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DEEPWATER-CE

WORKPACKAGE T3, ACTIVITY T3.4

D.T3.6.1 REPORT ON THE DESK ANALYSIS OF THE PILOT FEASIBILITY STUDY FOR MAR DEPLOYMENT IN FRACTURED AND KARSTIFIED AQUIFERS LOCATED IN SEMIARID KARST AREAS

REPORT D.T3.4.1.

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I. Introduction

Within the DEEPWATER-CE project a transnational decision support toolbox was developed on designating potentially suitable MAR locations in Central Europe (output O.T2.1, DEEPWATER-CE, 2020b). Based on this toolbox, pilot sites with applicable MAR types can be identified (deliverables D.T3.3-6.1-5). Furthermore, a common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies (deliverable D.T3.2.5) was proposed which can be used in combination with the transnational decision support toolbox to identify the potential of a MAR application.

For the assessment of MAR feasibility at the designated site, a collection of preliminary information about the pilot site (hereafter called desk analysis) is recommended. The scope of this step is to identify, with rudimentary and readily available information, the degree of difficulty of the project and to assess the suitability for the intended MAR design under application of reasonable efforts. This should be done with existing records in archives by the regional governments and also by field visits. Furthermore, the objective of MAR application will be addressed at this step, again, as already summarized in the good practice and benchmark report (DEEPWATER-CE, 2020). It can also be helpful to interact with the general public and stakeholders to investigate their aims and objectives and hence reduce the risk of lack of public or political acceptance (Lyytimäki and Assmuth, 2014).

This report on the desk analysis of the pilot feasibility study for MAR deployment in fractured and karstified *aquifers located in semiarid karst areas (D.T3.6.1)* is giving an overview on existing data for the feasibility assessment of the DEEPWATER-CE pilot site in Croatia. Based on the existing data, the further steps for determining missing data for a comprehensive feasibility assessment are developed and documented in a pilot action design plan. The feasibility assessment is incorporating risk management and cost-benefit analysis as well and will be addressed in further reports (D.T3.x.3-4).

In this report, we address the existing data and knowledge regarding the Croatian pilot site, the island of Vis. Vis is a remote island in the Adriatic Sea and its unique feature is the water supply from its own karst aquifer. The island has approximately 4,000 inhabitants, and the available groundwater resources cover the demand of the domestic population. However, the demand increases up to five times during the summer due to intensive tourism. Vulnerable and limited groundwater resources, coupled with increasing seasonal demand and an uncertain climatic future, make this island an excellent candidate for assessing the suitability of MAR.

II. Data availability and sources of data

Data	Source
Geomorphological map	Terzić (2004) and Krklec et al. (2012)
	Croatian Geological Survey
Topographical map (1:25000)	Croatian Geological Survey & DGU
Geological, hydrochemical and geophysical data & results	Croatian Geological Survey
Climate data: temperature, precipitation	Croatian Meteorological and Hydrological Service
Land use	The Ministry of Economy and Sustainable Development; Croatian Agency for Nature and Environment
Water supply data	Vodovod i odvodnja otoka Visa d.o.o
Flood hazard and flood risk maps	Croatian waters
River basin management plans	Croatian waters

III. Pilot site characterization based on existing data

3.1. Surface topography

Vis is a small remote island in the Croatian part of the Adriatic Sea. The island is 89.7 km^2 and it is approximately 45 km away from the Croatian mainland. Its coastal length is 84.9 km, with an indentation coefficient of 2.28. The highest peak on the island is Hum with an elevation of 587 m a.s.l. The main morphological and structural elements on the island have W-E orientation, or so-called Hvar strike, which differs from Dinaric strike (NW-SE) (Terzić, 2004).

The complex relief on the island of Vis is the result of interrelated geological, tectonic, paleo-geomorphological, paleo-climatological, and anthropogenic processes. The distribution of relief is in accordance with main structural and lithological characteristics (Figure 1). In the fault zones, due to intensive fracturing of the rock mass, depression, valleys, and karst *poljes* were formed. The most significant are Komiža-Vis valley and Podhumlje-Dračevo polje-Plisko polje (southern *polje*). In the central valley, Korita well field is situated, from where the majority of the groundwater is abstracted.

The northern and the southern coasts of Vis are W-E oriented, while the eastern coast is NE-SW. They are morphologically very steep resulting from the deformation of regional faults. The western coast (Komiža bay) has a subcircular shape due to the multiphase interaction between faults and the Komiža diapir.

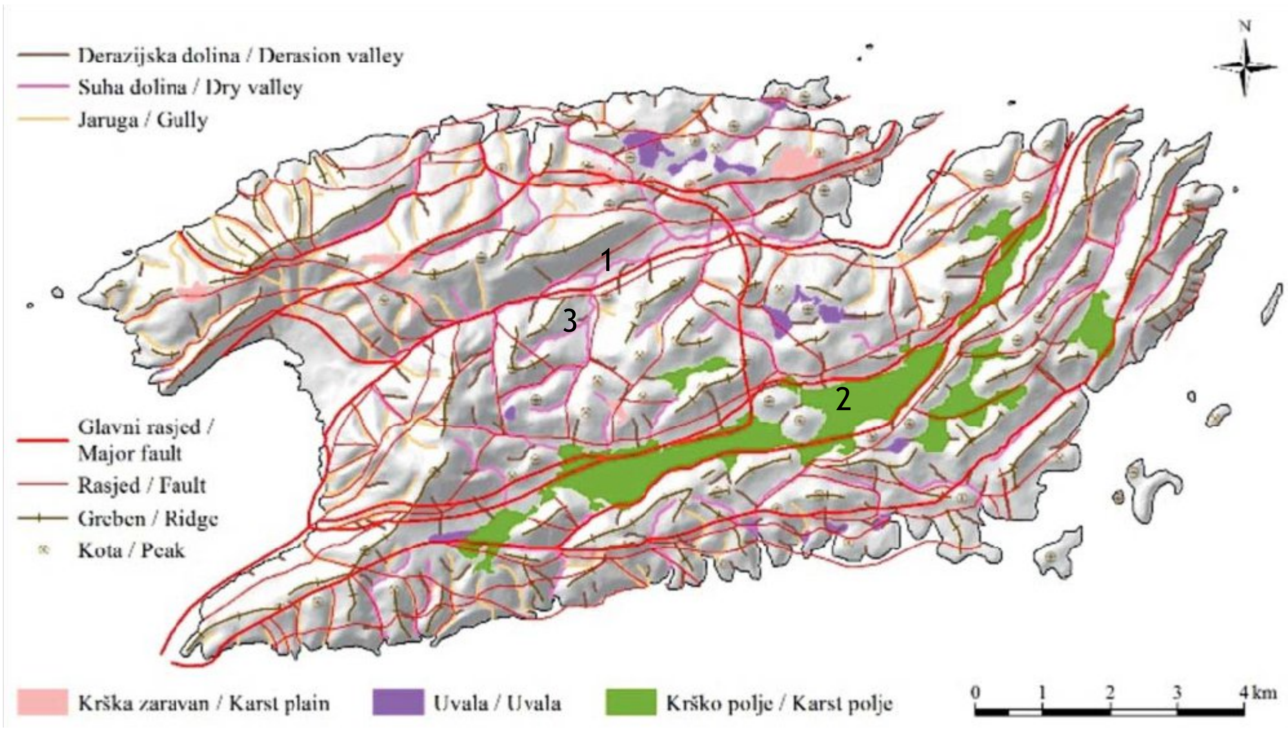


Figure 1. Geomorphological features on the island of Vis (Terzić 2004, modified by Krklec et al., 2012). Additional legend: 1 - Komiža-Vis valley, 2 - Podhumlje-Dračevo polje-Plisko polje, 3 – Korita well field

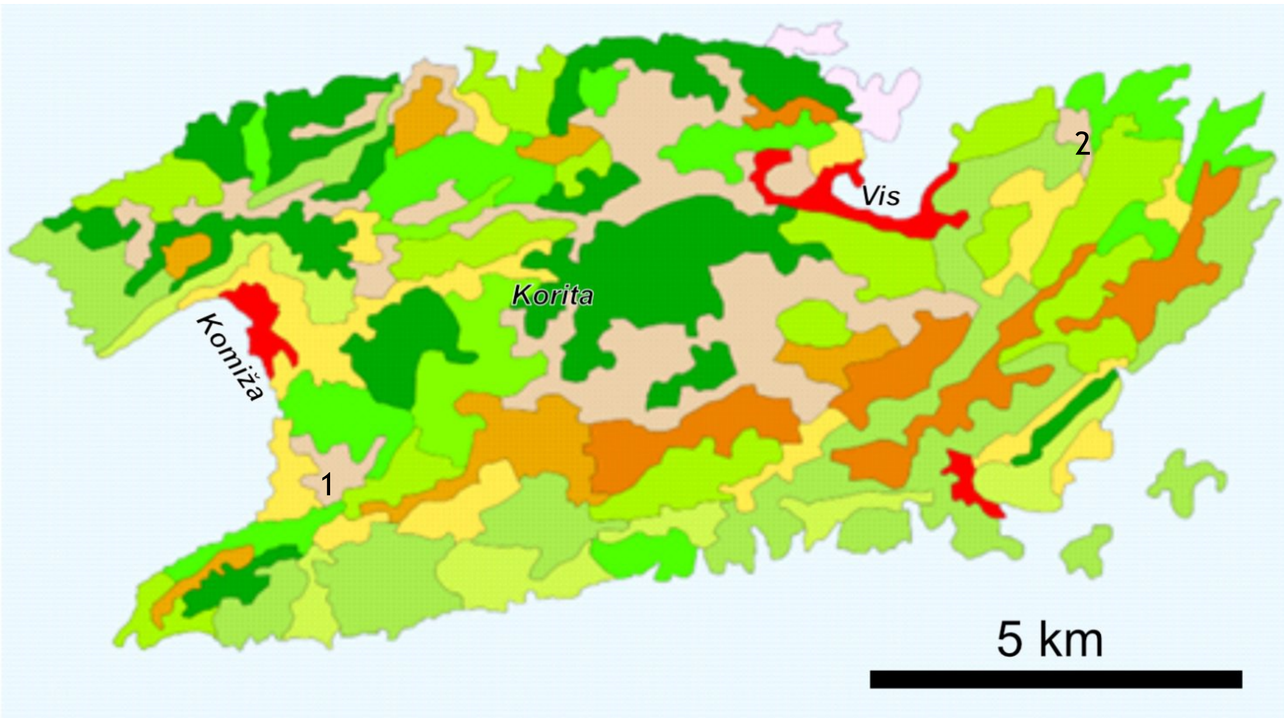
Furthermore, anthropogenic activity had a significant impact on the morphology of the island. In order to increase the arable land, many steep slopes have been terraced. At some areas, this intensive anthropogenic activity has intensified the denudation processes, resulting in erosion of the soil and exposure of barren karst on the surface. However, due to the massive abandonment of agricultural activity in the last decades, a reverse process has occurred, i.e. the succession and overgrowth by dense Mediterranean vegetation of previously arable agricultural land.

3.2. Climatic conditions

The climate on the island of Vis can be classified as a “Hot-summer Mediterranean climate” (Csa; Koppen 1936) with dry and hot summers and mild winters. Due to its position in the open sea, there is a strong maritime influence which is reflected in the mitigation of climate extremes and air temperature variations. Average insolation is approximately 2650 hours/year, making Vis one of the warmest islands in the Adriatic Sea. The mean annual air temperature at Hum station is 16.8 °C. The warmest month is July, and the coldest month is January. Mean annual precipitation is between 600 and 700 mm in the coastal areas and slightly higher in the central part of the island. Most of the precipitation occurs during the autumn and winter, while the summer season is very dry. The island is exposed to very strong winds due to its position in the open sea.

3.3. Land use and potential sources of surface and groundwater contamination

Forest and seminatural areas cover approximately 60% of Vis, followed by agricultural and artificial areas (36% and 4%, respectively). The distribution of land use is shown in Figure 2. The most dominant subcategories within the forest class are transitional woodland/shrub and sclerophyllous vegetation, followed by coniferous forest, mixed forest, and natural grassland. The most significant portion of agricultural land is covered by heterogeneous agriculture, followed by vineyards, complex cultivation patterns, and olive groves. Artificial surfaces do not cover a significant portion of the land and are connected with the cities of Vis and Komiža, and the Rukavac settlement.



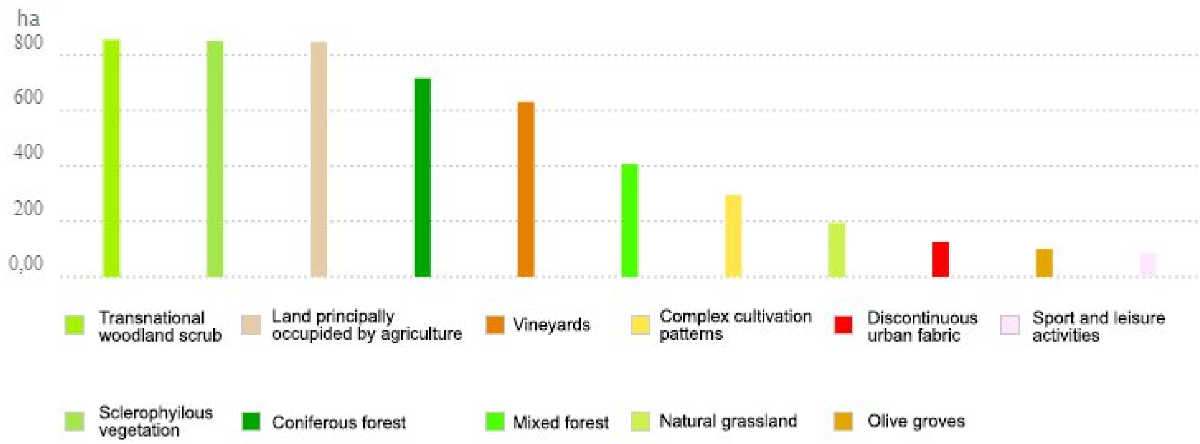


Figure 2. Land use map and distribution on the island of Vis (based on Corine Land Cover 2018). Additional legend: 1 – Šćeće waste disposal site, 2 – Wellington waste disposal site

There are no significant surface water bodies on the island. However, agricultural activity is a potential source of groundwater pollution. Excessive use of plant protection products (e.g. pesticides, herbicides, fungicides) and fertilizers could result in nitrogen and phosphorous surplus in the soil, which could be leached to the groundwater during heavy rains. There is not an intensive agricultural activity in the immediate vicinity of Korita wells (Figure 2; blue highlight), and the site is topographically higher than the karst *polje* Dol where a significant portion of the land is covered by vineyards and other crops. Furthermore, there are not relevant industrial sites or quarries that could be classified as potential pollutants. Dug shallow wells around Komiža are more prone to deterioration of the water quality, but they are not utilized in the public water supply system but rather for irrigation of surrounding agricultural fields.

There are two waste disposal sites on the island. In 2019, the waste disposal site of Šćeće near Komiža was closed and all the island's waste is now sent to Wellington site near the city of Vis. Šćeće was not a proper waste disposal site since the waste was dumped on barren karst surfaces. Due to the lack of impervious surfaces or other adequate landfill insulation bed (e.g. clay), the pollution could rapidly infiltrate to the underground and, potentially, to the groundwater. However, the landfill is located near the coast and it is outside the catchments of Korita. The Wellington site is currently under reconstruction and, once finished, the waste will be sorted, composted, and disposed of in a proper technical and sanitary manner.

The city of Vis has a fully operational sewage system, with two devices that purify the wastewater before its submarine discharge away from the city. The sewage system of Komiža is currently being expanded and the new submarine discharge pipeline is being laid to the south of the city. Additionally, many households, farms, and vacation houses still have cesspits that are often leaking and they are not regularly maintained and emptied. However, this type of sewage system is rare in the vicinity of the main water supply sources of the island, and it does not present a high risk to groundwater pollution.

3.4. Hydrology

There are no surface water bodies on the island of Vis. Karst *poljes*, covered by low permeability Quaternary deposits, are prone to periodical flooding during heavy rain events. The flood hazard map is shown in Figure 3 and the flood risk map is shown in Figure 4.

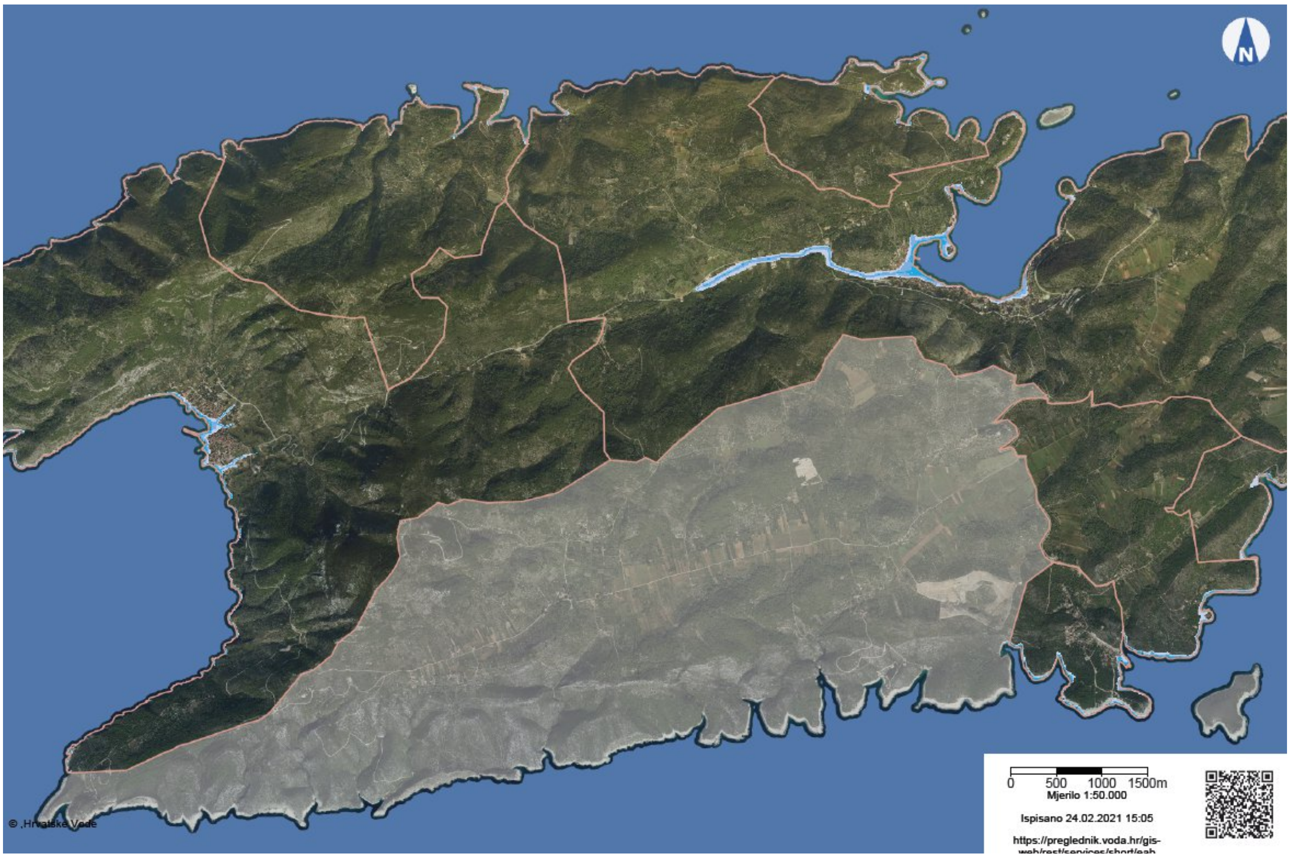


Figure 3. Flood hazard map for the island of Vis, high probability hazard (T=10 years) is highlighted in grey (Croatian waters, 2019).

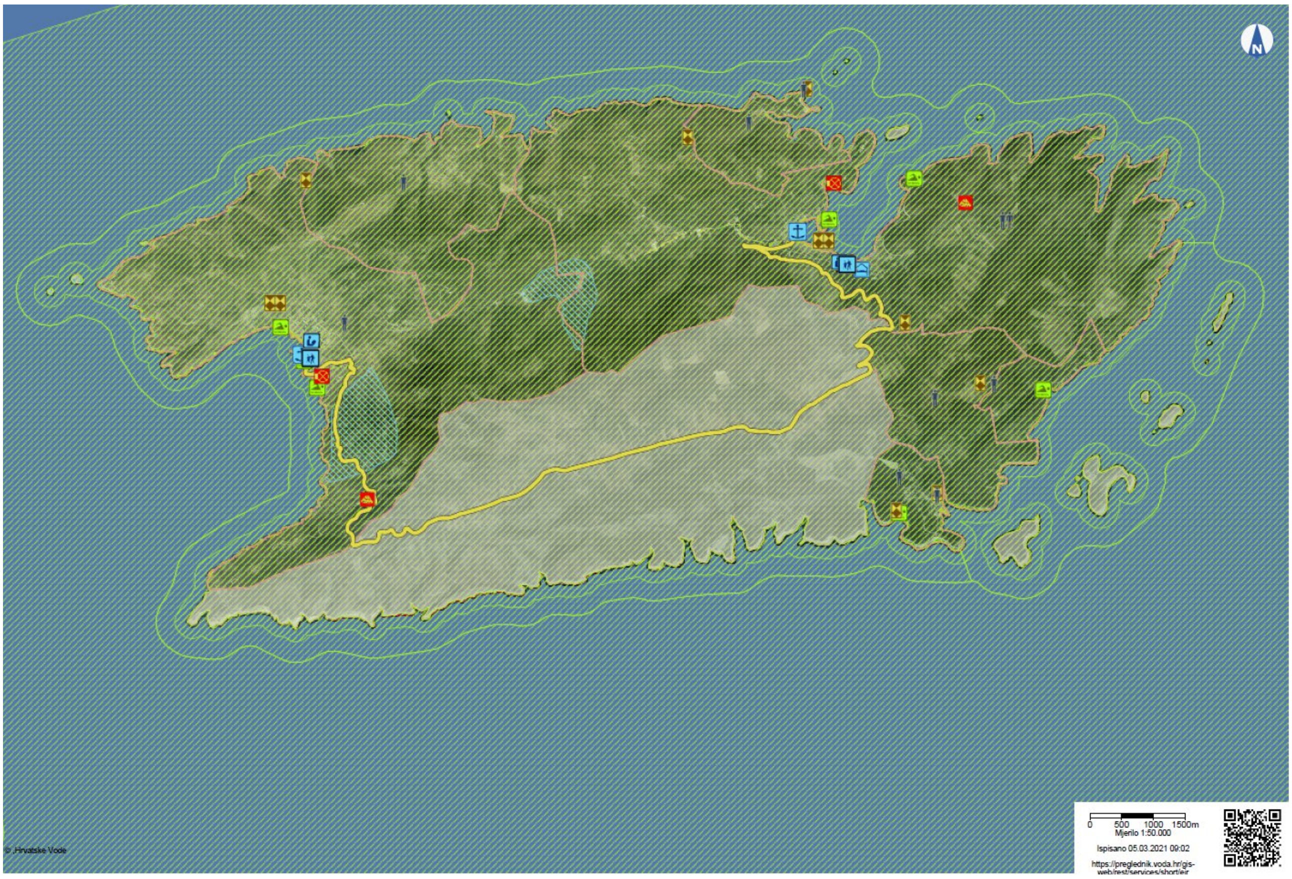


Figure 4. Flood risk map for the island of Vis, high probability risk is highlighted (T=10 years) in grey. (Croatian waters, 2019). The symbols represent different activities and sectors (e.g. tourism, recreation, infrastructure).

Besides karst *poljes* on the southern side of the island, there is a high probability of floods in the urban environment of Vis and Komiža cities (Figure 3). Particularly, the urban drainage systems collect both domestic sewage waters and meteoric waters and they do not have an adequate capacity to receive intensive rainfall during storm events. Furthermore, the high degree of urbanization and the amount of impervious surfaces cause periodical torrential flows of storm waters discharging them both into the sewage water system and the sea. Additionally, flood hazards are related to the dug canal that goes from the Korita pumping site through Dol *polje* towards the city of Vis.

River basin management plan (2016-2021) groups the groundwater bodies on the major Adriatic islands and provides a general assessment of their condition and vulnerability. GW body JOGN-13 (Adriatic islands) has an estimated groundwater recharge rate of 122×10^6 m^3 / year, while the utilization is 3.22×10^6 m^3 / year (0.26% of recharge) and the aquifers have a medium intrinsic vulnerability. Overall chemical status is good, but with low reliability; quantitative status is also good, but with high reliability. However, it is important to emphasize the shortcomings of this kind of assessment where all the islands are grouped into a single groundwater body, while the realistic conditions significantly vary between the islands (different types of aquifers, utilization status etc.).

3.5. Geology

The island of Vis is part of the Dinaric karst region and it is mostly composed of karstified carbonate rocks. The main structural elements are oriented W-E and slightly differ from the Dinaric strike (NW-SE).

Dominant rocks on the surface are Cretaceous carbonates (limestone, dolomite), Quaternary sediments (*terra rossa* in karst *poljes;* breccia; aeolian sands; colluvial deposits), and a mixture of volcanic-sedimentary-evaporitic rocks (andesite, gypsum, dolomite, siltite, tuffite; hereafter referred to as VSE) forming the Komiža diaper (Korbar et al., 2012).Three main faults occur on the island (from N to S: Ključna, Komiža-Vis, and Podšpilje-Rukavac faults), and the main water abstraction site Korita is located within/along the damage zone of the Komiža-Vis fault. The geological map of the island and the cross-section are shown in Figure 5. The lithological description of all geological formations, units, and members is in Annex 1.

The main structural elements are oriented W-E and slightly differ from the classical Dinaric strike (NW-SE).

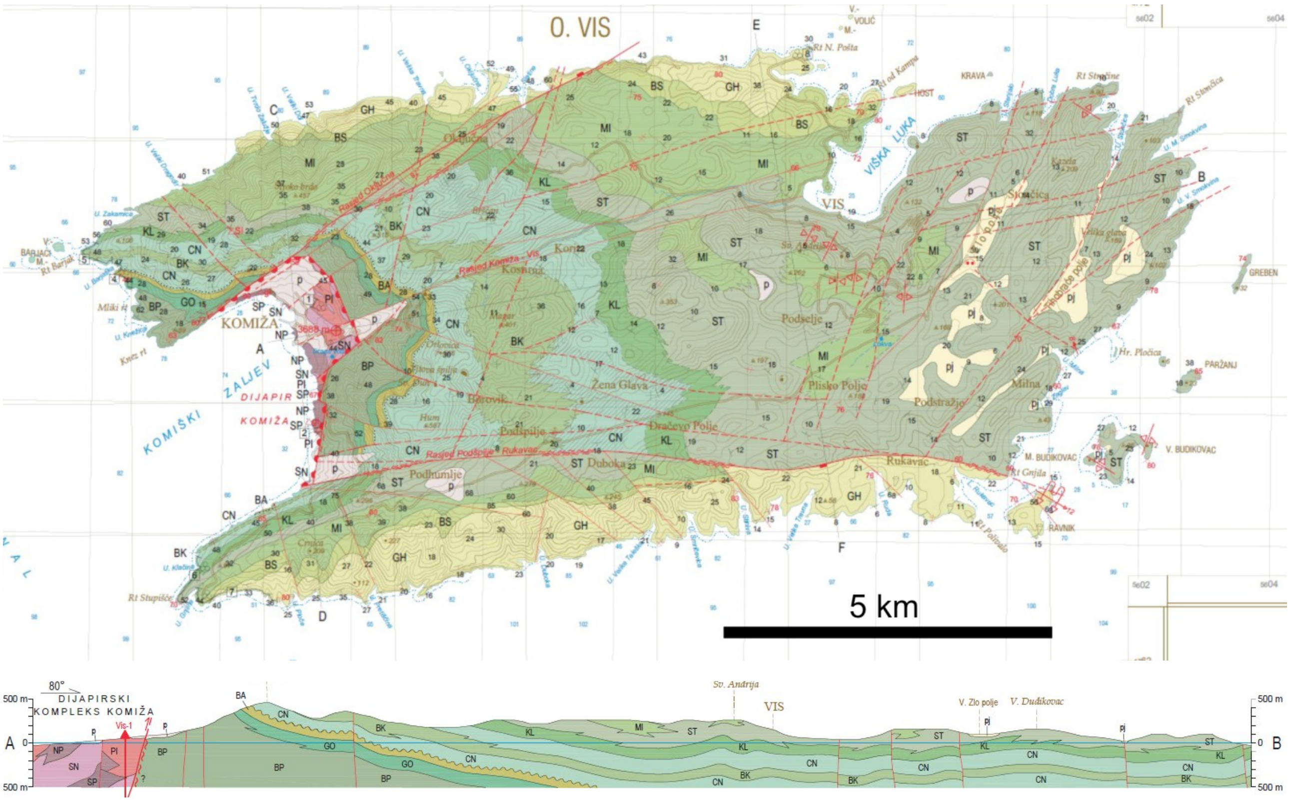


Figure 5. Geological map of the island of Vis and a cross-section (Korbar et al., 2012). The formations are depicted by their acronym and their description is in Annex 1.

3.6. Hydrogeology and water supply

Favourable geological and hydrogeological conditions enabled the formation of high-quality karst aquifers from which the groundwater is abstracted, hence the island of Vis is not connected to the mainland or any other island by water supply pipelines. The water supply system on the island of Vis consists of Korita well field, K-1 well, and Pizdica spring (Figure 6). The main contamination source of the Vis karst aquifers and its water supply is the seawater intrusion. The sole recharge of the island's aquifer is precipitation.

Korita well field was constructed in the late 1960s and consists of five active wells. It is located in the central part of the island and water is abstracted from the karst aquifer from the depth of approximately 120 m. Its maximum pumping rate is 42.5 l/s. The aquifer of Korita in the central part of the island is protected from seawater intrusions from the west by the impermeable rock formations of the Komiža diapir and from the south by the fine grain infilling of the fractures and karst conduits that leaches from the Quaternary polje deposits decreasing the permeability field of the underlying rock masses.

Pizdica is a small coastal spring formed at the contact of permeable Cretaceous carbonates and impermeable formations of the VSE diapir. An intake structure was drilled into the rock cliff to secure the water utilization during the possible nuclear attack of the Cold war. The maximum pumping rate is approximately 3.3 l/s. As this is the coastal spring at sea level, the spring is prone to increased salinity and concentration of chlorides. The water from Pizdica is pumped mainly during the summer months when the demand increases by a factor of five due to intensive tourism. Due to increased salinity, water from Pizdica and Korita is mixed in the ratio of ¼ before the distribution to the consumers, to keep the chloride content below maximum levels allowed for human consumption.

The K-1 well, located in the hinterland of Komiža, is the newest well and its pumping rates are up to 1.5 l/s. This well taps the dolomite aquifer of relatively low permeability behind the VSE barrier. Notwithstanding its low yield, it is very important because it is not prone to salinization.

In the western part of the island, there are several small springs (the most relevant are Gusarica, Dragevode, and Kamenice springs) that have been utilized since antique times. They are fed by the shallow subsurface flow through Quaternary breccia and clastic materials.

Previous hydrogeological investigations on the island of Vis included a water balance calculation, determination of hydraulic parameters of the aquifer from pumping test data, a tracer test, and hydrochemical sampling campaigns. This data is a part of the thesis by Terzić (2004) and will be available for further use in DEEPWATER WP T3.

The concept of applying the MAR scheme on the island of Vis is primarily focused on the two most prospective methods: (i) infiltration pond and (ii) aquifer storage and recovery (ASR). Other methods, i.e. recharge dam, underground dam, and induced bank filtration are not suitable since there are not surface water bodies on the island. An interesting fact is that there was a project to construct a reservoir on the island, but it was never fully developed. With the increasing tourism activity, there is a pronounced need for alternative solutions in the management of freshwater resources on the island due to increased seasonal demands, climate change, and high variability of seasonal precipitation. In 2020, a cumulative rainfall of 583 mm was recorded in Komiža, out of which 200 mm fell in December, while the majority of the year was extremely dry. Groundwater levels were very low and a warning was issued to the population of the island to minimize the water consumption. In the end, reductions in distribution were avoided due to less intensive touristic season as a result of the global pandemic of the COVID-19 disease.

Korita pumping site is conveniently located in terms of having enough land availability on site for potential construction of an accumulation structure which would be utilized as a source of water for MAR. Furthermore, the availability of essential infrastructure (road, telecommunication, water distribution, electrical power) and the high degree of security (in terms of potential pollution source) make this site potentially very suitable for the application of the proposed MAR schemes.

3.7. Regulatory limitations

In Croatia, MAR is not a part of any water strategy, legislation, or action plan. Water management (legislative aspect) is the responsibility of the Ministry of Environment and Energy – Administration of water management and sea protection, and Croatian waters is an executive body responsible for water management and the implementation and coordination of the implementation of state policy in the field of water, including the development of River Basin Management Plan.

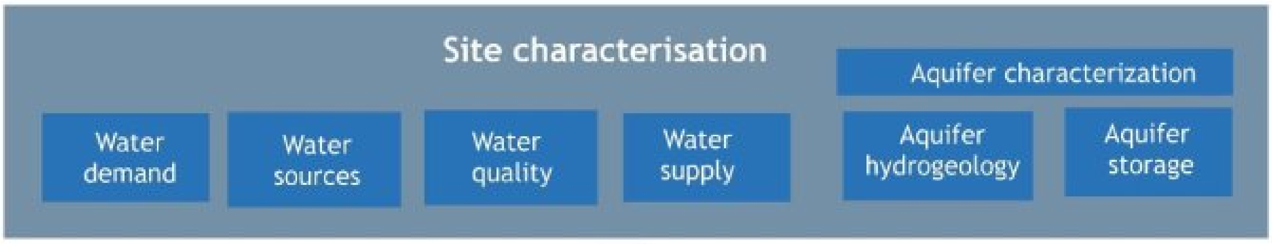
Most important elements of water management are contained within the *Water Act*, while the water quality control in the Republic of Croatia is regulated by the *Law on the Water Intended for Human Consumption*.

During the implementation of DEEPWATER-CE, a close cooperation is maintained with relevant stakeholders responsible for water management on local, regional, and country level. Furthermore, important asset is having a water supply company Split (ViK Split) and Croatian waters in DEEPWATER-CE partnership, who can efficiently push and promote MAR topics to decision and policy makers.

IV. Pilot action design plan

4.1 Aims

In order to provide an effective site characterization, the following concept proposed in the report on Common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies.



The first and the most important consideration for the development of an efficient and sustainable MAR system is the pronounced water demand. In these terms, the island of Vis is an ideal candidate for further suitability analyses due to the following characteristics:

- a remote island in the open sea,
- water supply from its karst aquifers with high intrinsic vulnerability (i.e. aquifer salinization),
- high peaks in the demands (water demand increases fivefold during summer months, when the groundwater levels are at the minimum),
- high variability in precipitation,
- possible adverse effects of climate change in an already semiarid area.

As the island's groundwater resources are recharged solely by precipitation, meteoric waters are the only possible water source for a MAR system. The available water balance (Terzić, 2004) estimates that the mean annual infiltration is 40% of precipitation. Furthermore, 99% of the infiltrated water diffusely outflows along the coastline, while only 1% is used for the water supply system.

The groundwaters abstracted at the Korita and K-1 sites are of high quality, while the groundwater on Pizdica coastal spring exhibits elevated chloride concentration as it mixes with the seawater. Hence, the groundwater is only chlorinated to eliminate bacterial content before being distributed to the consumers, and it does not need additional purification because of its good chemical status. During the pumping, there is a continuous monitoring of electrical conductivity, groundwater level, and pumping rates. These parameters have a long time series and are kept in the records of the local water supply company.

The hydrogeological characteristics of the Vis aquifers and their water supply system have been described in section 3.6. Hydrogeology. The water supply company distributes water to 4,150 users. The estimated annual groundwater volume exploited at the three main pumping sites is approximately 450,000 m^3.

Since every MAR solution has its specific requirements concerning the site, checklists containing the selection criteria are categorized by MAR types. Since general selection criteria for MAR cannot be defined, sets of selection criteria specific to MAR types have been developed in this project. Regarding the methods

(i) infiltration pond and (ii) ASR, we used the pre-defined selection criteria to narrow down from country level to potential pilot sites that meet the requirements. Preliminary results of general and specific mapping pointed out that the island of Vis is suitable for further pilot actions in the framework of our project.

Since the targeted aquifer for the application of the MAR scheme is karstic, special considerations in the investigation of site suitability and potentiality have to be taken into account. Particularities of karst aquifers, methods of investigation, and additional criteria have been thoroughly described in chapter 5.2 of the D.T4.1 *Final selection criteria and checklist methodologically sequenced*. In order to provide a precise and accurate suitability assessment of MAR in the specific study of the Vis karst aquifers, a description of planned investigation methods is given in the following subchapters.

4.2 Detailed geological and hydrogeological characterization based on previous field studies

The island of Vis, due to its important historical and geopolitical role, has been thoroughly investigated in the past. The geological framework of the Dinaric karst, and subsequently of the Vis island, has been investigated by numerous authors (Crnolatac, 1953; Poljak, 1953; Borović et al., 1977; Prelogović et al., 2003; Terzić, 2004; Vlahović et al., 2005, Korbar et al., 2012). The most significant hydrogeological research has been conducted by Terzić (2004; 2012), namely, the definition of hydraulic parameters of karst aquifer, delineation of catchments, and tracer testing.

Investigations within DEEPWATER-CE will evaluate, use, and capitalize upon the results of previous investigations. The results of these investigations will provide an added value to the understanding of karst aquifers on the Vis island and will significantly contribute to MAR suitability investigation in other karst areas in Croatia and beyond.

Planned field investigation within DEEPWATER-CE include:

- geophysical investigations (electrical resistivity tomography, magnetotelluric sounding, and refraction seismic) in the most prospective areas from a hydrogeological standpoint;
- design of 3D conceptual, geological, and hydrogeological model based on the acquired field data and existing data;
- structural-geological investigation of tectonic features (fractures, conduits, faults, beds) to provide input for the numerical model;
- water balance calculation.
- time series analysis of groundwater levels, EC, and pumping rates provided by the local water supply company.

4.3 Chemical and isotopic analyses of groundwater, surface water and soil/sediments

A prerequisite for a sustainable and efficient MAR operation is the detailed and precise monitoring of chemical parameters of groundwater before and during the operation. As karst aquifers are characterized by irregular and rapid flows and are generally vulnerable to pollution, it is necessary to investigate a long time series of hydrochemical data in order to precisely determine background chemistry, background processes, and interaction between precipitation and the ambient groundwater. Planned hydrochemical analyses are conducted periodically (monthly resolution) and continuously by groundwater loggers:

- in situ measurements of groundwater levels, pH, T, O_2, EC, and HCO_3^-;
- laboratory analyses of stable water isotopes and principal ion composition;
- laboratory analyses of $\delta^{34}S$ and $\delta^{18}O$ from sulphate anions in the water and ^3H activity analyses (mean residence time);
- continuous measurement of groundwater levels, EC, and T.

The investigated locations include natural springs, water supply wells, and exploration wells. The map of the monitored locations is shown in figure 6.

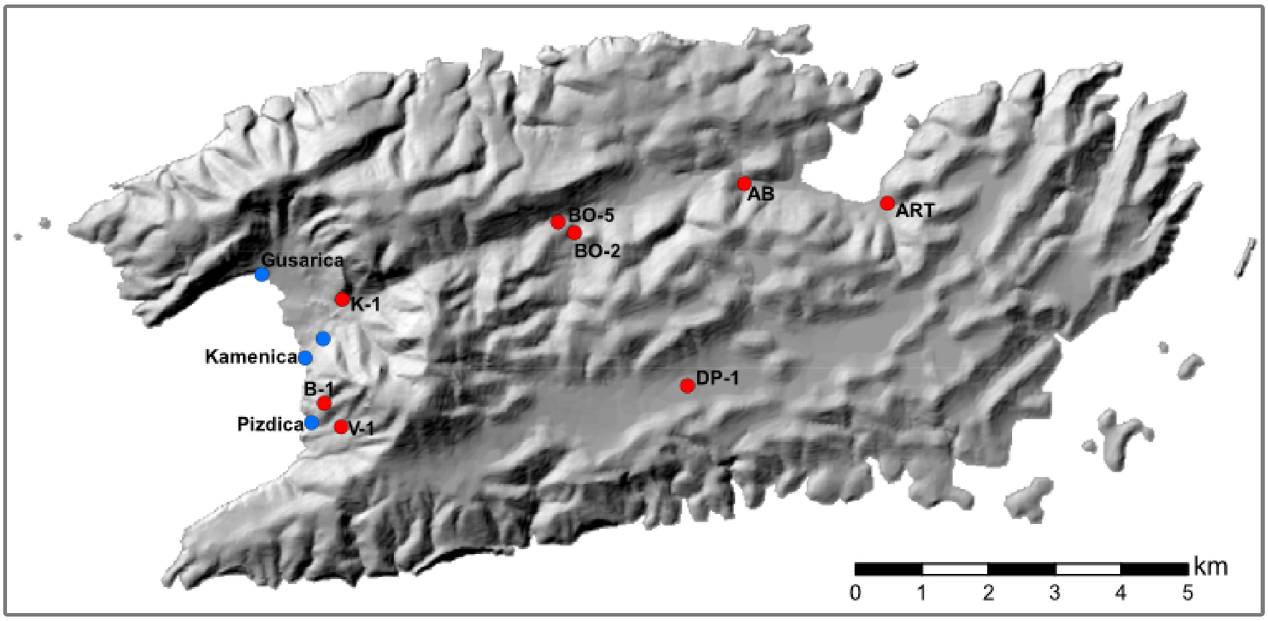


Figure 6. Map of the monitored locations on the island of Vis. Springs are shown in blue, and wells in red

4.4 Hydrogeological modelling

Despite the strategic importance of the Vis groundwater resource and its potential endangerment by salinization and climate change, the karst aquifer of the Vis island has never been the object of hydrogeological numerical modelling.

A numerical model of the entire island will be constructed based on the results of the geological reconstruction and the hydrogeological conceptual modelling. This model will be aimed to:

- reproduce the current potentiometric level and EC/salinity data and their variations through an average hydrological year under the effects of different pumping rates.
- perform predictive scenarios of the climate change effects on the water resource including the possible increase of recharge due to MAR.

The simulations will include both fluid flow and mass transport modelling in order to evaluate the possible salinization of the water resource due to increasing pumping rates and/or climate change.

The numerical modelling workflow will go through:

- a simplified „block-like“ model that will be used to perform a first calibration of the hydrogeological and transport parameters and to roughly evaluate the effects of climate change and MAR.

- a detailed model reproducing the geometries of the main geological and structural elements that will be used to refine the previous calibration and the climate change and MAR scenarios.

V. Conclusions

The investigation of the MAR suitability in a karst environment is a complex task, mainly due to the high anisotropy and heterogeneity of karstic systems and also due to the relatively low number of implemented schemes on the global scale when compared to MAR schemes in the alluvial environments with intergranular porosity aquifers. To conduct a more reliable assessment, it is necessary to use any available and relevant resource at the researcher's disposal. Although it is possible to achieve a high degree of certainty related to the MAR suitability assessment, it is hard to provide a definitive judgment on suitability and efficiency in a karst environment without the operating test site or facility. As a consequence of their high heterogeneity, it is practically impossible to quantify the karst aquifer's response (changes in chemical composition, flow & discharge patterns, and groundwater levels) to the injected/infiltrated water without detailed high-resolution monitoring of the numerous parameters. The suitability assessment will provide a major step towards an improved understanding of numerous implications and will also contribute to the relatively poor knowledge base of MAR application in the karst environment.

VI. Literature

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ANNEX 1. Lithological description of formations/units/members

Quaternary

Slope deposits [p] (colluvium). Unsorted slope deposits. Karst debris and blocks of surrounding rocks as unconsolidated or poorly consolidated sediments (silt-sand size of matrix particles), and slope breccias. Thickness < 10 m

Aeolian sands [pj] (Zlopolje sands). Massive to cross-laminated sands. Unconsolidated or poorly consolidated, well sorted, non-rounded, tiny grained, mostly carbonate, sands with lens of poorly sorted karst debris. Thickness < 10 m

Upper Cretaceous

Gornji Humac formation [GH] (Turonian - Coniacian). Thin to thick-layered limestones, locally layered into slabs. Decimeter-thick intercalations of fenestral mudstone, wackestone-packstone with *Thaumatoporella*, peloidal-skeletal-bioclastic-intraclastic wackestone to grainstone, and floatstone with *Radiolitidae*. Rarely with emersion surfaces. Sporadic cyanobacterial laminite, oncoidal floatstone, *Hippuritidae*, sponges, solitary corals, and sea urchin and other. Locally crystalline dolomite. Thickness 250 m

Basina formation [BS] (Upper Cenomanian - Lower Turonian). Massive, medium to very-thick limestone, locally with nodular layers. Bioclastic-skeletal wackestone to packstone, rarely bioclastic floatstone with fragments of *Radiolitidae* and *Caprinidae* and thin (around 1 m) lens of tiny bioclastic wackestone with calcispheres. Thickness 40 m

Milna formation [Ml] (Cenomanian). Thin to thick-layered limestone. Decimeter-thick intercalations of fenestral mudstone, peloidal-skeletal-bioclastic-intraclastic wackestone to grainstone, floatstone with *Chondrodonta* and *Radiolitidae*, and cyanobacterial laminite. Common corrosion cavities and emersion surfaces. Locally crystalline dolomite. Thickness 115 m + Stupišće and Klačina units thicknesses

Stupišće unit [ST] (Middle Cenomanian). Medium to very thick-layered dolomite and dolomitized breccia. Mainly crystalline dolomite, and in minor part relicts of dolo-bindstone. Thickness 120-160 m

Klačina unit [KL] (Lower - Middle Cenomanian). Thin to medium-thick-layered limestone. Centimeter-thick intercalations of mudstone with ostracods, peloidal-skeletal-bioclastic-intraclastic wackestone to grainstone with *Miliolidae* and cyanobacterial laminite. Thickness 60-100 m

Lower Cretaceous

Crna formation [CN] (Upper Aptian? - Albian). Thin to medium-thick-layered limestone. Decimeter- to centimeter-thick intercalations of mudstone with ostracods, skeletal mudstone-wackestone with *Miliolidae*, peloidal-skeletal-bioclastic-intraclastic wackestone to grainstone/floatstone with gastropods, tiny shellfish and oncoids. Rarely cyanobacterial laminite. At the top of formation, clayey limestone and lens of silicified limestone. Thickness 270 m + Barjak unit thickness

Barjak unit [BK] (Albian). Medium-thick-layered crystalline dolomite with indistinct stratification, rarely dolo-bindstone. Thickness 50 m

Barjaška formation [BA] (Lower Aptian). Thin-layered to massive limestone; dolomite in the lower part. Pronounced vertical and lateral diversity of lithofacies: mudstone, bioclastic-skeletal wackestone, rarely packstone-grainstone with variable *Nubecularia*, and shellfish, rarely with solitary corals and *Bacinella* oncoides. Packstone with *Palorbitolina*, bioclastic-skeletal floatstone with *Requieniidae*, rarely with *Caprinidae*, *Ostraidae*, nodules and interlayers of chert. Thickness 75 m

Goveđari formation [GO] (Barremian). Thick to very thick-layered limestones. Decimeter- to centimeter-thick intercalations of fenestral mudstone, skeletal wackestone-packstone and cyanobacterial laminae, often with emersion traces (black intraclasts). Thickness 90 m

Babino polje formation [BP] (Valanginian? - Hauterivian). Thick to very thick-layered crystalline dolomite. Rarely, thin layers of limestone with algae and foraminiferae. Thickness > 415 m

Middle - Upper Triassic

KOMIŽA DIAPIR COMPLEX:

Pištica unit [PI] (Ladinian). Siltites, marls, tuffites, thin-layered clayey limestone and dolomite with secondary and autigenic gypsum, partly bitumenous.

Nova pošta unit [NP]. Massive vulcanic agglomerates.

Sveti Nikola unit [SN]. Massive andesites.

Stara Pošta unit [SP]. Massive and chaotic dolomite-gypsum breccias with karst debris and block of various lithotypes. It is the “megabreccia” matrix of the Komiža complex. Total thickness of the diapir complex > 200 m.