D.T3.3-6.5 COMPARATIVE REPORT ON DEEPWATER-CE PILOT FEASIBILITY STUDIES

REPORT D.T3.3-6.5

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I. Foreword

This report was prepared by the consortium of the project DEEPWATER-CE with the aim of developing an integrated implementation framework for Managed Aquifer Recharge (MAR) solutions to facilitate the protection of Central European water resources endangered by climate change and user conflicts. Main author is the Technical University of Munich. This report is a summary of the partnership work from deliverable reports of activities A.T3.3-6 (see contributors list for detailed information).

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II. Summary

In the following table, a summary of the main attributes and outcomes of the MAR feasibility studies (O.T3.1-4) in the four pilot site countries (Poland, Slovakia, Hungary and Croatia) are given.

Table 1: Overview of the main attributes and outcomes of the MAR feasibility studies.

	POLAND	SLOVAKIA	HUNGARY	CROATIA
Pilot area and site	Tarnów commune and municipality, Świerczków well field	Danubian Lowland, Žitný ostrov	Békés County, vicinity of Medgeysbodzás and Csanádapáca	Split-Dalmatia County, Vis Island
MAR type	infiltration ditches and induced riverbank filtration (IBF)	recharge dam	underground dam	infiltration pond and aquifer storage and recovery
Main usage of MAR scheme water	drinking water	irrigation water	irrigation water	drinking water
Aquifer Type	Unconfined aquifer of Quaternary age, composed of alluvial sands, gravels and pebbles	Unconfined aquifer (Quaternary); alluvial and terrace gravels, sandy gravels, and sands	Shallow groundwater body, Quaternary and Holocene fluvial sediments	Unconfined aquifer of Cretaceous age, composed of karstified carbonates (fracture-cavernous porosity)
Economic feasibility (outcome of CBA, feasible or not?)	Yes	Yes	For the maximum scenario	Yes
Main risks	Clogging of the wells and infiltration ditches Flooding Water scarcity and quality deterioration resulting from extreme climate events Unacceptable groundwater quality due to insufficient natural attenuation of groundwater High turbidity of the water entering MAR system	Economic risks due to low price of water, high installation costs, or lack of private/public funding Risk of low water storage, improper hydraulic settings or swelling clays Water scarcity due to droughts and a changing rainfall event periodicity	Economic risks due to low price of water, high installation costs, or lack of private/public funding Low price of irrigation water, effect of swelling clays	Economic risks due to low price of water, high installation/ maintenance costs or requirements, or lack of private/ public funding Insufficient national legislations and strict regulations regarding drinking water protection zones Water scarcity due to droughts Clogging Structural damages due to natural hazards or aquifer dissolution
Technical feasibility	Yes	Yes	More data needed	More data needed

III. Introduction

Managed Aquifer Recharge (MAR) refers to a suite of methods that are increasingly being used to maintain, enhance and secure the balance of groundwater systems under stress. These methods apply processes by which, e.g., excess surface water is intentionally directed into the subsurface. This can be done by spreading water on the surface, by using recharge wells, or by altering natural conditions to increase infiltration in order to replenish an aquifer and store water below the surface. MAR techniques offer promising solutions for water management, also with regard to tackling future climate change impacts (e.g. Casanova et al., 2016; Dillon et al., 2019; Dillon, 2005; Sprenger et al., 2017).

Within the DEEPWATER-CE project, we investigate the potential to implement MAR schemes in four partner countries: Hungary, Poland, Slovakia and Croatia, considering socio-economic, geological, hydrogeological, technical, regulatory and human health aspects. In the first of four work packages we have started to review common practices and conducted a benchmark analysis of MAR solutions in the European Union in order to build up a **transnational knowledge base** (deliverable D.T1.2.1, DEEPWATER-CE, 2020a). Then, in the second work package, we developed a transnational **decision support toolbox** on designating potentially suitable MAR locations in Central Europe (output O.T2.1, DEEPWATER-CE, 2020b), abbreviated decision support toolbox in the following text. Based on this toolbox, pilot sites with applicable MAR types could be identified (deliverable D.T3.2.1). In the third work package, we developed a common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies (deliverable D.T3.2.5, DEEPWATER-CE, 2020c), abbreviated **common methodological guidance** in the following. The common methodological guidance includes guidelines for consideration of the regulatory framework, pilot site characterization (including the determination of water demand and supply), risk management related to MAR implementation and operation, Cost-Benefit Analysis (CBA) of the MAR scheme and a comparison of solutions alternative to MAR. These guidelines were applied to the potentially suitable pilot sites (D.T3.1.2) and reported in deliverables D.T3.3-6.1-4 as well as within outputs O.T3.1-4. The comparative reports D.T3.3-6.5 aim at summarizing the outcomes of the common methodological guidance for each pilot site and comparing them in a common report. The partnership decided to not draft for different comparative repots as initially intended in the DEEPWATER-CE Application Form, but rather combined them in one comparative report for easier reading and understanding. The regulatory frameworks of the partner countries are described detail in D.T4.1.1, and the frameworks are compared in D.T4.1.2; hence in this report we will not repeat this information.

IV. Poland

MAR Method and Objective

At the Polish pilot site, a feasibility study was carried out for 2 types of MAR: induced riverbank filtration (IBF) and infiltration ditches. These two methods can potentially be very useful in the selected pilot site to increase groundwater resources and to limit the deterioration of groundwater quality due to the presence of large chemical industry zones. The water source for the selected MAR techniques is the Dunajec river (Figure 1). Fluctuations of the water table in the river related to floods and droughts are compensated by the operations carried out at the two dam reservoirs in Czchów and Rożnów located upstream. In the research area, at the Tarnów-Świerczków well field, a MAR system is already implemented, which will probably be further expanded. The aim is to provide a stable drinking water supply for the city of Tarnów.

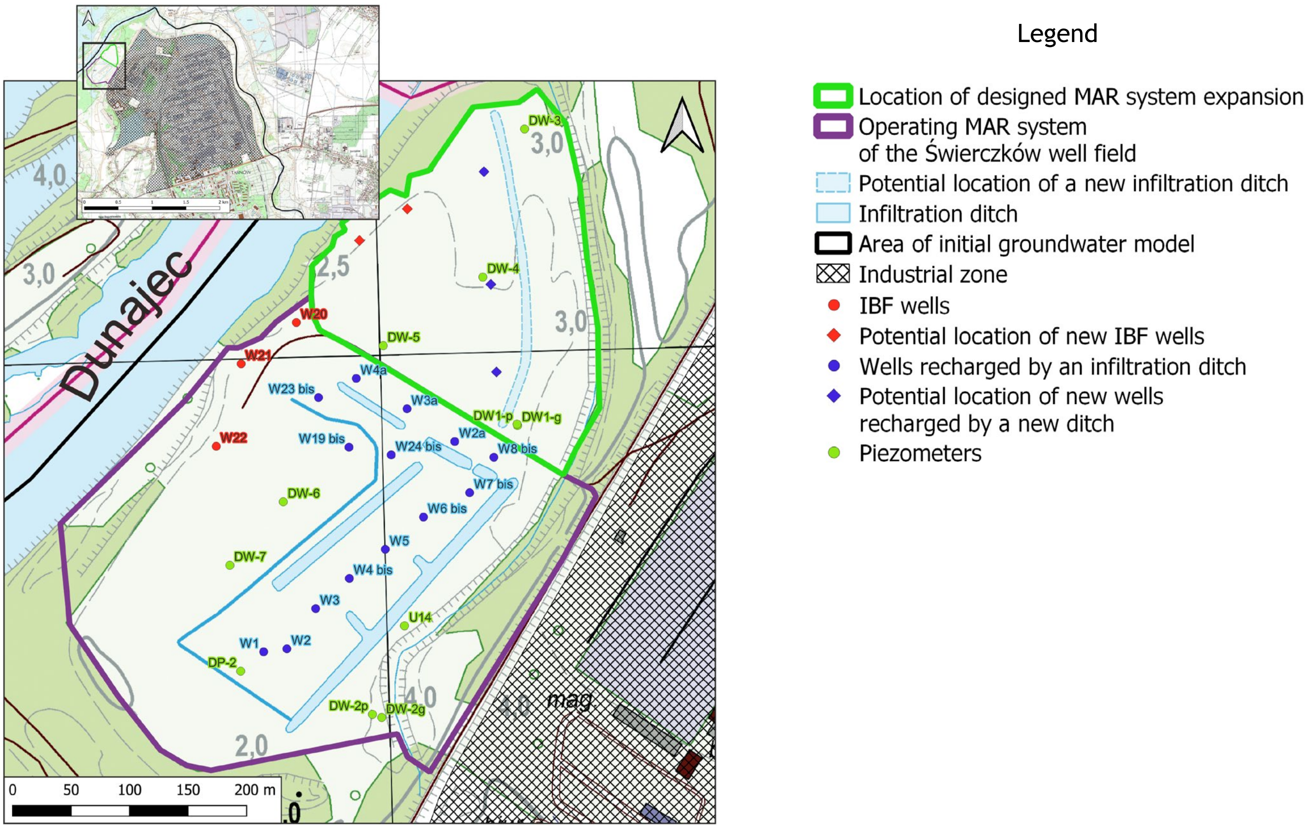

Figure 1: MAR system on the Świerczków well field and the location of its potential expansion.

Water Demand and Supply Situation

In recent years, the total water abstraction by Tarnów Waterworks did not exceed 10 million m³ per year, while both retail and wholesale water sales have also been stable, with a slight upward trend (3.5%) from 2017 to 2020. An important task is to ensure the continuity of water supply within shorter periods, in the situation of large periodic fluctuations of water abstraction (between from ~20 000 to >40 000 m³/d). Particularly critical are hot summer periods with extremely high abstraction caused by, e.g., filling backyard pools, or by watering lawns and gardens. As a result of climate change and the expected more frequent occurrence of extreme weather events (droughts and floods), ensuring a rational and continuous supply of good-quality drinking water to residents will be an increasing challenge.

The existing MAR scheme covers approximately 24% of the potable water produced by Tarnów Waterworks – a major water supplier at the pilot area. The extension of the MAR scheme is expected to increase this share by 6%. The additional MAR scheme will help to provide a more reliable water production during drought periods in the future. In addition, it will also allow the city to increase its water reserves in case of failure of other water supply sources.

Geological Settings

The investigated region is located within the Carpathian Foredeep Basin, a deep mountain basin between the massifs of the Carpathians and the Świętokrzyskie Mountains. The basin is filled with a thick series of Miocene sediments deposited inconsistently above Precambrian, Palaeozoic and Mesozoic deposits and covered by Quaternary sediments (Wojtal et al., 2009; Kruk et al., 2017). In general, the top 10 to 20 m (for the northern and southern part of the research area, respectively) are Quaternary deposits. They consist of loams (muds), silts and organic silts or clays in the upper part of the profile (particularly in the northern part), and alluvial deposits in form of sands and gravels with a substantial fraction of pebbles in the lower part of the profile. The Quaternary deposits lie on a clay Neogene (Miocene) bed (the further south, the higher their thickness).

Hydrogeological Settings

One of the hydrogeological classifications valid in Poland is the subdivision into Main (Major) Useful Aquifers, based on the Hydrogeological Map of Poland in 1:50 000 scale (Herbich, 2005). The most important unit in the study area according to this classification is associated with the formations filling the valleys of the Dunajec and Biała Tarnowska rivers. This unit has been identified as an unconfined Quaternary aquifer with sand and gravel as dominant materials (with silt (mud) as subordinate sediment) and underlying sand. The hydrodynamic-geomorphological type of this aquifer is that of a floodplain (Gorczyca and Gągólski, 2018; Gorczyca and Koziara, 2018). The described deposits frequently contain pebbles. The Quaternary aquifer lies on an impermeable Miocene clay layer and is mostly covered with silts and loams (Treichel et al., 2015).

Conducted Field and Laboratory Work

Field and laboratory work was conducted between December 2019 and September 2021. A geophysical survey was carried out applying Electrical Resistivity Tomography (ERT). With manual drilling, near-surface sediments were identified. On this basis, a map of the area's vulnerability to contamination from the surface was prepared, and the hydrogeological parameters of the sediments were examined (hydraulic conductivity, grain size distribution, bulk density). Another part of the investigation included sediments from the bottom of infiltration ditches. As part of the pilot feasibility study, new piezometers were drilled to gain a more detailed understanding of the geological and hydrogeological conditions in the study area (existing well field and the parcel designated for possible expansion). The hydrogeological investigations included monthly measurements of the groundwater table and surface water levels at the Świerczków well field. The investigations were supplemented by continuous (hourly) groundwater level measurements with dataloggers installed in five piezometers and in one infiltration ditch. In addition, water temperature was measured continuously with all these loggers, electrical conductivity with three loggers and the concentration of ammonium and nitrate with one multiparameter probe. Physicochemical parameters of groundwater, surface water and precipitation, concentrations of inorganic forms of nitrogen and the isotopic composition ($\delta^{18}O$ and $\delta^{2}H$) of the water were examined monthly. Concentrations of major ions, pharmaceuticals and personal care products, microplastics, surfactants and organic pollutants were measured at a lower frequency.

Risk Assessment and Management

A qualitative risk analysis matrix was used that takes into account the probability of risk occurrence and risk severity (e.g. Swierc et al., 2005). The most severe risks to MAR viability were found to be those of clogging (wells and infiltration ditches), long residence times of water in settling tanks (from which water is derived to the ditches), a high turbidity of the water entering MAR system, as well as flooding and the lack of water available for recharge due to extreme climate events. Also, regional hydrogeology and hydrochemistry problems might be a constraint.

As a second method, probabilistic risk assessment was carried out using fault tree analysis with the MAR-RISKAPP tool set up within a Microsoft Excel® spreadsheet (developed within the EU FP7 project MARSOL, Rodríguez-Escales et al., 2018). This method evaluates the risk of MAR failure considering technical and non-technical aspects. The application of this method revealed that the highest risk may derive from a low quality and/or quantity of water. This may arise from physical clogging or from sanitary and biological aspects (the latter only for the design phase). Moreover, water scarcity and flooding, resulting extreme climate events, may harm MAR facilities (e.g., structural damage as a result of a flood). Important risks are also related to an inadequate water quality, such as due to insufficient natural attenuation or water disposition failure (e.g., pipe leakage).

Technical risks were found to dominate, with a 98% and 89% probability of MAR-failure within design and operational phases, respectively, in case no preventive actions are taken. Attention has also to be paid to non-technical aspects, such as economical or legal constraints, for which probabilities for MAR-failure of 68% for the design phase and 59% for the operational phase were found (without preventive actions).

Results of Cost-Benefit Analysis

The net present value (NPV) was used as a profitability indicator assessing the economic feasibility of the MAR scheme. NPV is a sum of private and socio-environmental net cash flows (the difference between the present value of benefits and the present value of costs over a selected time horizon). For the Polish case study, calculated NPV values indicate that the MAR scheme's extension and operation are economically feasible under all considered scenarios.

In order to estimate both use (availability of water resources) and non-use (socio-environmental) benefits, a survey was conducted to explore the maximum amount of money that the local population is willing to pay (evaluation of the willingness to pay, WTP) to enable a stable drinking water supply, also ensuring a sufficient quality and an improvement of the ecological status of the aquifer. Regarding the ways of conducting the survey required for this task, along with more conventional ways of distributing the survey (in paper and via e-mail for self-filling), a social media ad (on Facebook) was used to spread the survey description and related online link, aimed at increasing awareness among the targeted population (citizens of Tarnów and surrounding areas). Obtained survey results suggest that the non-use benefits of the MAR scheme are particularly important for the local population.

Possible socio-economic risks associated with the MAR scheme at the pilot study area should be considered by policymakers, especially those risks exhibiting a high probability of realization and/or major risk consequences. Based on assessments that have been done by local experts for the pilot study area, changing standards for the end-user was found to be the only risk with major consequences that can be expected to realize.

V. Slovakia

MAR Method and Objective

The Slovak pilot area is located on the largest river island in Europe - Žitný ostrov, which is a part of the Podunajska Lowland. This area is used mainly for agricultural land use. According to long-term climate forecasts, the Podunajska Lowland will be vulnerable to extreme weather events such as droughts. The focus on agricultural production, along with a predicted unfavourable climate change, makes this area dependent on water resources that are especially related to the availability and quality of irrigation water.

The pilot site area is delineated by three channels, namely Gabčíkovo-Topoľníky (SVII), Vojka-Kračany (AVII) and Šuľany-Jurová (BVII), which are equipped with technical tools for water flow regulation. This creates the MAR-type of recharge dams (Figure 2). The main water source for this MAR system is the seepage channel running left-hand of the inlet canal to the Gabčíkovo Waterworks. Hrušov reservoir (as a part of the Gabčíkovo waterworks) is the main source of the infiltrated water to the seepage channel.

The aim of the feasibility study was to investigate the possibilities of groundwater recharge from channels to shallow aquifers. Furthermore, possible regulation of surface water was analysed for enabling groundwater replenishment and thus possible later use of groundwater for irrigation during periods of water shortage.

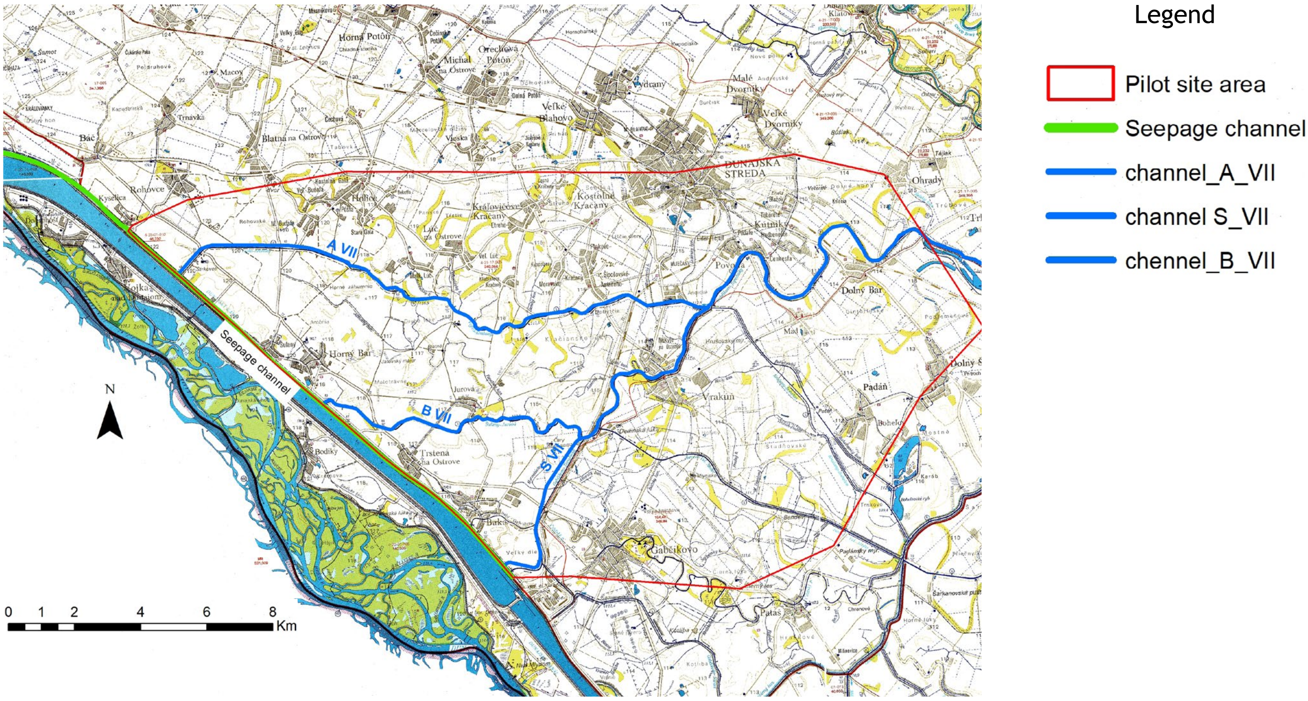

Figure 2: Pilot site area *(Výskumný ústav vodného hospodárstva, 1999)*.

Water Demand and Supply Situation

According to the water balance of Slovakia, the hydrogeological rayon (region) Q 052 (Quaternary of the south-western part of the Danube Lowland), i.e., the pilot site area, is in a good water balance status. The current water demand for irrigation is ensured by the existing water supply structures based on the channels. It is expected to change in the future due to climate change impacts and intensified agricultural activities, requiring higher amounts of irrigation water. Water demand estimation for a period of 30 years was done based on data for the northern part of the Podunajska lowland as a reference, since no data was available for the pilot site area. Agricultural production is similar in both areas. Estimated potential water supply of the newly intended MAR schemes indicates that the water demand by future irrigation needs can be met.

Geological Settings

The pilot site is located in the Slovak part of the Danube Basin, i.e., at north-western part of the Pannonian Basin system. The geological characteristics of this area are the result of complex process associated with polyphase back-arc rifting, post-rift thermal subsidence and basin inversion (Šujan et al., 2021). This complex development manifests in several tectonically distinct depocenters (depressions). The largest and deepest of them is the Gabčíkovo-Győr depression, which represents the study area. The sedimentary in-fill of the depression is represented by Neogene and Quaternary sediments. In the deep structure of this basin, Neogene sediments discordantly overlie Paleozoic granitoid rocks (Fusán et al., 1987), and Neogene intrusive and extrusive volcanic rocks are present (Hrušecký, 1999).

Hydrogeological Settings

The pilot site is part of the hydrogeological rayon (region) Q 052 *Quaternary of the south-western part of the Danube Lowland* (Šuba & Mihálik, 1998). Due to complex geological conditions in the Danube basin, all three characteristic layers of groundwater bodies distinguished in Slovakia can be identified in the wider surroundings of the pilot area. The two deeper layers are groundwater bodies of pre-Quaternary age (Neogene), and the upper one is of Quaternary age.

Prevailing aquifers in the upper-most groundwater body consist of alluvial and terrace gravels, sandy gravels and sands, while the aquifers of the groundwater body below are dominated by limno-fluvial sediments. Further below, the third groundwater body is characterized by geothermal anomalies; main aquifers consist of sands and gravels. Only the upper-most aquifers (Quaternary sandy gravels) are relevant for MAR systems.

Conducted Field and Laboratory Work

Field work covered surface water flow measurements in channels, determination of channel geometries, groundwater table measurements, soil sampling and identification of soil/rock hydraulic properties. The latter was done by applying the auger hole method in the field and determining soil water retention curves in laboratory. Soils samples were evaluated in laboratory in order to derive hydraulic soil/aquifer parameters for the modelling of saturated and unsaturated flow (using the numerical models MODFLOW and HYDRUS 2D, respectively).

Risk Assessment and Management

Similar to the risk assessment carried out at the Polish study site, we have used a probabilistic risk assessment method developed by the MARSOL EU FP7 project (RodríguezEscales et al., 2018) and a qualitative risk assessment method specific for MAR systems (Swierc et al., 2005), which is in accordance with Australian MAR-guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009).

Concerning non-technical risks during the design and construction phase, the lack of private/public funding was identified as a very high risk. Possible risk treatment can be to report benefits of the MAR schemes in order to raise interest for potential investors. Furthermore, high risks were found with respect to low water prices on the market and high installation cost. Low water prices may also pose relevant risks during the operational phase. These risks can be overcome by additional support for the use of MAR facilities (such as state support or private financial sources) in order to promote financial viability of MAR.

Identified technical risks during the design and construction phase include technical difficulties related to the construction of MAR facilities, a low water storage and complex hydrogeological settings. These risks can be treated by an adequate technical planning of the MAR project and sufficiently detailed geological and hydrogeological investigations. During the operational phase, high risks can be associated, among others, to swelling clays, high concentrations of dissolved nutrients, droughts and heavy rainfall events (and their changed periodicity due to climate change), as well as changes in water demand and supply. Potential risk treatment includes: (i) a detailed study of geological, hydrogeological and rock mechanic conditions of the channels banks, (ii) pollution control (pollution originating from agriculture might e.g. be avoided by applying good agricultural practice procedures, and pollution originating from waste water e.g. by centralized sewage systems and adequate waste water treatment plants), (iii) efficient regulation of water flow in channels, (iv) adequate monitoring of water quantity and quality.

Results of Cost-Benefit Analysis

Based on the comparison of direct costs and benefits, the net present value was calculated as indicator of the economic feasibility of the MAR system in the Slovak pilot area. Furthermore, a willingness-to-pay survey was conducted and provided insights on agricultural production, irrigation water use and farmers' awareness of groundwater issues at the pilot area. To incorporate uncertainty in the analysis, scenarios with plausible variations of core parameters, such as expected irrigation water demand and levels of revenue per drop, were developed. For all these scenarios, the MAR scheme in the pilot site is expected to be economically feasible within the project's horizon (30 years). However, since the analysis relies substantially on data from a reference area, obtained cost-benefit analysis results should be treated as more indicative and thus rather with some cautiousness.

In terms of socio-economic risks, policy makers need to pay particular attention to risks with a high probability of realization and major risk consequences when designing the MAR scheme, which for the Slovak pilot study are the lack of funding and changing standards for end users.

VI. Hungary

MAR Method and Objective

The aim of the Hungarian pilot action is to examine the possibility of increasing the amount of available irrigation water in the Maros alluvial fan by applying an underground dam MAR scheme (Figure 3). In this way, sustainable water use can be achieved, especially during periods of water scarcity. Furthermore, due to a decrease of unregistered wells, the vulnerability of the drinking water aquifers can be decreased.

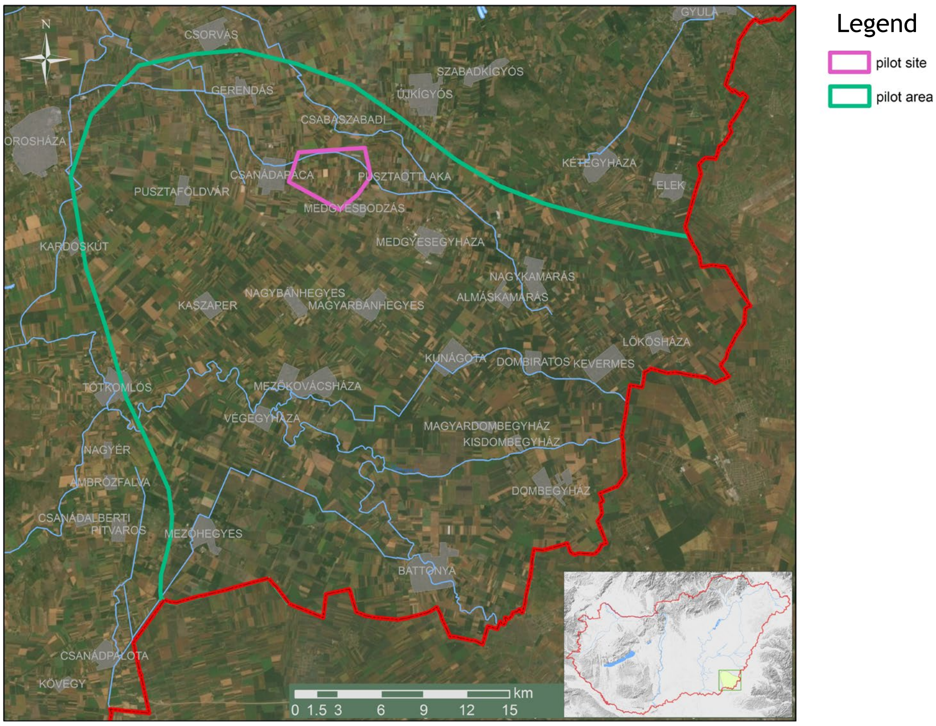

Figure 3: Location of the Hungarian pilot area.

Water Demand and Supply Situation

The presence of a low relief and the moderately warm and moderately dry climate determine that land use in the considered region is dominated by agriculture. According to the River Basin Management Plans, it is difficult to supply irrigation water to the northern and eastern parts of the region, resulting in crop failures during drought periods. The main source of irrigation water for farmers in the region is surface water, supplemented by groundwater. The sparse natural surface water network and trends predicted in climate change models indicate an expected increasing demand for irrigation water in the region. The calculated increased water demand in the future can be supplied by the MAR scheme.

Geological Settings

Hungary is located in the Pannonian Basin which is one of the largest sedimentary basins in Europe. As a result of the uneven subsidence in the late Middle Miocene and subsequent basin inversion, the Pannonian Basin was divided into sub-basins filled with several thousand-meter-thick Neogene sediment series (Royden and Horváth, 1988). In the southern part of the Great Hungarian Plain there are two important depressions: the Békés Basin and the Makó Trough, which are separated by the Battonya Basement High. The Békés Basin was filled with Neogene sediments (Juhász, 1998). The pilot area is situated at the western edge of the Békés Basin and the eastern part of the Battonya High. During the Pleistocene a thick

Quaternary series built up from the alluvial complex of the ancient Maros River. This alluvial fan is built up by several fluvial sequences (Gábris and Nádor, 2007, DEEPWATER-CE 2021).

Hydrogeological Settings

The geological settings of the alluvial fan built by the Ancient Maros River determine the hydrogeological conditions of the pilot area. The fluvial sediments were deposited in channels, point bars, islands and incised valleys of the fan act as aquifers, while fine grained silts and clays and formations derived from floodplain environments represent the aquitard layers (Borsy, 1989, 1990, Mike, 1991, Gábris and Nádor, 2007, DEEPWATER-CE, 2021). Due to their relatively high silt content, the aquitards of the Maros alluvial fan do not show aquiclude characteristics, so that hydraulic communication between neighbouring aquifer layers is possible. As a result of the semi-permeable behaviour and lenticular appearance of the aquitards the whole alluvium forms a hydraulically connected aquifer system (Zólyomy et al., 1985, DEEPWATER-CE, 2021).

Conducted Field and Laboratory Work

The aim of the fieldwork activities was to provide supplementary information on the geological-geophysical characteristics of the site, including geological and hydrogeological information, groundwater level and chemical characteristics for the feasibility study. In order to achieve this, electrical resistivity tomography (ERT) measurements were performed, first perpendicular to the paleo river channels of the Ancient Maros River and then parallel to them, in order to obtain information on the shallow aquifer lithology and geometry. Geophysical Cone Penetration Tests (GCPT) were performed to calibrate the ERT profiles, and they also contributed to the geological and hydrogeological interpretation of the sediment layers. In addition, groundwater sampling was carried out from GCPT probes. Groundwater sampling was planned to further facilitate the hydrogeological characterization of the site and to provide data for the validation of the 3D hydrogeological modelling. Groundwater level data loggers have additionally been installed, complementing the existing monitoring data in the pilot area, in order to get information on the groundwater levels at the pilot site.

Risk Assessment and Management

As at the Polish and Slovak sites, a qualitative risk analysis method was used, where the likelihood and severity of risks were examined, as well as their joint interpretation. This was done based on a risk factor matrix indicating the total magnitude of a risk (Swierc et al., 2005). Into this system, a list of risk events was incorporated based on the MAR-specific study of Rodríguez-Escales et al. (2018), which compiles risk events identified from a literature review considering 51 MAR facilities.

The category of very high risks was assigned mainly to non-technical (economic) risks in the MAR design phase: low water prices, high installation costs and lack of private/public funding. A very high technical risk was found for low water storage. High-risk events in the design phase could furthermore be the lack of coordination, the lack of commitment of stakeholders, fear of behavioural changes of the local society, construction difficulties, risks of low recharge rates, or the lack of geological and hydrogeological information. In the MAR operation phase, high risks may be associated to low water prices, the effect of swelling clays, decreased amounts of usable water due to local pollution and changing drought-rainfall periodicities. Furthermore, we might expect significant changes in current water demand and supply, effects on protected drinking water reserves and decreasing groundwater tables due to MAR operation. As a summary, the MAR design phase is most affected by non-technical risk events, while operation is rather depending on the successful preparation for technical issues. To decrease the probability of a risk event to realize, suited risk treatment methods have to be chosen. Concerning high and very high risks, an adequate support by regulators and the public should be reached, (e.g. via information sharing and education), thorough preliminary research should be done, and appropriate monitoring has to be carried out.

Results of Cost-Benefit Analysis

Results of the willingnesstopay (WTP) survey suggest neither individual farmers nor agricultural producers are willing to pay for MAR. Consequently, conclusions about the economic feasibility of the MAR scheme were made based on a comparison of only direct costs and benefits.

In order to address uncertainty in the cost-benefit analysis (CBA), scenarios with plausible variations of core parameters, such as cost values and levels of crop revenue per amount of applied irrigation water, were developed. Under all scenarios except the maximum one, the net present value is negative over the project’s lifespan, which means that it is not profitable to put the MAR scheme in place since expected benefits values are insufficient to cover incurred construction costs. Since cost estimates are rather rough and benefit value calculations rely on very limited data, it is vital to emphasize that obtained CBA results should be treated rather indicative and thus with caution.

Based on the assessment of local experts, socio-economic risks associated with the MAR scheme with a high probability of realization and/or major risk consequences are mainly economic, namely lack of funding, unplanned additional costs and low prices of irrigation water for agricultural producers.

VII. Croatia

MAR Method and Objective

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). The conceptual model is based on the revitalization of an old riverbed (highlighted in blue, Figure 4) that runs through the site and the construction of an accumulation lake (source water for MAR). With an 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 a high seasonal variability in precipitation. An additional benefit of a MAR scheme is the mitigation of seawater intrusion to the freshwater aquifer.

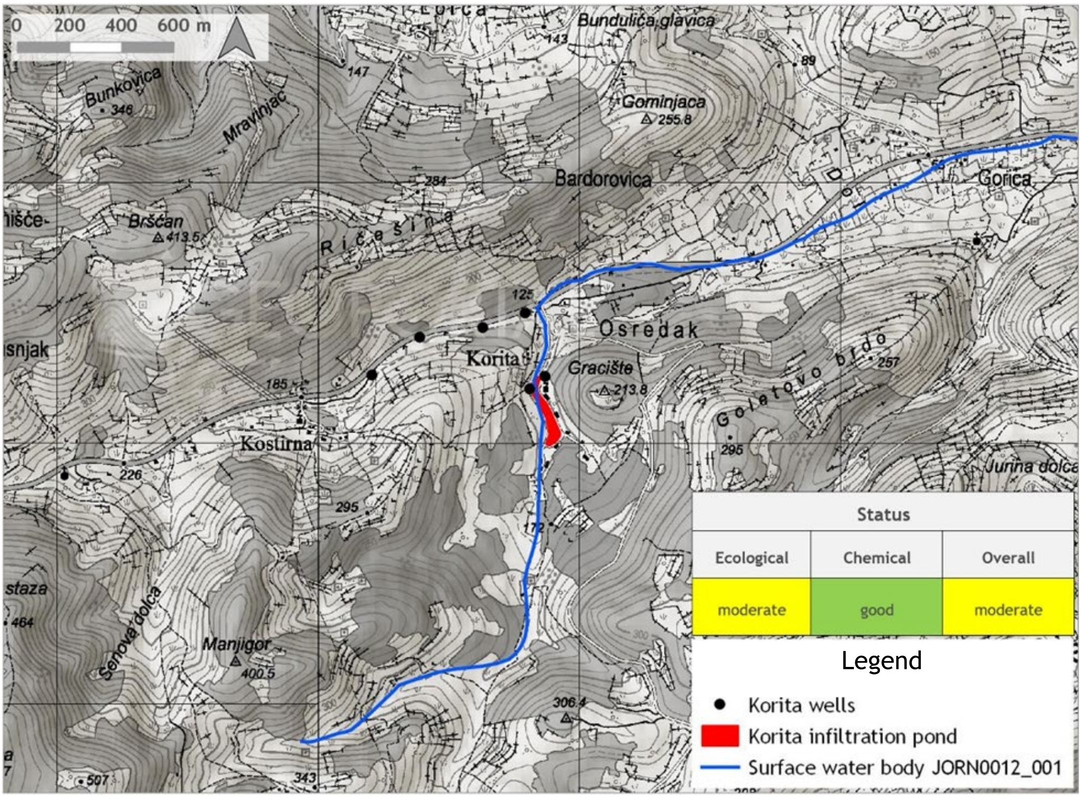

Figure 4: Pilot area – Korita water supply site on the island of Vis.

Water Demand and Supply Situation

Groundwater can be drawn from the high-quality karst aquifers, which is why the island of Vis is not connected to the mainland or other islands by water supply pipelines. The water supply system on the island of Vis consists of the Korita well field and the Pizdica spring. The Korita well field was built in the late 1960s in the central part of the island. It consists of five active wells, and it is protected from seawater intrusion. Pizdica is a small coastal spring and is therefore prone to increased salinity and chloride concentration.

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 summer due to intensive tourism.

From projections of future water demand on the island and the calculated amount of water provided by MAR, it appears that the entire additional water demand on the island can be met within the first six years of operation. Later, around half, and in the long term (with the increasing trend of water demand on the island), about one third of all additional needs are expected to be met.

Geological Settings

The island of Vis is part of the Dinaric karst region and consists mainly of karstified carbonate rocks. The main structural elements are oriented W-E and deviate slightly from the Dinaric strike (NW-SE). The predominant rocks on the surface are Cretaceous carbonates (limestone, dolomite), Quaternary sediments (*terra rossa* in karst poles; breccias; aeolian sands; colluvial deposits) and a mixture of volcanic-sedimentary-evaporitic rocks (andesite, gypsum, dolomite, siltite, tuffite) forming the Komiža diapir (Korbar et al., 2012). Three main faults occur on the island (from N to S: Oključna, Komiža-Vis and Podšpilje-Rukavac faults), with the main water intake, Korita, located within/along the damage zone of the Komiža-Vis fault.

Hydrogeological Settings

The River Basin Management Plan of Croatia (2016-2021) groups the groundwater bodies of the major Adriatic islands to GW body JOGN-13 with an estimated groundwater recharge rate of 122×10^6 m^3/year, while the utilization is 0.26% of recharge and a medium intrinsic vulnerability of the aquifers. Overall chemical status is good, but with low reliability; quantitative status is also good, but with high reliability. However, realistic conditions significantly vary between the islands. Favourable geological and hydrogeological conditions enabled the formation of high-quality karst aquifers on the island of Vis. The main source of pollution of the aquifers is seawater intrusion. The sole recharge of the island's aquifer is precipitation.

Conducted Field and Laboratory Work

Periodical monthly field and laboratory investigations began in September 2019 and lasted until September 2021. Field investigation included hydrogeochemical investigations such as in-situ monitoring of pH, temperature, O_2 content and electrical conductivity, determination of major ion and bicarbonate concentrations, and analysis of stable and radioactive isotopes at monthly intervals. In addition, hydrogeological investigations such as monitoring of the groundwater level, temperature and electrical conductivity were carried out at hourly intervals. Geophysical investigations included electrical resistivity tomography and the magnetotelluric method. In addition, the water balance was determined with the help of measurements of climatological parameters such as air temperature and precipitation, calculation of evapotranspiration and development of climate models up to the year 2100. The structural geological investigation included mapping of faults, fractures, and other structural elements.

Risk Assessment and Management

Risk assessment was conducted for the Korita water abstraction site on the island of Vis, where a MAR site is not yet implemented. The assessment was also based on the methodology of the qualitative risk analysis matrix (e.g., Swierc et al., 2005) with additionally developing a probabilistic risk assessment based on fault trees (Rodríguez-Escales et al., 2018).

Most significant risks (i.e., high, and very high rating) identified are mainly associated with non-technical risks: national territorial constraints, health legislation, insufficient technical knowledge and commitment of stakeholders, lack of coordination, and perception of effectiveness by the society. Economic risks arise from unclear funding sources, high installation and maintenance costs and low water prices. Water quality considerations due to sanitary/ biological restriction, turbidity/ particles, or water mixtures, as well as water scarcity due to droughts and rainfall event periodicity need to be taken into account. Looking at the hydraulic and hydrogeological settings, there is a high risk due to clogging, low water storage, high thickness and non-shallow aquifers, unsuitable hydrogeological settings. In addition, the lack of water pre-treatment infrastructures and structural damages due to natural hazards or aquifer dissolution pose high risks. During the operational phase of the MAR facility, there is a high risk of groundwater level changes.

Results of Cost-Benefit Analysis

The CBA (cost-benefit analysis) was concluded for both technologically possible drinking water MAR schemes on the pilot location on the island of Vis: the infiltration pond method and the aquifer storage and recovery method. The willingness-to-pay survey was performed online with an invitation through local Facebook groups and profiles. The survey results show that about one third of respondents would financially support such a plan and are willing to participate with their financial contribution in different amounts. The net present value (NPV) was found to be positive resulting from positive values from the third year of the potential MAR project. The feasibility of MAR schemes under different scenarios was assessed with a sensitivity analysis of NPV to changes in the input variables. The results show positive economic net present values in all cases.

VIII. References

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