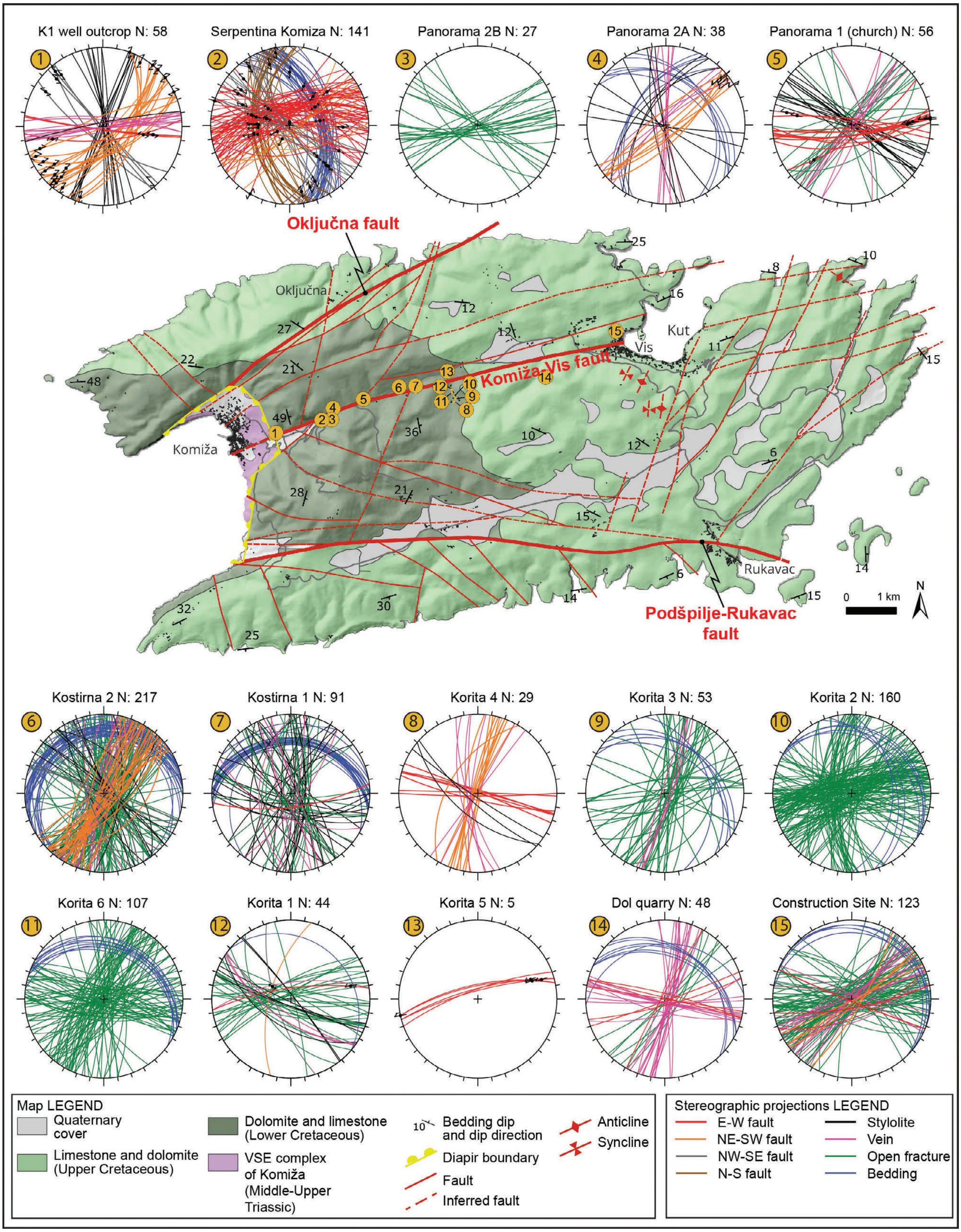

Fig. 6 - Simplified geological map of the island of Vis after Korbar et al. (2012). Structural measurement sites are in orange and numbered 1-15. Deformation structures are plotted in stereographic projections lower hemisphere Wulff nets (Daisy 3 software; Salvini 2004).

Fig. 6 - Schema geologico dell'Isola di Vis, semplificato a partire da Korbar et al. (2012). I siti delle stazioni strutturali sono rappresentati in arancione e numerati da 1 a 15. Le strutture deformative sono rappresentate come proiezioni stereografiche sul reticolo di Wulff (Daisy 3 software; Salvini 2004).

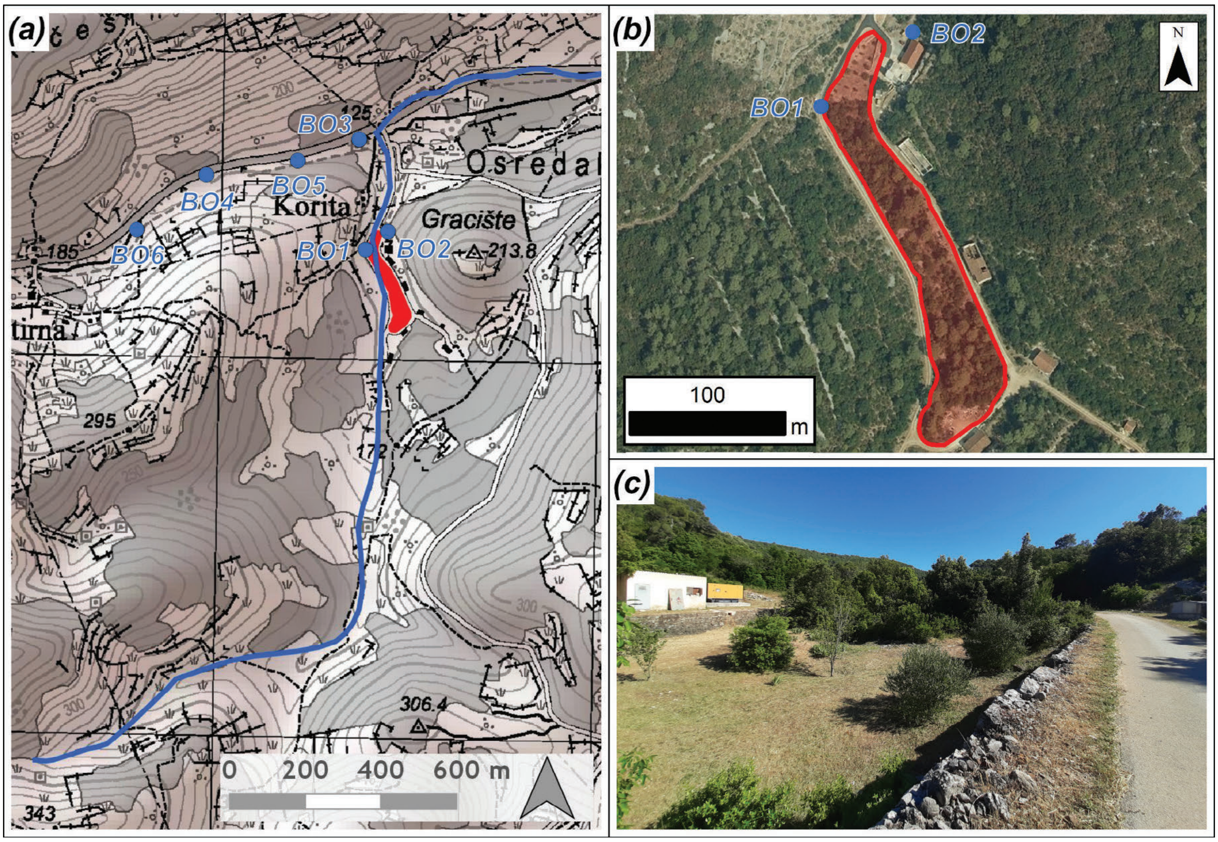

Fig. 7 -(a) Proposed location of the accumulation structure in Korita (red) in relation to the abandoned channel (blue line) and Korita wells (blue dots), (b) aerial view of the infiltration pond, (c) current situation of the structure. The base map (a) and the ortoimage (b) were taken from the Geoportal Državne geodetske uprave portal (https://geoportal.dgu.hr/).

Fig. 7 - (a) Ubicazione del bacino di accumulo nell'area di Korita (poligono rosso) in relazione al canale di deflusso abbandonato (linea blu) e ai pozzi (cerchi blu), (b) ortofoto dell'area di Korita, e (c) situazione attuale del bacino di accumulo. La mappa (a) e l'ortofoto sono tratte dal portale Geoportal Državne geodetske uprave portal (https://geoportal.dgu.hr/).

and dry seasons. This result was corroborated by the analyses of ^{3}H activity, pointing to a mixture of sub-modern and modern waters.

The Korita aquifer is protected from seawater intrusions and has excellent water quality, making it the most suitable and safe for MAR implementation. A sufficient storage capacity was evidenced by the high transmissivity values (Terzić et al. 2022) that also suggested a homogenous groundwater flow through a densely fractured, "porous-like" aquifer. These characteristics are favorable since they allow a diffuse infiltration without a quick discharge toward the sea through large karstic conduits. In particular, the E-W fractures represent a preferential path for water infiltration and flow. This set of fractures is characterized by larger aperture and terra rossa infilling suggesting a transtensional regime that promotes their opening.

From the point of the groundwater quality, the highest uncertainty is related to the differences in the chemical composition of the infiltrated water and the groundwater as well as the water-rock interactions, which can change the groundwater chemical status (Ringleb et al. 2016; Xanke 2017). In particular, the infiltration of slightly acidic water results in increased $CaCO_3$ dissolution leading to increased karstification. The physico-chemical parameters of rainwater on the island of Vis were not investigated, but literature data are available. Beysens et al. (2010) reported high variations in rainwater pH and EC, with mean values of 6.4 and 132 µS/cm, respectively, while Skevin-Sovic et al. (2012) reported precipitation pH values from 3.94 to 8.06, showing that acid rain could occur. These parameters could be favorable since pH higher than 5.5 and low $CaCO_3$ content were recommended for MAR solution in karstic aquifers (e.g., Rolf 2017).

Despite the groundwater resource quality and the hydrogeological characteristics of the aquifer, MAR implementation has to account for the subsurface geometry. Geophysical investigations (i.e., ERT survey) in the vicinity of Korita highlighted a relatively homogeneous sequence of the rock mass below an approximately 10 m thick Quaternary cover. These data could contribute to a more detailed construction plan for the MAR solution (e.g., removal of the topsoil), decreasing the design risks.

A tentative project of a MAR solution on Vis could be the revitalization of an old artificial channel and the associated pond system used to evacuate storm and flood waters from hilly areas of Hum and Korita towards the E and its conversion into an accumulation structure (Fig. 7).

The possible conceptual design of the infiltration pond at Korita should include: (i) the revitalization of the abandoned channel and pond system, (ii) the construction of an accumulation dam at its lowest point, and (iii) the topsoil removal enhancing the natural infiltration. The volume of the proposed pond is approximately 25,000 m^3 (Fig. 7b). Generally, surface recharge methods are preferred in karst since the epikarst zone acts as a buffer for slow, delayed, and diffuse water infiltration (Daher et al. 2011), promoting the degradation of pollutants and reducing the risk of contamination. Considering the specific climatological, geological, and hydrogeological conditions of the Korita site, the major constraints for a surface recharge could be: (i) differential infiltration rates, (ii) clogging, (iii) high evaporation, and (iv) algae and plankton blooms. Spatially differential infiltration rates could be caused by the heterogeneity of the epikarst zone. The presence of sinkholes or karstic conduits could cause the rapid inflow of the source water, while epikarst with significant soil infill (i.e., clayey terra rossa) could hinder the infiltration. Furthermore, the infiltration rate could be diminished by mechanical (fine particles) or biological (algae) clogging, affecting the quality of the source water as well. High evaporation, variable climate conditions (prolonged dry periods), and climate change (extreme meteorological events) could affect the availability of the source water.

The construction of an infiltration ditch or gallery in the pond could mitigate some of these quality and quantity issues. This structure could surpass the epikarst zone avoiding uncontrolled infiltration or prolonged water stagnation that could promote clogging and algal bloom. It could be combined with pre-treatment systems that could improve the quality of the source water. Considering the existing infrastructure of the Korita well field, one of the nearby wells could be used for injecting the water accumulated in the pond using a combined pond-aquifer storage and recovery approach. Although direct injection into the phreatic zone should be avoided due to possible degradation of groundwater quality and unwanted water-rock interaction (Daher et al. 2011), the obtained results indicate that this method could be suitable for the Korita aquifer.

However, the current major threat for the Korita water resource is represented by the possible seawater intrusion through the highly permeable damage zone of the Komiža-Vis fault. This problem could be aggravated by increasing pumping rates and sea-level rise. The MAR solution could increase the hydraulic gradient in the Korita aquifer mitigating the possible seawater inflow. Furthermore, it could be accompanied by monitoring piezometers located downstream of the Korita well field. The monitoring network could be used to: (i) evaluate the efficiency of the MAR system, (ii) monitor the quality of the groundwater, and (iii) establish an early warning system for the seawater intrusion.

The most significant constraint for MAR implementation on the Vis island is represented by the current legislation that does not allow the development of MAR solutions, especially in drinking water protection zones. This issue requires detailed and site-specific research, which could promote MAR solutions as a safe and sustainable approach for increasing the groundwater quality and quantity, and the sensibilization and collaboration with key stakeholders and decision-makers.

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Competing interest

The authors declare no competing interest.

Author contributions

Data collection by all authors; data analyses by Patekar M., Kosović I., Lucca A.; manuscript conceptualization by Patekar M., Pola M., Terzić J., Borović S.; writing original draft by Patekar M., Bašić M., Pola M., Kosović I., Lucca A., Mittempergher S., Berio L.; graphical editing by Bašić M., Pola M., Mittempergher S., Berio L.; review of the final draft by all authors.

Additional information

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