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PILOT FEASIBILITY STUDY OF MAR SCHEMES WITH INTEGRATED ENVIRONMENTAL APPROACH IN POROUS GEOLOGICAL CONDITIONS IN HUNGARY

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Foreword

The activities and results presented in this report have been carried out within the framework of the DEEPWATER-CE project, 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 potential user conflicts. This document has been compiled by the Mining and Geological Survey of Hungary (MBFSZ) with the aid of Geogold Kárpátia Ltd. Further contributions as well as inputs and revisions have been provided by TUM (see contributors list).

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1. Summary

This report documents the preliminary feasibility study of a Hungarian MAR pilot site evaluated within the DEEPWATER-CE Interreg project. Partners from five countries participating in the project. In Hungary, Poland, Slovakia and Croatia the feasibility of implementing Managed Aquifer Recharge (MAR) schemes taking into account the socio-economic, geological, hydrogeological, technical, regulatory and human health aspects for a specific region were investigated. The Hungarian MAR scheme investigated is an underground dam, a novel approach in Europe.

The Hungarian pilot site is in the South-Eastern part of the Great Hungarian Plain, in the Maros alluvial fan between the two largest tributaries of the River Tisza (River Körös and River Maros). The Quaternary fluvial fan of the River Maros is one of the most characteristic distributive fluvial systems in the Hungarian Quaternary succession. Quaternary sediment deposition started in the Upper Miocene when a delta complex of about 2000 m thickness was formed in the South-eastern part of the Pannonian Lake, which has been seismically investigated by Mattick et al. (1994). Based on sequence stratigraphic reconstructions, the dominant direction of progradation was west and northwest.

Despite of its large catchment area, the water network of the Maros alluvial fan is sparse and except for the artificially maintained channels, most of the surface waters are temporary. According to historical meteorological data the region fits into the heavy drought - extremely heavy drought category (Pálfai 2002), with climate exposure models showing the region to be highly exposed to the negative effects of climate change.

Given the exceptionally suitable conditions for agricultural production (approximately 90% of the total area is agricultural land), agriculture is the main economic activity in the area. Since crop production relies heavily on the availability and quality of irrigation water, satisfying irrigation water demand is one of the core pressures of the area.

We have investigated the feasibility of an underground dam from different aspects, as a measure to relieve the pressure on scarce water reserves.

As part of this activity, we have checked the relevant regulatory framework. National legislation is in line with the European Union's legislative framework regarding the implementation of Managed Aquifer Recharge solutions. Core legal acts that are relevant to MAR schemes are the Water Framework Directive (WFD), the Groundwater Directive (GWD) and the Drinking Water Directive. While this legislation does not include specific MAR regulations, different provisions shape broad regulatory frameworks for MAR systems.

An in-depth fieldwork activity has been carried out, in order to ensure a sound, accurate, geological-geophysical hydrogeological characterization of the pilot site. Electrical resistivity (ERT) measurements were performed both perpendicular and parallel to the paleo river channels of the ancient River Maros river. In addition to providing information on the shallow aquifer lithology and depth, these measurements were used to help in defining the locations of the Geophysical Cone Penetration Tests (GCPT) and groundwater sampling points. The GCPT measurements were performed to calibrate the ERT profiles and contributed to the geological and hydrogeological interpretation of the sediment layers. Groundwater sampling also supported the hydrogeological characterization of the pilot site and provided 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. Detailed information about the fieldwork activities and its results are documented in the project's fieldwork report (D.T3.3.2, DEEPWATER-CE 2021c).

A detailed interpretation of these complex data provided sufficient geological-hydrogeological knowledge of the pilot site to support the hydrogeological modelling part of the preliminary feasibility study.

Based on well-logs and GCPT data, log correlations were prepared with a targeted depth of investigation of about 60 m, representing the Upper Pleistocene and the I and II regional cycles of the Middle Pleistocene. Based on the log correlation, the regionally correlated sands at the top of the fluvial cycles could have been identified in the pilot site, and isolated sand bodies could also have been detected in the lower silty part of the cycles. Two upper, regionally correlated sand horizons have been delineated as aquifers with different flow systems, separated by a silty-clayey quasi-impermeable layer. The upper is an unconfined aquifer, a local recharge area with local flow path, greatly exposed not just to the effects of climate change, but also to pollution, reflected in high nitrate and locally high sulphate, chloride, strontium and bromide concentrations. The lower aquifer is semi-confined, with no or rare signs of pollution. The aquifers used for drinking water supply can be found below this second aquifer. Preliminary results show they contain Pleistocene infiltration. The second regionally correlated sand horizon in the North-western part of the pilot site, might also contain Pleistocene infiltration, however, this preliminary data must be checked by new, repeated sampling and analysis. Pleistocene infiltration at a depth of about 30-33 meters below surface would suggest no infiltration from the surface and very strong aquitard characteristics for the overbank deposits, but even so, intermediate flow paths would be expected to have "flushed away" the "original" porewater. The sedimentary sequence of these aquifers is very likely to be hydraulically connected.

Determination of the amount of irrigation water and related demand was a difficult task. There is no standard method to estimate future irrigation water demands. Measured volumes at registered wells, licensed amounts and declared irrigation volumes or needs in statistical surveys show large discrepancies when we have compared statistics from different sources. To assess the water demand at the pilot site we collected and combined statistics from the Central Statistics Office of Hungary (KSH), the Water Resource Fee (WRF) registry of the Hungarian General Directorate of Water Management (OVF), the agricultural land use data and cultivation categories from 2010 (Corine Lan Cover), and the result of a survey on the water demands and irrigation development needs in Hungary provided by the Institute of Agricultural Economics (AKI) carried out in 2017 (AKI, 2018).

Since there is no permanent surface water in the pilot site the estimated irrigation water demand has to be supplied mostly from groundwater. Although licensed and abstracted water amounts for settlements in the pilot site are available, it is hard to give an exact value of the real need for irrigation water without the abstracted amount from unregistered wells, which is supposed to be significant. In the case of irrigation water only the authorized amounts and a rough estimate for illegal abstractions exist. According to the estimation of the Hungarian Chamber of Agriculture (2019) the number of wells for irrigation was between 10 000 and 100 000 all over in Hungary. Only 1% of farmers have a water right permit for irrigation, despite the fact that the costs of using water for irrigation are negligible for farmers. The weighted yearly average of irrigation water per hectare is estimated to be about 1229 m3.

In order to check the feasibility of a potential underground dam, a 3D finite element (FeFlow) groundwater model was built and tested. With the help of it, the two upper regionally correlated sand horizons were built into the model and the effects of different infiltration rates and dam properties have been simulated. Net infiltrations of 5 and 10 mm, their 10%, 25% and 50% infiltration and underground dam installed into the uppermost regionally correlated or to both sand horizons were simulated. Water levels behind the dam increased by 0.3-0.2 m, and respectively decreased by 0.6-0.3 m in front of the dam, depending on the different scenarios. The net groundwater volume (with 0.2 effective porosity) varies in the range of about 540,000 – 1,570,000 m3.

To assess the sensitivity for extreme climate events of the underground dam MAR system sets of selection criteria were collected to simulate extreme situation cases and a site-specific cause-effect chain was identified. This cause-effect chain evaluation process originates from climate extreme events which induce hazardous events. The hazardous events might cause specific negative effects on the MAR schemes described in the form of cautions to MAR systems as end results of the sensitivity analysis according to the methodology described in the "Transnational decision support toolbox for designating potential MAR locations in Central Europe" DEEPWATER-CE project report (D.T2.4.3; DEEPWATER-CE, 2020a). The cautions listed in the report provide suggestions which should be taken into account during MAR scheme implementation. The cautions for both climate extremes (wet and dry periods) relate to risks of structural damage to any MAR infrastructure, water quality and water quantity problems. This MAR specific checklist comprises the relevant criteria which should be taken into consideration in evaluating sequential and combined effects induced by extreme climatic events on underground dam MAR systems with an ultimate purpose to identify the potential risks posed to them.

To decrease the possibility and severity of any harm which might cause injury or damage to human health, or damage to property or the environment, a risk management plan has been developed to cover underground dam MAR systems.

Our risk analysis methodology is based on suggestions in the Australian guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009), where the likelihood and the severity of a risk is examined and their joint interpretation — based on a risk factor matrix — indicates the total magnitude of a risk. We have also incorporated a list of risk events of the MAR-specific study of Rodríguez-Escales et al. (2018) which compiles the risk events of literature reviews of 51 MAR facilities. Additionally we have slightly modified this list to better fit the underground dam MAR type, resulting in a risk identification list of 82 different possible risk events. Risk analysis was carried out in 2 temporal phases, separately for the design and construction, and for the time of operation phase of the MAR facility, respectively. From a list of possible risks, 46 events were assessed as of low risk, 21 as of moderate risk, 14 as of high risk and 4 as very high risk

A very high risk category was assigned mainly to non-technical (economic) risks in the design phase, like low price of water, high installation costs and lack of private/public funding. One technical event of very high risk was determined to be the risk of low water storage. High-risk events in the design phase could be the lack of coordination, the lack of commitment of stakeholders, fear of behavioural changes of the local society, construction difficulties, risk of low recharge rates, or an improper hydrogeological setting. In the operational phase high-risk events include a low price of water, the effect of swelling clays, decreased amounts of usable water due to high levels of metal content or nutrients, and drought-rainfall periodicity change. Expected results include significant changes in current water demand and supply, any effect on protected drinking water bases, and the risk of negative changes in the position of the groundwater table due to the MAR operation. In summary, the design phase of the MAR system is mostly affected by non-technical risk events, while operation is depends more on the successful preparation for technical issues.

To limit the possibility of a risk event, some risk treatment methods have been suggested for all 111 risks.

In addition to hydrogeological considerations and assessment of institutional feasibility, MAR projects require an economic appraisal, which in most cases aims to check whether the net benefit of the project's implementation is positive. To meet this objective, economic, efficiency analysis is applied, and more specifically in this report cost-benefit analysis (CBA).

Among the many potential benefits of MAR schemes, the major ones include increased sustainable water supply and ensured water quality. Despite all potential advantages, it is still important to perform an economic evaluation to ascertain that the benefits of the underground dam MAR scheme can justify anticipated costs. In this report, we outline the methodology and results of the CBA study for this pilot site. This study investigated whether the introduction of an underground dam MAR solution in the pilot site is economically feasible and whether the total economic value of the MAR scheme's extension (which includes both use and non-use benefits) meets or exceeds the costs of putting this system in place and maintaining it.

Accounting for uncertainty is an integral part of CBA studies. In order to incorporate, we have tested scenarios with plausible variations of the main CBA parameters and checked how sensitive the net present value (NPV) of the MAR scheme is to them. An important section of this report is the assessment of two dimensions of socio-economic risks associated with the MAR scheme: their probability and magnitude of consequences. Based on the conducted analysis, we provided policy recommendations for the implementation of the MAR scheme in this pilot site from a socio-economic perspective.

It is essential to mention that there are currently no operating underground dams in Hungary or in Central Europe, meaning estimates of costs are quite rough with a wide range of possible values. Also, survey results suggest that a noticeable share of individual farmers currently don't normally irrigate crops, thereby direct benefits were estimated under a few assumptions using very limited data. Thus, CBA results should be treated as more indicative and with an amount of cautiousness.

The results of the groundwater modelling indicate that changes in the morphology of the buried riverbed in the study area have a major impact on the flow directions. The modelling was used to investigate the boundaries of the buried riverbed, whether it is directly connected to the infiltration area or not. The model response was significantly different in both cases, so this should not be neglected in further works. The measurements carried out in the framework of the project and the available data did not provide sufficient information to answer this question, so this can only be verified by further field studies. In the 3D hydrogeological model runs, we investigated the movement of particles starting from the area before the dam and travelling with the groundwater flow. The model runs resulted in particle tracking times of approximately 500-900 days in the first aquifer. These results correlate well with the results from the groundwater residence time studies, which show that the first aquifer has water ages generally less than 10 years, so that the recharge of the uppermost regionally correlated aquifer is highly dependent on the recharge from precipitation. In all the model variants tested, the increase in water volume due to the groundwater dam exceeded the required irrigation water use.

2. 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. MAR techniques offer promising solutions for water management, also with regard to tackling future climate change impacts (Casanova et al., 2016; Dillon, 2005; Dillon et al., 2019; 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 these socio-economic, geological, hydrogeological, technical, regulatory and human health aspects. In the frame of the DEEPWATER project during the previous work transnational decision support toolbox have already been developed, which primarily addresses site selection (DEEPWATER-CE, 2020a) and the guidance and methodology of the feasibility study of MAR schemes was described (D.T3.2.5, DEEPWATER-CE, 2020b).

According to these methodologies suitability maps were compiled for Hungary to designate potentially suitable MAR locations (D.T3.1.2., DEEPWATER-CE, 2021a), a pilot area was characterized at the Maros alluvial fan and based desk analysis and preliminary field investigations pilot site was selected in the vicinity of Csanádapáca and Medgyesbodzás for underground dam MAR scheme (D.T3.3.1., DEEPWATER-CE, 2021b). Detailed field investigation was carried out in several measurement campaign (D.T3.3.2., DEEPWATER-CE. 2021c). The aim of the present report is to examine the preliminary feasibility of a theoretical underground dam MAR solution in the identified pilot site and to test how this MAR scheme can be adopted in alluvial fun environment. It is important to mention, that the result of this feasibility assessment will not followed by direct implementation of the MAR establishment, but describe the possibility and difficulties of such.

The main components of this report are (a) Consideration of the regulatory framework; (b) Desktop study; (c) Pilot site characterization, including the determination of water demand and supply, (d) Risk management, (e) Cost-Benefit Analysis, and (f) Comparison of alternative solutions.

3. Regulatory framework

In Hungary the Minister of Interior is responsible for legal and administrative organisation of water policy and water governance including the implementation of Water Framework Directive (WFD). The 12 Regional Water Directorates implement the water policy which is coordinated, supervised and controlled by the General Directorate of Water Management, as a central governing body operating under the direction and supervision of the Ministry of Interior.

The national legislation of Hungary is in line with European Union legislative framework for implementation of Managed Aquifer Recharge solutions. Core legal acts that are relevant to MAR schemes are the Water Framework Directive (WFD), Groundwater Directive (GWD) and Drinking Water Directive. These legislations do not include specific MAR regulations, but their provisions shape broad regulatory frameworks for MAR systems.

The WFD (2000/60/CE), particularly Article 11(3) (f)) consider MAR schemes as a supplementary measure which needs “controls, including a requirement for prior authorization of artificial recharge or augmentation of groundwater bodies. The water used may be derived from any surface water or groundwater, provided that the use of the source does not compromise the achievement of the environmental objectives established for the source or the recharged or augmented body of groundwater. These controls shall be periodically reviewed and, where necessary, updated”. Thus, WFD is aimed to ensure that basic measures are in force to safeguard application of MAR system against causing any harm to the quantitative and qualitative status of the groundwater bodies.

Regarding Groundwater Directive (2006/118/EC), its core objective is the protection of the groundwater against pollution through the requirement to identify the chemical status of groundwater. To achieve this aim GWD establishes limit values for a series of chemical parameters. At the same time GWD, under Article 6(3)(d), states that particular exemptions, including artificial recharge, from the established measures are possible since it might be technically infeasible to eliminate all inputs of hazardous substances, especially those that are environmentally insignificant and do not pose a danger to groundwater.

In line with the European regulation Act LVII of 1995 on water management supports the recharge of underground aquifers by artificial recharge and reinjection. Although there is no specific regulation for artificial recharge and MAR systems, the “Government Regulation 123/1997. (VII.18.) on the protection of vulnerable water supplies” concerns their protection measures and the criteria of protection zones for groundwater abstraction sites, especially for drinking water reserves. The “Government Decree 219/2004. (VII.21.) on the protection of groundwater” regulates the artificial recharge and reinjection in order to preserve the quality and quantity of the underground water resources. This regulation also sets out conditions and makes it subject to official water protection authorization.

Groundwater utilization for irrigation purposes is limited by the “Governmental Decree No. 147 of 2010 (IV.29.) on general rules regarding activities and facilities serving for the utilization, protection and prevention of damages of waters”. This also contains that groundwater can be applied for irrigation purposes only the case of lacking of surface water supply possibilities, where requisition of shallow groundwater resources is desirable. Considering the protection of the neighbouring drinking water reserves is mandatory.

Despite of the strict regulation illegal wells are used very often for irrigation purposes. Approximately only 1% of farmers have a water right permit for irrigation.

4. Characterization of pilot sites

4.1. Description of the pilot site

The Hungarian pilot area is located in the South-Eastern part of the Great Hungarian Plain, on the Maros alluvial fan between two largest tributaries of River Tisza (Körös and the Maros), where the Ancient-Maros River entered from the mountain area into the lowland (Figure 1). The special geographical settings (climate exposure, low relief, etc.) determine the land use, water demand and possibilities in water supply (deliverable D.T3.3.1, DEEPWATER-CE 2021b).

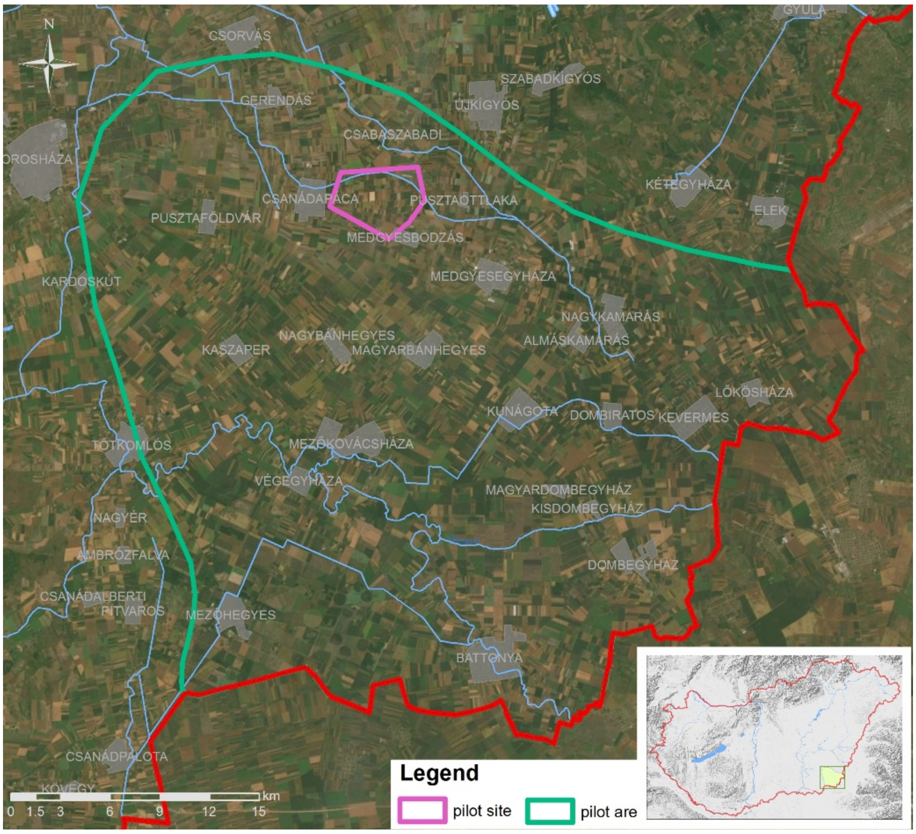


Figure 1. Location of the pilot area and the pilot site

The region of the Maros alluvial fan forms a flat area emerging a little bit from its surroundings. The region is situated between 96.6 m and 106.8 m above sea level, slightly inclining to the direction NW. The average relative relief is very small, only 1 m/km^2, reaching values above 2 m/km^2 only in the southern parts.

Despite of its relatively large catchment area, the water network of the Maros alluvial fan is sparse and characterized by low surface runoff. Most of the watercourses are temporary, except those channels which are artificially maintained. All the watercourses belong to the drainage network of the Tisza River.

The climate is warm-dry, the number of hours of sunshine per year is extremely high, varies between 2000-2020 hours, about 810 hours in summer and is about 190 hours in winter. The annual rainfall varies between 550-620 mm, the average during vegetation period is approx. 340 mm. According to historical meteorological data the region can be classified to heavy draught and extremely heavy draught category

(Pálfai 2002).

Given exceptionally suitable conditions for agricultural production (approximately 90% of the total area is agricultural land), agriculture is the main economic activity in the area. At the same time, the area where the pilot site is located is one of the warmest regions in Hungary during the summer period and temperatures are expected to increase further due to climate change. Since crop production relies heavily on the availability and quality of irrigation water, especially under increasing temperature levels, satisfying irrigation water demand is one of the core pressures for the area. After the wet periods, water shortages appear in the summer, which affect most of the region, causing serious damages since the agricultural activity. After the wet periods, water shortages appear in the summer, which affect most of the region, causing serious damages since the agricultural activity (D.T3.3.1).

With a few exceptions the main source of irrigation water for farmers in the area is supplemented by groundwater. According to experiences illegal wells are used very often for irrigation purposes. These wells are usually drilled without considering any regulation and technological guidelines. Therefore they can endanger the drinking water aquifers to pollute or can abstract water from the same aquifers. Considering this situation applying MAR systems for irrigation can have significant environmental benefits even in the case they are more expensive.

The introduction of the underground dam MAR scheme is a potential solution that allows to reduce groundwater flow and, as a result, to increase the amount of groundwater stored behind the dam.

The main objective of the MAR scheme is to secure the supply of irrigation water during periods of water scarcity, while provide increasing security for the adjacent drinking water reserves.

4.2. Geological - hydrogeological - hydrogeochemical characteristics of the pilot site

4.2.1. Geology

4.2.1.1. Physiographic setting of the pilot site

The Quaternary fluvial fan of the Maros River is one of the most representative distributive fluvial systems in the Hungarian Quaternary succession. The related catchment area of 30 700 km^2 is extended to the southern part of Transylvania, including parts of both the Southern and Eastern Carpathians, which were significantly affected by Quaternary mountain glaciations and permafrost developments. The deposition was started in the Upper Miocene when a delta complex of 2000 m thick was formed in the South Eastern part of the Pannonian Lake, which was investigated seismically by Mattick et al. (1994). Based on sequence stratigraphic reconstructions, the dominant direction of progradation was west and northwest.

4.2.1.2. Quaternary development of the fluvial fan

The Quaternary, terrestrial part of the distributive fluvial deposit reaching 450–500 m in thickness, was also a target of geophysical and geological investigations due to its hydrogeological importance. As a result of this regional mapping, three fully cored and paleontologically investigated parameter boreholes of 500 m depth (Franyó 1992) (Figure 2). Using the data of these parameter boreholes, dip and strike oriented log correlations of the Quaternary succession were performed (Figure 3 and 4). To ensure Quaternary geochronological framework, in Figure 3 the succession of the fluvial fan is correlated to the parameter boreholes of the Körös Basin. In this correlation, the magnetically confirmed and chronologically interpreted “early postglacial magnetic susceptibility episodes” are considered (Püspöki et al. 2021).

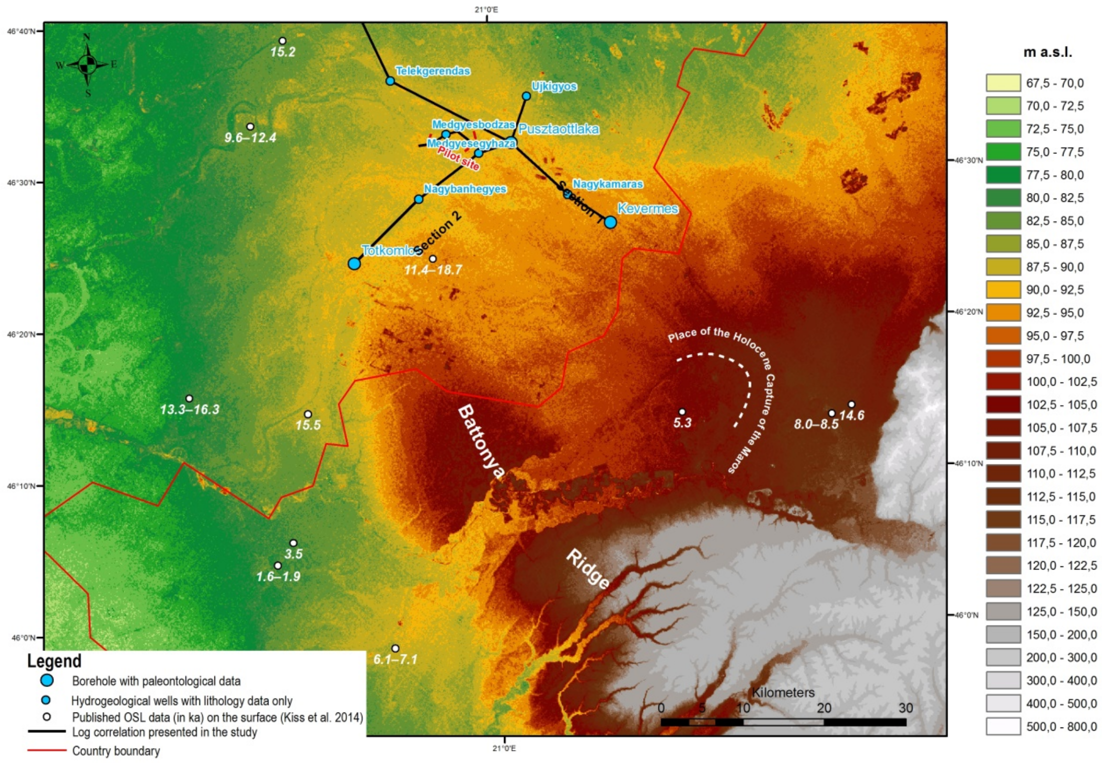


Figure 2. Topography (elevations based on Shuttle Radar Topography Mission (SRTM) data, published Optically Stimulated Luminescence (OSL) data (Kiss et al. 2014), well and boreholes of the cross-sections

The most important sedimentological feature of the presented log correlations is the existence of stratigraphically correlated sand bodies on the top and sometimes within the regional cycles. This observation is in line with the results of modern researches on the geology of alluvial fans (Weissmann et al. 2013). According to the interpretations, these “stratigraphically correlated” sand bodies in Figure 3 and 4 can be considered as stratigraphic units representing the “glacial recession” periods of the Carpathians in the Quaternary succession of the Maros fluvial fan. These “glacial recession” periods can be correlated to the also “early postglacial magnetic susceptibility episodes” reconstructed in the Körös Basin (Püspöki et al 2021), thus the stratigrapchic correlation with the regional magnetic susceptibility cycles has also climatostratigraphic reasons.

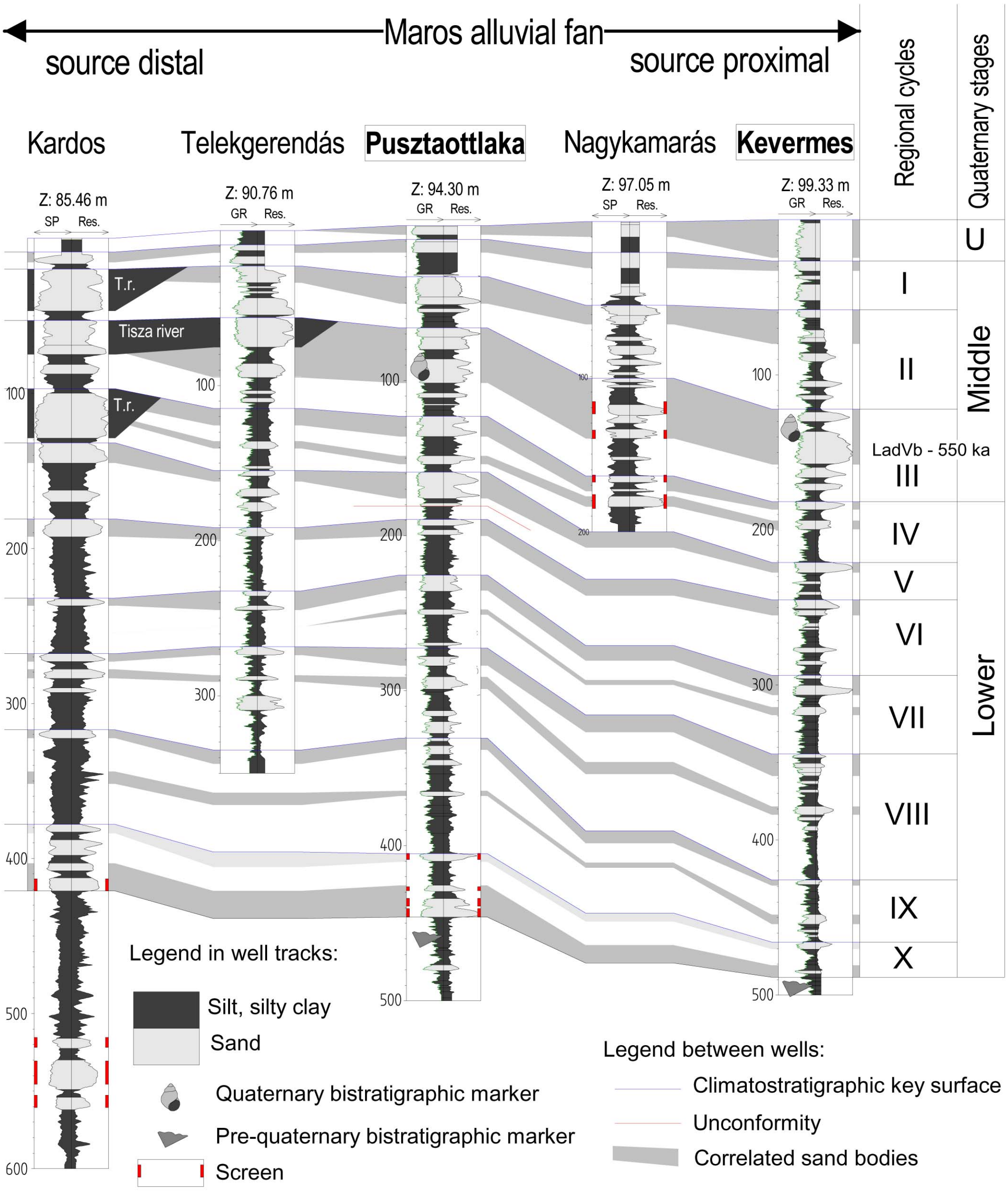


Figure 3. Dip oriented log correlation of the Maros fluvial fan (Section 1)

(for the position of the correlated boreholes see Figure 3)

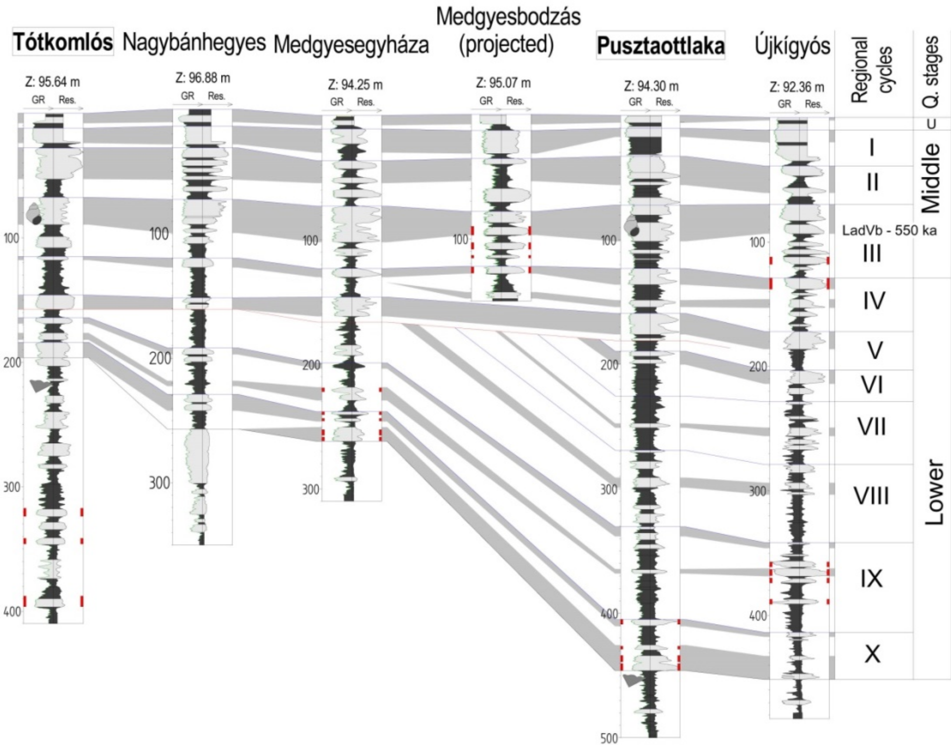


Figure 4. Strike oriented log correlation of the Maros fluvial fan (Section 2)

(for the position of the correlated boreholes see Figure 3)

The Late Pleistocene stage of the fluvial development can be investigated based on the topography and geomorphology of the area. The high resolution Shuttle Radar Topography Mission (SRTM; https://srtm.csi.cgiar.org/) model on terrain elevations (Figure 2) indicates that recently the source-proximal, most elevated part of the alluvial fan is situated in Romania right at the margin of the Great Hungarian Plain (GHP), while the Hungarian part represents the distal lobes of fluvial accumulation differentiated from the mostly alluvial parts of the distal basin centre.

Based on topographic models, well documented braided and meandering channel plan-forms can be observed and were reported (Sümeghy et al. 2013) on the top of the distal fan. The shapes and positions of the paleo-channels clearly follow the topographic elevation of the Battonya Ridge (Figure 2), which reflects that the relative elevation of the Battonya Ridge in the Late Pleistocene could affect the shape of channels and the spatial trend of channel and lobe switching events.

A drastic change of fan development occurred at 5.3–7.1 ka when one of the small rivers south-westward of the Battonya Ridge formed and incised valley (DEEPWATER-CE. 2021b) through the ridge and captured the Maros, resulting the abandonment of the fluvial belts in the main lobes of the distal fan. This event is also documented by published OSL data by Kiss et al. (2014) (Figure 2).

4.2.1.3. Setting, stratigraphy and sedimentology of the pilot site

The pilot site of the recent project is situated on one of the distal lobes of the fan abandoned due to the Holocene capture of the Maros (Figure 2). The focused site (Figure 5) is a fluvial belt detected on SRTM topography and presenting the already mentioned bending shape caused by the Late Pleistocene relative elevation of the Battonya Ridge.

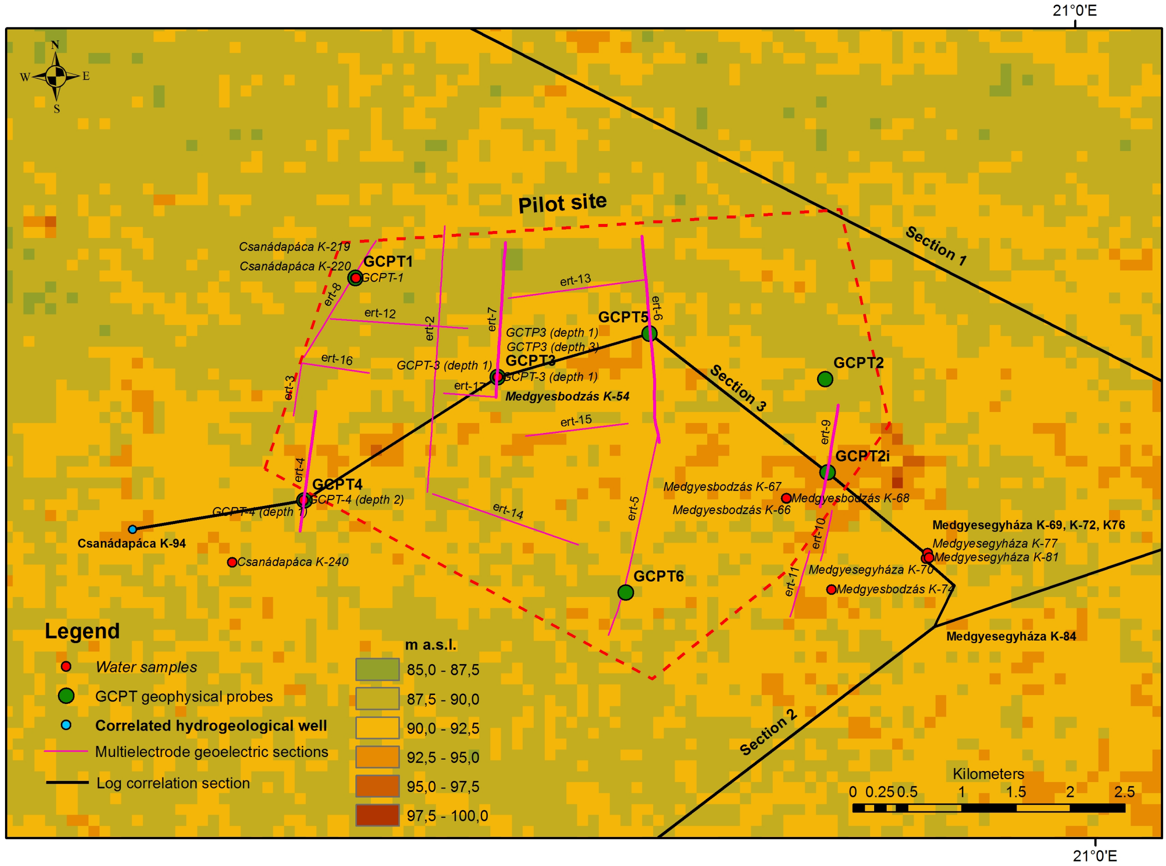


Figure 5. SRTM topography and research objects of the Pilot site

Based on well-logs andGeophysical Cone Penetration Test (GCPT) data, a log correlation section is presented along the axe of this bending fluvial belt (Figure 6). The targeted depth of investigation is 60 m, representing the Upper Pleistocene and the I and II regional cycles of the Middle Pleistocene. Based on the log correlation, the regionally correlated sands at the top of the fluvial cycles can be observed in the pilot site, and isolated sand bodies can also be detected in the lower silty part of the cycles e.g. in the Upper Pleistocene cycle at the places of GCPT-5 and GCPT-2i.

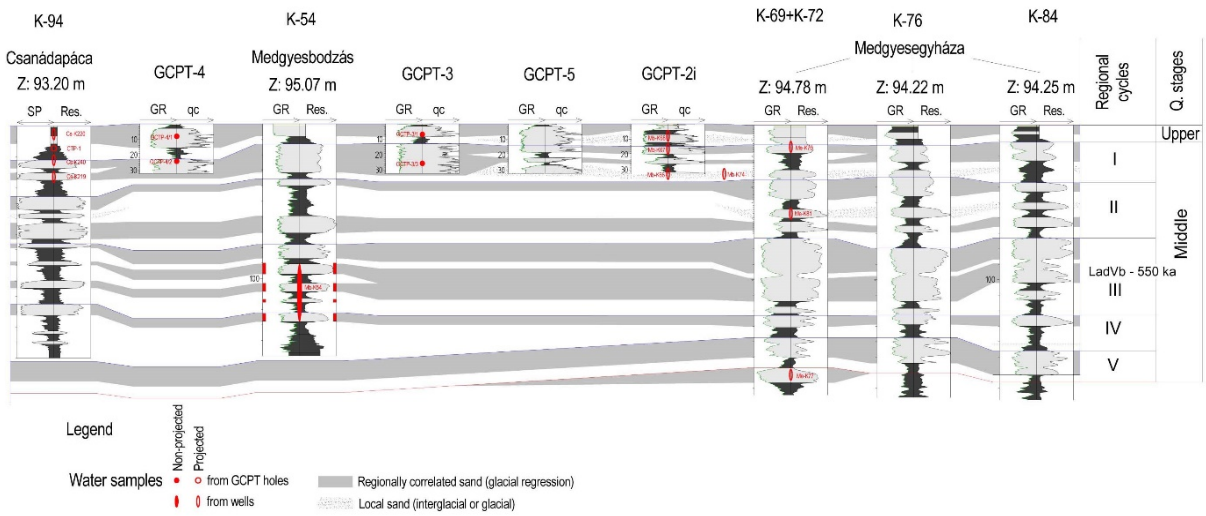


Figure 6. Log correlation of the Pilot site and the stratigraphic position of the water samples (for the position of the correlated boreholes and GCPT probes

Experimental geoelectric sections were measured perpendicular to the axis of the bending river belt and thus perpendicular to the log correlation section, touching the stratigraphically interpreted GCPT points (Figure 7). The occurrence of the Upper Pleistocene fluvial sand of high resistivity and its sharp contact towards the underlying silty materials of low resistivity is marked in the upper, high-resolution parts of the geoelectric sections. The lateral termination of this high resistivity zone to North and South in sections and its continuous occurrence on sections parallel to the log correlation section can be identified. These sections prove the existence of the Upper Pleistocene river belt suggested by the SRTM topography.

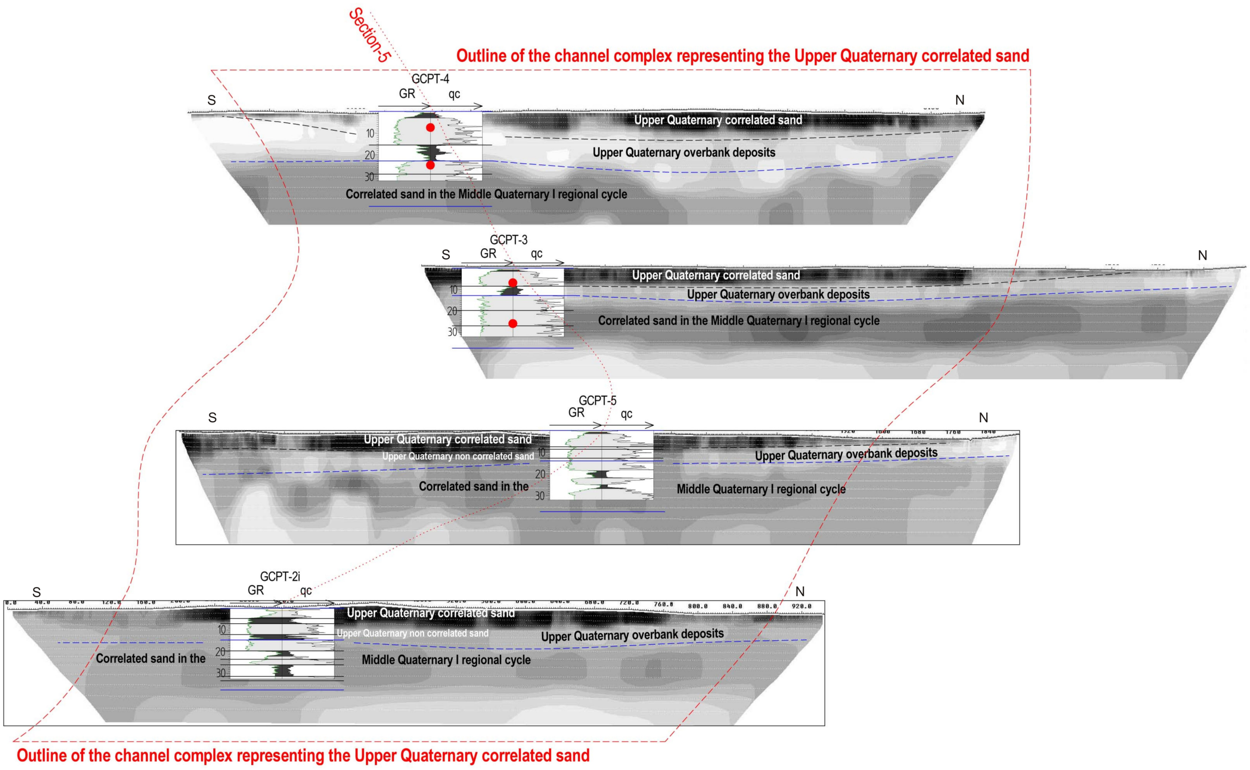


Figure 7. Stratigraphic and facies interpretation of the geoelectric sections in combination with GCPT logs

Below the silty material of the Upper Pleistocene fluvial cycle, another layer of high resistivity can be detected on the lower, moderate-resolution parts of the geoelectric sections. This can be interpreted responsibly as the occurrence of the regionally correlated sand at the top of the regional cycle I in the Middle Pleistocene. In the vicinities of CPT-5 and CPT-2i the geoelectric sections indicate that the Upper Pleistocene and Middle Pleistocene correlated sandy units are joined by sandy material of high resistivity, which can represent an occasional sand body in the lower part of the Upper Pleistocene cycle, and may cause hydrodynamic communication between the mostly separated sand layers.

4.2.2. Hydrogeology and aquifer characteristics

Aquifer characteristics are determined by the depositional environment of the Quaternary sediment series. The fluvial sediments deposited in channels, point bars, islands, and incised valleys of the fan act as aquifers, while fine grain silts and clays derive from floodplain environments representing the aquitard layers. Although the entire alluvial complex forms a hydraulically connected aquifer system, in the conceptual hydrogeological model of the detailed interval (the upper 60 m) of the pilot site, four hydro-stratigraphical units can be distinguished according to the analysis of the fluvial cycles.

Based on the stratigraphic and facies interpretation of the geoelectric sections in combination with GCPT logs (Appendix A and B of D.T3.3.2, DEEPWATER-CE 2021c) the fluvial belt detected on SRTM topography was extended to the depth and it was identified as the uppermost aquifer of the pilot site (it is identified as the uppermost part of the Upper Quaternary fluvial cycle). The shape of this sand body in the deeper intervals roughly follows the surface manifestation of the fluvial belt, elongating to the direction E-W and laterally thinning. The thickness of this aquifer layer varies but it is mostly in the range of 5-15 m. Based on the results of the GCPT probes the layer consists of mainly sand of different grain sizes (from fine grained silty sand to coarse sand) which result in unconfined conditions.

The underlying layer (it is identified as the lower part of the Upper Quaternary fluvial cycle) with fine grained sediments is considered the first impermeable layer in the conceptual hydrogeological model of the pilot site. According to the ERT measurements it can be identified throughout the pilot site and consists of clay, silty clay, silt in different proportion confirmed by the GCPT probes. Usually it has a significant thickness of 15-25 m. Where the first aquifer is missing or wedges out the first aquitard layer is outcropping. Locally isolated sand bodies can also be detected within the layer (e.g. GCPT-5 and GCPT-2i). Where the thickness of the first aquitard is higher (exceed 20 m), it can hydraulically separate the neighbouring aquifers, but due to the heterogeneity semi-permeable behaviour can be dominant and locally hydraulic connection cannot be excluded between the uppermost and the lower aquifers (ERT-2, ERT-3, ERT-9, ERT-15, ERT-16).

The lower aquifer represents the upper part of the I. Middle Quaternary cycle. The thickness of the lower aquifer exceeds the first aquifer with the values between 10-20 m. This confined layer can be identified all over the pilot site and can be characterized with varying proportion of silt content.

The second aquitard separates the near surface aquifers from deeper situated drinking water aquifer layers. It also has significant heterogeneity as the result of combined effects of the location, variable width and heterogeneity of the fine-grained layers. A direct connection cannot be identified between the near surface layers and the drinking water resources of the pilot sites, although indirect hydraulic connection cannot be excluded.

The groundwater table is located in the upper aquifer at a depth of 1.5-4.5 m below surface. The direction of regional groundwater flow is SSE—NNW. A map of the regional groundwater table is provided in Figure 8. This map was constructed based on average values of monitoring well data of the wider area, but it is consistent with the actual groundwater level measurements carried out in the GCPT probes during the field work within this project. The groundwater table is unconfined in the area of the ancient channel belt characterized by sandy sediments, and it is confined where the first aquitard layer is outcropping.

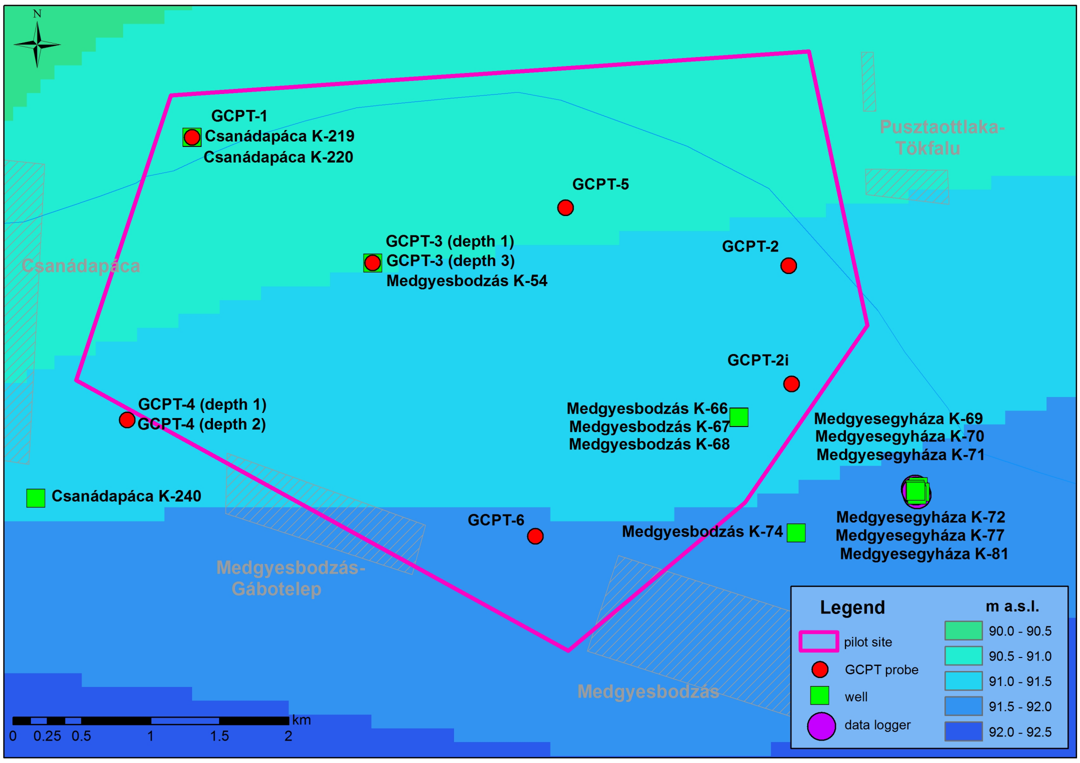


Figure 8. Regional groundwater table (average value of the period 1961-2009)

The channel belt zone slightly emerges from its surroundings as it can be observed on the high resolution topographic map (Figure 5), therefore it can be identified as local recharge area. Groundwater level measurements performed at different depths of the GCPT probes and nests of wells at the same locations indicate a descending groundwater level showing local recharge. This is validated by the detected time series in the monitoring of different depth intervals, see Figure 9.

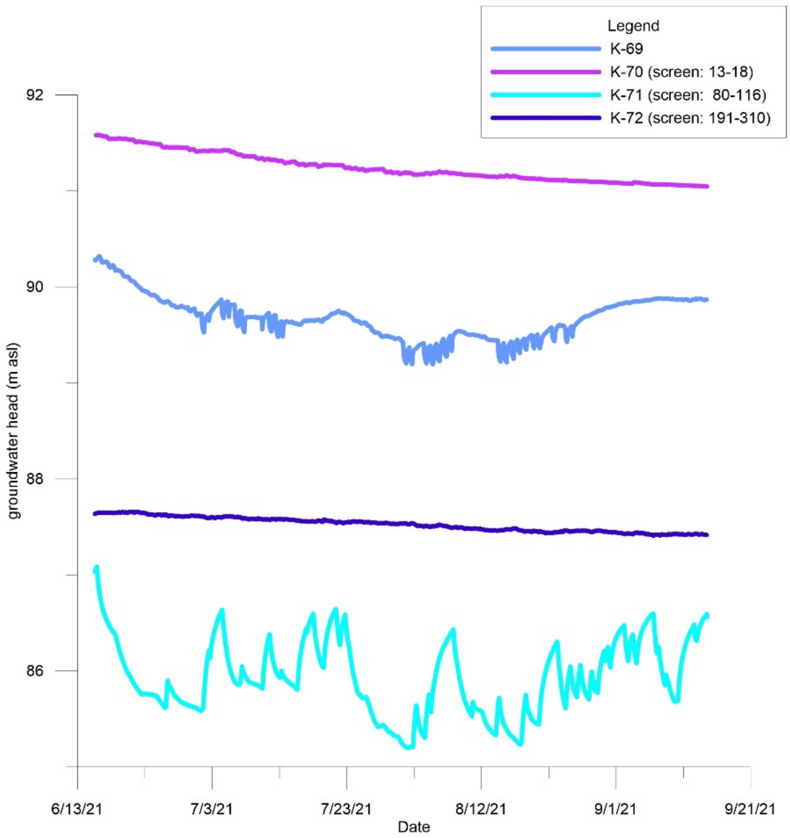


Figure 9. Registered groundwater level changes in the monitoring wells

The deeper aquifers are situated in the transitional zone of the intermediate and regional groundwater flow system, but hydraulic heads and local flow directions are significantly influence by the abstraction of the nearby drinking water supply wells. The regional groundwater flow in the deeper zone is dominated by the horizontal flow component. Flow paths are approximately parallel to the main flow direction of shallow groundwater , starting from the regional recharge area (situated in the hilly and mountainous region outside the national border in Romania) and continuing to the discharge area of the regional flow system along the Körös and Tisza Rivers (DEEPWATER-CE. 2021b).

4.2.3. Hydrogeochemical characteristics of the pilot site

Groundwater sampling was performed in order to refine the hydrogeological conceptual model and to provide independent parameters for the validation of a 3D hydrogeological numerical model of the pilot site. Analysis of groundwater samples collected according to the National Accreditation methodology provides information about groundwater flow systems, while improving model reliability. Samples were collected for chemical, water isotope and noble gas composition analysis. Chemical composition provides information on general groundwater characteristics, potential pollution, and ensures information regarding the operation of a future MAR system. Chemical composition can be also important regarding irrigation requirements. Water isotope and noble gas analysis provide information on apparent groundwater recharge time, helping us to understand the origin of groundwater, local infiltration processes and groundwater storage and recharge possibilities of the investigated site. In total 23 groundwater samples have been collected from 14 sites, 11 wells and 3 GCPTs. Location of sampling sites are shown in Figure 5. Precipitation samples were collected on a monthly basis in Mezőhegyes between October 2020 and May 2021.A detailed methodology description and sampling location information is provided in the fieldwork report of the DEEPWATER-CE project (D.T3.3.2, DEEPWATER-CE 2021c).

The collected groundwater samples were grouped into five categories or hydrogeological facies (HF1 to HF5) based on the stratigraphical correlation of Quaternary sediments, presented in chapter 4.2.2. The five categories of the groundwater samples (re-evaluated since the D.T3.3.2, DEEPWATER-CE 2021c fieldwork report) are shown in Table 1.

Samples of the regionally correlated uppermost (or first) sand horizons are represented by HF1. Its sediments from the climatic cycle 0 are upper Pleistocene (100-150 ka). This sand horizon is generally less than 10 meters below surface, with slightly deeper depth in the East of the pilot site. In the North-western part of the pilot site it is pinched out and overbank sediments can be found on the surface. HF2 is a silty-clayey layer between the first and second sand horizon, which has very low permeability. HF2 acts as a locally quasi-impermeable layer under natural conditions (under no groundwater abstraction). Its sediments from the climatic cycle 0 are middle Pleistocene (120-200 ka). Not being an aquifer, only one groundwater sample could be collected from it, from a GCPT probe, for major and trace elements. Samples from about 13-33 m deep below surface were grouped in HF3, which is the second regionally correlated sand horizon. These sediments belong to the climatic cycle I, middle Pleistocene (200-250 ka). Locally, sand layers can be detected between the regionally correlated sand horizons in the silty-clayey sediments, which can have a substantial impact on the hydraulic connectivity between the regional sand horizons. HF1 represents the upper, while HF3 represents the lower aquifer of the numerical 3D hydrogeological model (see chapter 4.4).

HF4 is the third sand horizon, also from the middle Pleistocene but from 300-350 ka. This sand horizon detected in one of the sampled wells, could not be regionally correlated. Based on the available data, it is interpreted as a sand horizon with a local extent. HF5 represents the deepest investigated regionally correlated sand horizons and is a lower Pleistocene aquifer.

Table 1. Aquifers - Hydrogeological facies (HF) Location of groundwater sampling sites and on-site field measurements including their depth and groundwater level data are presented in the fieldwork report (D.T3.3.2, DEEPWATER-CE 2021c, Table 1, Appendix C)

Groundwater Sample ID	Sample site	HF categories	Stratigrapy	Geochronologic cycles
DW-0101	GCPT-3 (depth 1)	1	1st regionally correlated sand layer	climatic cycle 0; upper Pleistocene
DW-0102	GCPT-3 (depth 1)	1	1st regionally correlated sand layer	climatic cycle 0; upper Pleistocene
DW-0201	Csanádapáca K-220	1	1st regionally correlated sand layer	climatic cycle 0; upper Pleistocene
DW-0202	Csanádapáca K-220	1	1st regionally correlated sand layer	climatic cycle 0; upper Pleistocene
DW-0301	Csanádapáca K-219	3	2nd regionally correlated sand layer	climatic cycle I; middle Pleistocene
DW-0302	Csanádapáca K-219	3	2nd regionally correlated sand layer	climatic cycle I; middle Pleistocene
DW-0401	GCPT-1	2	1st silty-clayey layer. overbank deposit	climatic cycle 0; middle Pleistocene
DW-0501	GCPT-3 (depth 3)	3	2nd regionally correlated sand layer	climatic cycle I; middle Pleistocene
DW-0502	GCPT-3 (depth 3)	3	2nd regionally correlated sand layer	climatic cycle I; middle Pleistocene
DW-0601	Medgyesbodzás K-54	5	deep regionally correlated sand layer	climatic cycle III-IV; lower Pleistocene
DW-0602	Medgyesbodzás K-54	5	deep regionally correlated sand layer	climatic cycle III-IV; lower Pleistocene
DW-0701	Medgyesbodzás K-68	1	1st local sand layer	climatic cycle 0; upper Pleistocene

Groundwater Sample ID	Sample site	HF categories	Stratigrapy	Geochronologic cycles
DW-0801	Medgyesbodzás K-66	3	2nd (local) sand layer; regionally not correlated	climatic cycle I; middle Pleistocene
DW-0802	Medgyesbodzás K-66	3	2nd (local) sand layer; regionally not correlated	climatic cycle I; middle Pleistocene
DW-0901	Medgyesbodzás K-67	3	2ndregionally correlated sand layer	climatic cycle I; middle Pleistocene
DW-1001	Medgyesegyháza K-77	5	deep regionally correlated sand layer	climatic cycle VI; lower Pleistocene
DW-1101	Medgyesbodzás K-74	3	2nd (local) sand layer; regionally not correlated	climatic cycle I; middle Pleistocene
DW-1102	Medgyesbodzás K-74	3	2nd (local) sand layer; regionally not correlated	climatic cycle I; middle Pleistocene
DW-1201	Medgyesegyháza K-81	4	3rd (local) sand layer, regionally not correlated	climatic cycle II; middle Pleistocene
DW-1301	Medgyesegyháza K-70	3	2ndregionally correlated sand layer	climatic cycle I; middle Pleistocene
DW-1401	Csanádapáca K-240	3	2nd regionally correlated sand layer	climatic cycle I; middle Pleistocene
DW-1501	GCPT-4 (depth 2)	3	2nd regionally correlated sand layer	climatic cycle I; middle Pleistocene
DW-1601	GCPT-4 (depth 1)	1	1st regionally correlated sand layer	climatic cycle 0; upper Pleistocene

Figure 10 shows the hydrochemical facies of the groundwater in the shallow uppermost sand horizon (HF1), which varies across a wide range, both regarding its cation and anion composition. The dominant cations are Ca^{2+} and Mg^{2+}, but higher Na^{+} and K^{+} concentrations can be observed in the Csanádapáca region. Beside the HCO_3^- and CO_3^{2-} dominance, high SO_4^{2-} can also be detected. Different local infiltration conditions can exist, which are reflected by a wide spectrum in the water types in the upper two sand horizons. DW-1601 (GCPT-4 depth 1) and DW-1401 (Csanádapáca, K-240) show the effects of local pollution, with high sulphate and chloride content. As the latter is from the second regionally correlated sand horizon (HF3), this shows either a connection between the two sand horizons or could be due to incorrect well construction. A repeated sampling (without pumping) suggests the pollution is present in the second sand layer and it is not the result of drawdown during sampling. Both samples show also outlying high Sr^{2+} and Br^- concentrations. Cation exchange takes place along flow paths, therefore $NaCaHCO_3$ and then $NaHCO_3$ type groundwater dominate in HF4 and HF5. This is also supported by $(Na^+ + K^+)/(Ca^{2+} + Mg^{2+})$ ratio increases from HF1 to HF5 (D.T3.3.2, DEEPWATER-CE 2021c). As presented in the fieldwork report, the concentration of HCO_3^- does not increase along the flow paths and low TDS characterise the groundwater composition of the deeper aquifers. Similar to the hydrogen bicarbonate, the chloride concentration is also the lowest in HF4 and HF5.The low chloride concentrations suggest infiltration conditions during a cooler climate, with low level of evaporation and soil/sediment dissolution during infiltration.

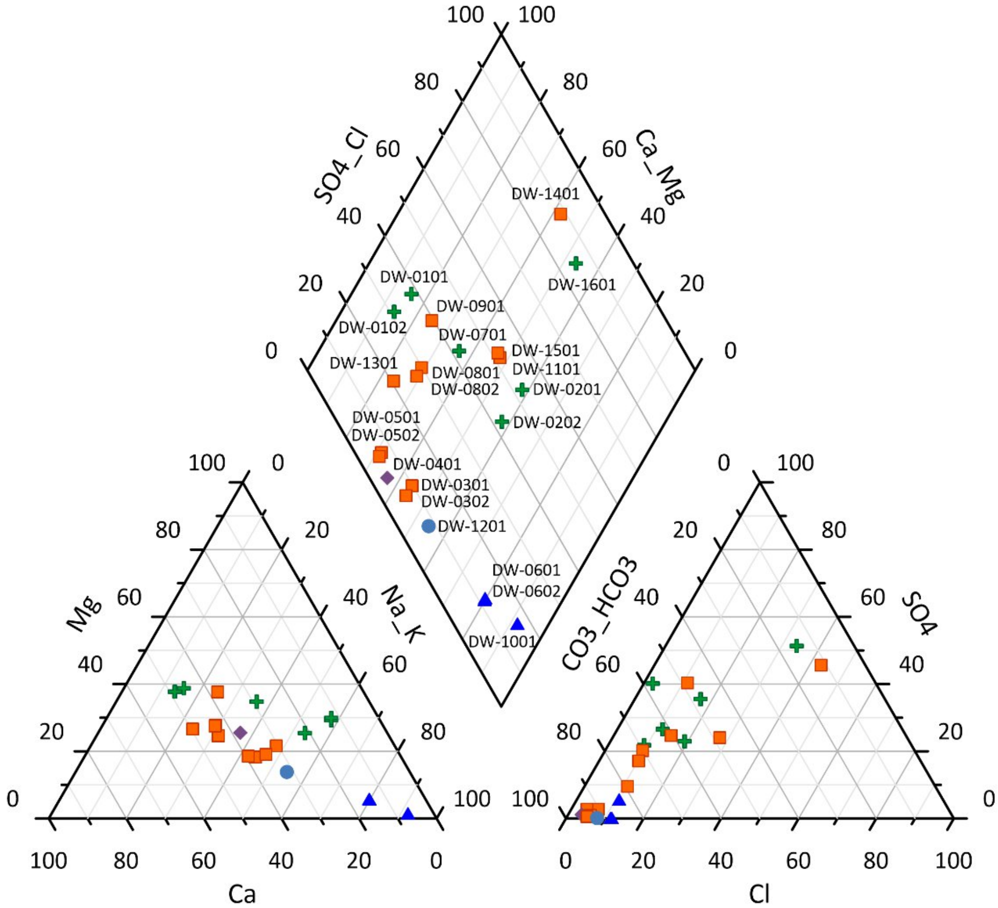


Figure 10. Chemical types of groundwater samples shown in Piper diagram

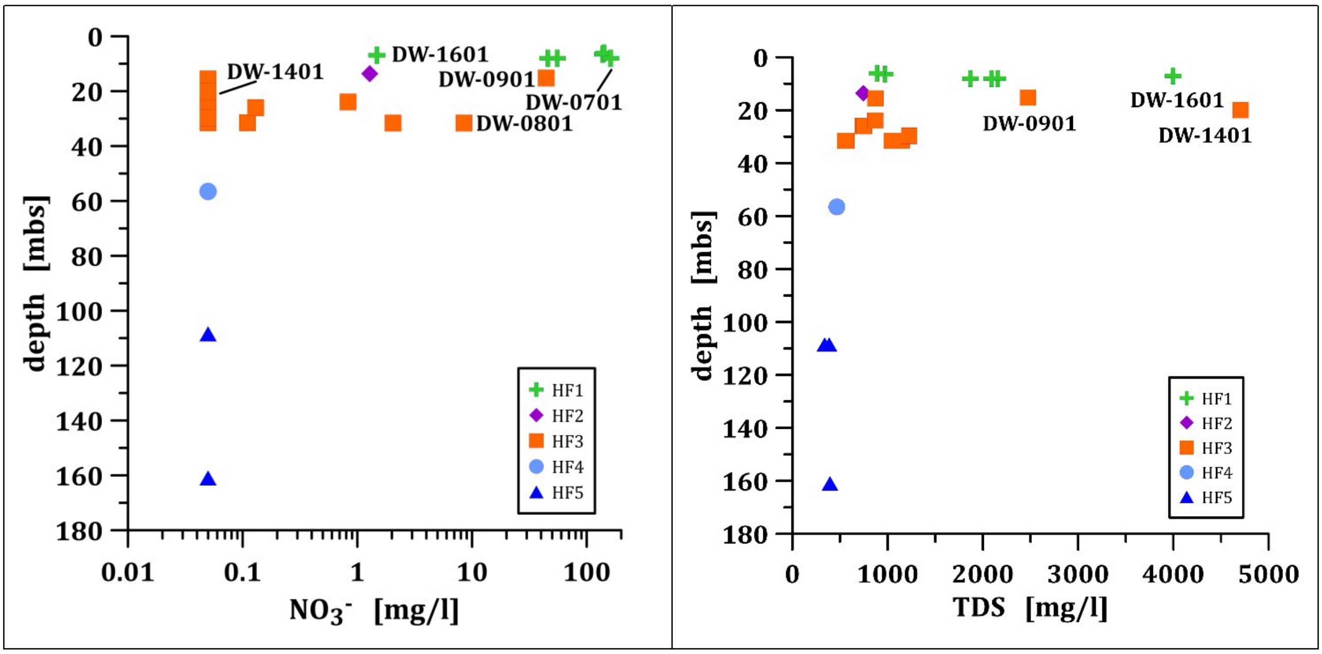


Figure 11. Nitrate concentration (left) and TDS distribution (right) vs. depths in the pilot site

The nitrate concentration covers a wide range (Figure 11), from below detection limit (shown with 0.05

mg/l values) up to more than 100 mg/l, reflecting the effects of the agricultural activity. High concentrations can be detected in the topmost sand layer HF1. Only one sample of the regionally correlated sand horizon (DW-0901, Medgyesbodzás K-67) shows high (about 44 mg/l) nitrate concentration and a bit deeper local HF3 sand layer (DW-0801, Medgyesbodzás K-66) potential nitrate pollution effect. These wells are located in an orchard. The high nitrate concentration in the second sand horizon at DW-0901 might be due to pumping, which perhaps resulted in the drawdown of the groundwater from the first sand horizon. All samples deeper than about 33 meters below surface have nitrate concentrations below or around the detection limit.

The total dissolved solid (TDS) content shows a similar pattern as the nitrate, apart from two samples DW-1401 and DW-1601, the two outliers from Csanádapáca (Figure 11). Their TDS is much higher than the rest of the samples. The TDS of DW-0901 is the second highest between the HF3 samples, which is due to its higher sulphate and chloride concentration. These data might indicate the impact of a more intense land use in the past.

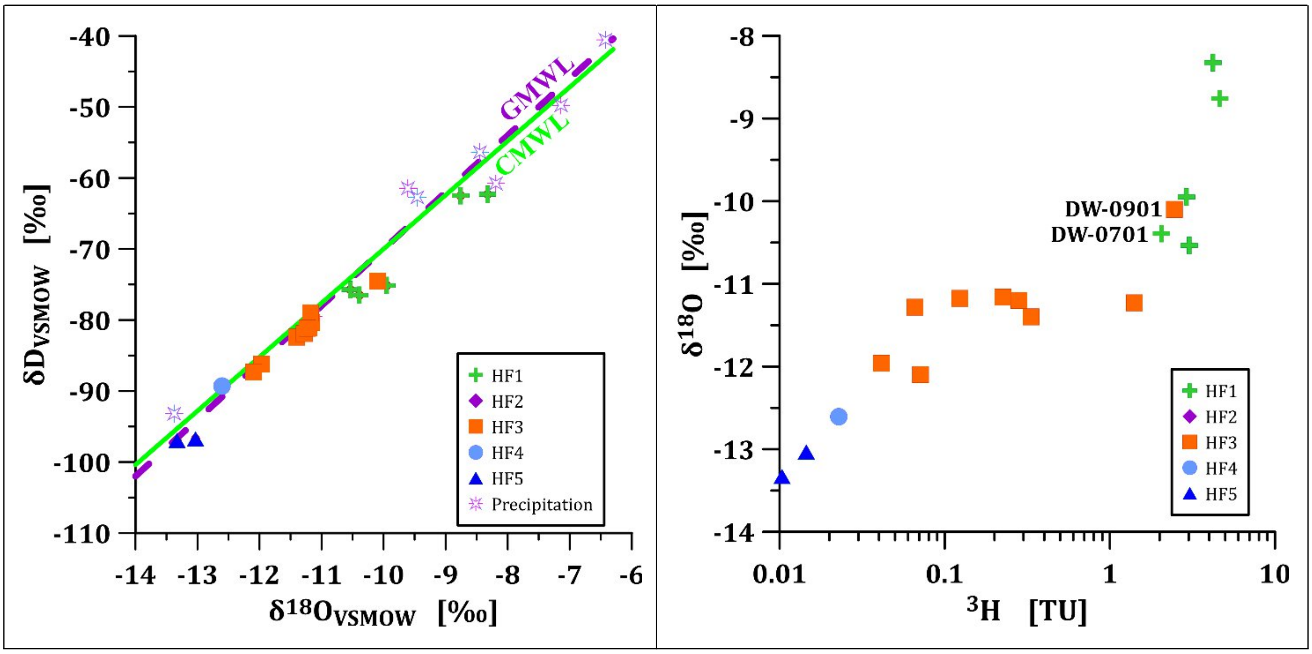


Figure 12. δ^{18}O vs. δD and ^{3}H vs. δ^{18}O distribution data (groundwater and precipitation water)

GMWL - Global Meteoric Water Line; CMWL – Carpathian basin Meteoric Water Line

The δ^{18}O vs. δD distribution (Figure 12) shows that all groundwater samples are of meteoric origin, since they lie on, or are next to the Global Meteoric Water Line (GMWL). Samples of the first sand horizon show a Holocene origin, while HF4 and HF5 show Pleistocene infiltration origin (Deák et al., 1996; Deák J., Coplen T. 1996). HF3 is perhaps also of Pleistocene infiltration origin. (There are no δ^{18}O and δD data for HF2.) The precipitation data reflects seasonal differences, with heavy oxygen isotopes being depleted during cold winter periods and enriched in warmer periods. A clear relation exists between the δ^{18}O and ^{3}H data, with higher tritium values in the Holocene water samples (up to 4.63 TU) and tritium contents below the detection limit in the Pleistocene water samples. Tritium contents are close to the detection limit in groundwater taken from most of the second regionally correlated sand horizons. Where tritium content can be detected in this lower regionally correlated sand horizon this supports the possibility of hydraulic connectivity between the first and second sand horizons. Such potential connection between the upper and lower higher resistivity layers was highlighted during the interpretation of Electric Resistivity Tomography (ERT) profiles within the fieldwork report (D.T3.3.2, DEEPWATER-CE 2021c).

4.3. Water demand and supply, water source for MAR

The pilot region is characterized with rural land use, therefore, there is a great need for irrigation water. Since, climatic exposure of the pilot site is one of the highest in Hungary, agricultural production (especially crop production) predominantly depending on the accessibility of water for irrigation (D.T3.1.2; DEEPWATER-CE 2021a). Due to the very sparse river network groundwater abstraction is significant both for drinking water and irrigation purposes. With a few exceptions groundwater is the main source of irrigation water. In the last decade, temporary surface water shortages increased this trend and resulted in additional use of groundwater. Accurate determination of the amount of groundwater used is difficult in the absence of exact registries.

Determination of irrigation water volumes and related demand in agricultural regions of Hungary was a difficult task. There is no uniform method to estimate future irrigation water demand. Measured volumes at registered wells, licensed amounts and declared irrigation volumes or needs in statistical surveys show large discrepancy when we comparing statistics from different sources. This is due to interest of farmers and companies in selecting an approach that produces values that are best fitting to the conditions of the available grant applications offering special supports for their farms. In addition, large ratio of the water volumes used for irrigation is unknown due to the extensive use of unregistered or illegal wells. This means there is no direct statistics or summary on the actually used volumes at settlement or even county level, but instead, different approaches had to be combined to reach a well supported estimate on the magnitude of the water use.

Since there is no permanent surface water in the target area, therefore the estimated irrigation water demand has to be supplied mostly from groundwater. Although we have the licensed amounts and abstracted water amounts for settlements in the pilot site, it is hard to give an exact value for real need for irrigation water without the abstracted amount from unregistered wells, which is known to be significant in the area.

To assess water demand at the pilot site we collected and combined statistics from the Central Statistics Office of Hungary (KSH), the Water Resource Fee (WRF) registry of Hungarian General Directorate of Water Management (OVF), the agricultural land use data and cultivation categories from 2010 (Corine Lan Cover), and the result of a survey on the water demands and irrigation development needs in Hungary provided by the Institute of Agricultural Economics (AKI) carried out in 2017 (AKI, 2018).

To best fit to objectives of the Cost-Benefit Analysis (CBA) (water demand and supply data needed for cost and benefit calculations) the area of interest was defined as the administrative area of the two settlements (Csanádapáca and Medgyesbodzás) where our pilot site is located (Figure 1). As most of the national statistics are prepared in county level, and not for individual settlements, the available data had to be downscaled by the use of basic estimations. During downscaling, it was supposed that statistical averages in county level are valid in the pilot site, thus an area proportional downscaling is valid. To check the reliability, the results were compared to the calculated values considering the registered amounts in the WRF registry, irrigation water amounts declared in our pilot CBA survey for 2020 and a non-expert estimation of total water demand of cultivated plants calculated as the sum of the cultivation area of each crops in 2010 multiplied by a nominal water demand of that plant (SAPS - Single Area Payment Scheme).

At the 1st step of water demand estimation the average total irrigated area was calculated (in hectares) and the specific value of average irrigation volume (m^3/ha/year) based on KSH statistics for Békés County. As a 2nd step the actual ratio of the irrigated area was estimated and the ratio of the area where irrigation can occur after potential development of the irrigation system. Both values were related to

Békés County. This estimation was done based on KSH statistics and the data after survey of AKI (2018) respectively. In the 3rd step the actually and the potentially irrigated area in the pilot site was estimated using the above calculated ratios. Finally the water demand was derived based on the irrigated area and the specific average irrigation volumes applied for each hectare. Results were compared and validated by other approaches and datasets to improve the reliability of the potential water demand (Table 2 and 3).

Table 2. Statistics from Békés County

Parameter	*Source*	*Value*
Area of Békés County (ha)	Corine	562,967
Non-urban area in Békés county (ha)	Corine	534,378
Ratio of non-urban area (%)		94.9
AVG reported irrigated area (ha)	KSH (2003-2019)	19,017
STD of the reported irrigated area (ha)	KSH (2003-2019)	4,595
Ratio of the irrigated area to total non-urban area (%)		3.6
STD for ration of irrigated area (%)		0.9
Irrigated area based	AKI, 2018	20,138
Area for developing irrigation potential	AKI, 2018	46,047
Total area where irrigation is expected	AKI, 2018	66,185
Ratio of the area where irrigation is expected (%)	AKI, 2018	12.4
AVG volume of water used for irrigation (m^3/ha/yr)	KSH (2003-2019)	**1,311.5**
STD of volume of water used for irrigation (m3/ha/yr)	KSH (2003-2019)	215.6
AVG volume of water used for irrigation (m^3/yr)	AKI, 2018	21,678,890
AVG volume of water used needed for developing irrigation potential (m^3/yr)	AKI, 2018	35,950,885
AVG specific volume of water used for irrigation (m3/ha/yr)	AKI, 2018	1,076.5
AVG volume of water used needed for developing irrigation potential (m^3/ha/yr)	AKI, 2018	780.7

Table 3. Statistics for the pilot site

Parameter	*Value*
Area of the pilot site (ha)	8297
Non-urban area in pilot site (ha)	7099.8
Ratio of non-urban area (%)	85.6
Estimated AVG irrigation area based on county level statistics (ha)	252.7
STD of the estimated irrigated area (ha)	61.0
Ratio of non-urban area of pilot site to area of Békés County (%)	1.3
Estimated AVG irrigation area with irrigation development (ha)	879.3

Parameter	*Value*
Estimated AVG area for irrigation development (ha)	626.7
Estimated AVG water demand (3.6% irrigated area, KSH data) (m^3/yr)	331,361
STD for water demand (3.6% irrigated area, KSH data)	96,839
Estimated AVG water demand (12.4% irrigated area, AKI, 2018)	1,153,229
STD water demand (12.4% irrigated area, AKI, 2018)	N/A
Estimated AVG water demand based on AVG water uses of AKI, 2018	761,267
STD water demand based on AVG water uses of AKI, 2018	N/A
AVG total water demand of crops (m3/yr) estimated based OVF data	8,727,596
Water demand of crops for 3.6% of the area	314,193
Water demand of crops for 12.4% of the area	1,082,222
Weigted AVG of water used for irrigation per ha (m^3/ha/yr)	1229.279

It has to be noted that, the water demand of different crop types are diverse, the highest water volumes are used for watermelon, asparagus and tomato.

In case of irrigation water only the authorized amounts and rough estimation for illegal abstractions exist. According to the estimation of the Hungarian Chamber of Agriculture (2019) the number of wells for irrigation is between 10 000 and 100 000 all over in Hungary. Only 1% of farmers have a water right permit for irrigation, despite the fact that the costs of using water for irrigation are negligible for farmers (the Ministry of the Interior estimates an average of 5000 HUF/hectare/year (it means cc. 15 Euro/hectar/year). According to the data of the General Directorate of the Water Management in 2013 (which is the most recent data) 8.867.000 m^3 groundwater was withdrawn and used for irrigation purposes in agriculture and another 21.601.000 m^3 for other agricultural purposes.

In the future, the Ministry of Agriculture will handle the authorization procedure instead of the Ministry of Interior. Then the water permit for wells used for agricultural purposes will be taken over by a new institution, the National Land Center. This transformation is currently in progress.

4.4. Hydrogeological modelling

4.4.1. Brief description of the model inputs

For the current FEFLOW software model there was a lot of available information from previous drinking water protection modelling studies performed in the area.

- The distribution of hydraulic conductivity is based on surveys and investigations of drinking water protection studies carried out in the area, while
- defined layer surfaces are based on geophysical measurements in boreholes and surface geophysical measurements.

Output data from previous modelling works:

- steady-state boundary test results.

4.4.1.1. Characterization of the model area

The definition of the model area was based on the distribution of the available data from the Maros alluvial fan and the conceptual model described above, resulting in a rectangular area of approximately 17x14 km in an E-W direction (Figure 13 and Figure 14).

When defining the model area, morphological catchment boundaries were taken into account and the area of intervention was chosen to be the least affected by boundary effects.

When defining the model area, morphological catchment boundaries were taken into account and the area of intervention was chosen to be the least affected by boundary effects.

Corner coordinates of the rectangle around the model area:

- EOV X min: 125492   EOV X max: 140257
- EOV Y min: 785729   EOV Y max: 803142

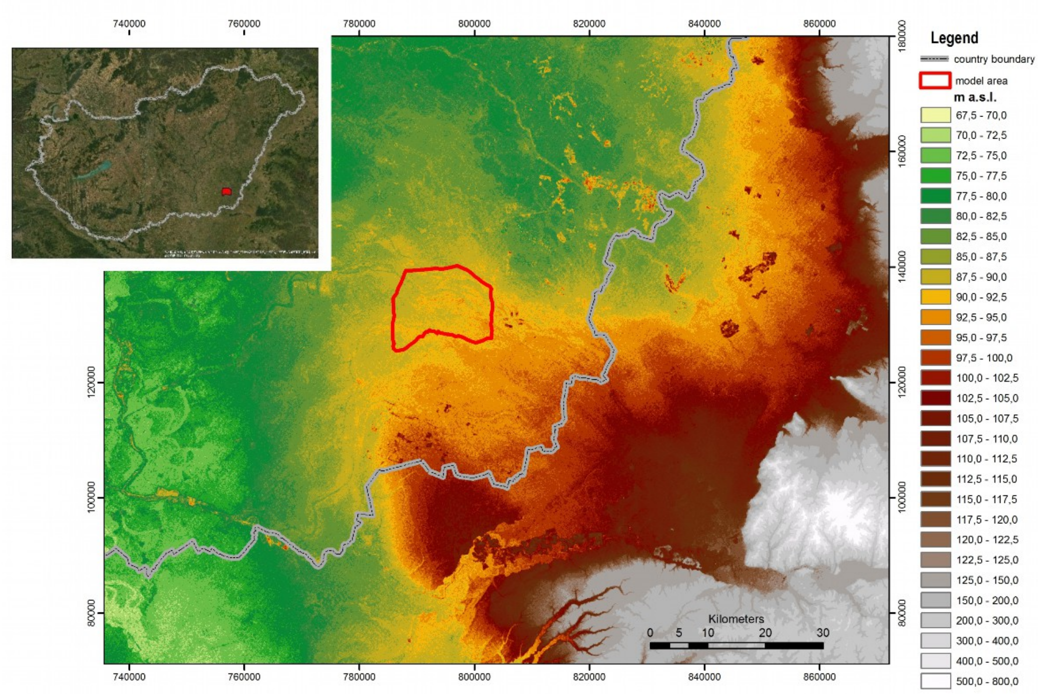


Figure 13. The location of the defined model area

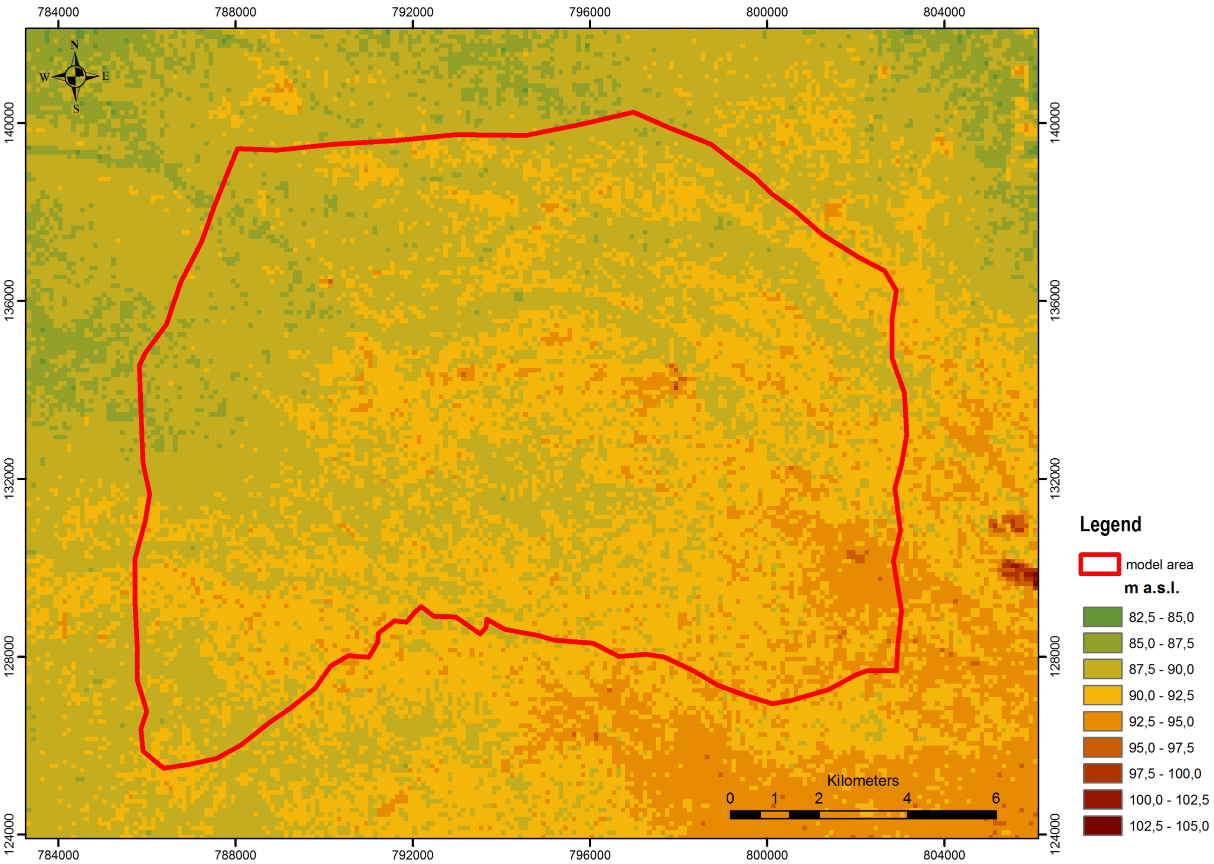


Figure 14. Topography of the model area

4.4.1.2. Horizontal mesh structure

At the beginning of the model calculations, the mesh density was set low, given the large model area and the number of expected runs.

In the FEFLOW version of the model, the number of elements was 76 128 and the number of node points was 49 145. The smallest size of the elements in the vicinity of the dam reached 15 m (Figure 15).

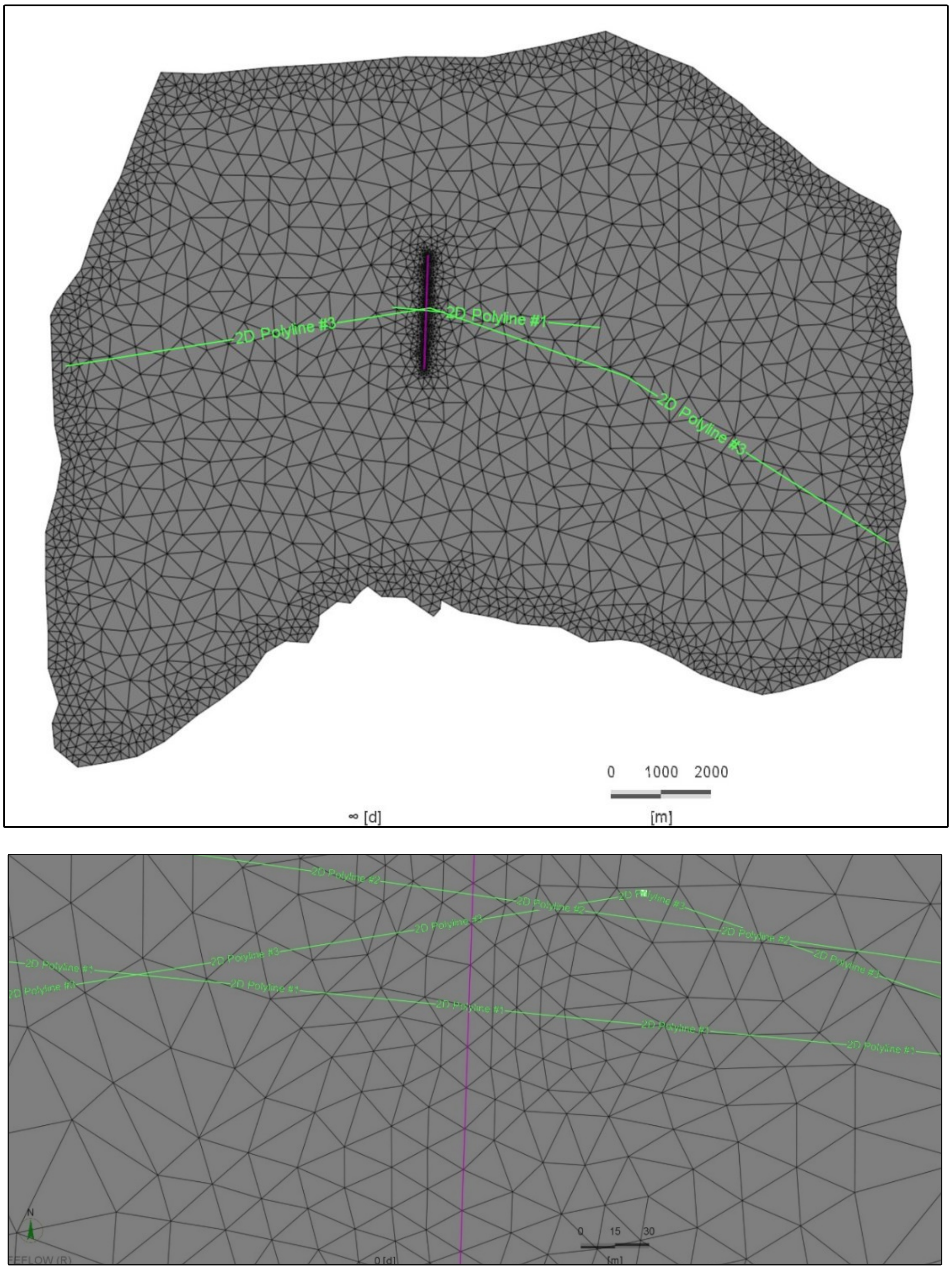


Figure 15. Horizontal resolution of the mesh

4.4.1.3. Vertical mesh structure

In the modelling, the geological structure of the study area was determined from the interpretation of borehole geophysics in the area, and from interpolated data from electrical resistivity tomography (ERT) geophysical measurements and cone penetration tests (GCPT) carried out in 2020 and 2021 (Figure 16).

The model was built from the available dataset, focusing on the problem we wanted to model. The model space was divided into 4 layers.

The model area is characterized by the following geometry:

- width: 17412.9 m

- length: 14765.0 m
- depth: 79.96 m
- area: 194.08 km^2
- volume: 11.22 km^3

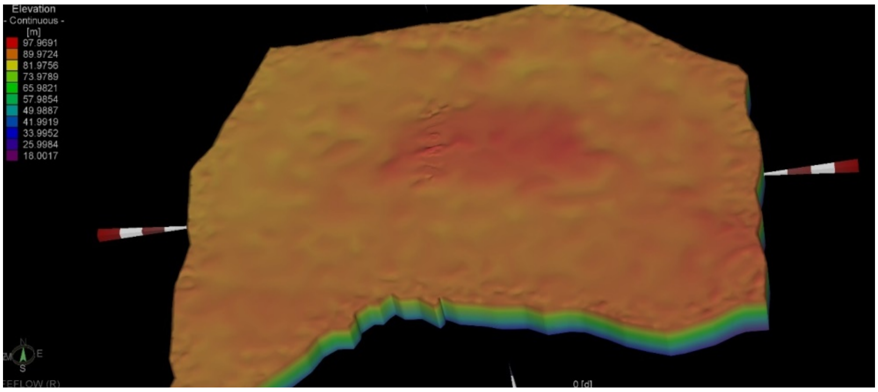


Figure 16. 3D representation of the model area MH:V=1:20

Before dividing the whole model area into separate geological layers, the geomorphological and geophysical conditions of the smaller prospect area – covered by the geophysical measurements and investigations – were investigated. Based on the study, the relationship between the areas of higher topography and the location of the uppermost aquifer can be clearly seen (Figure 17).

Based on geophysical measurements, the uppermost aquifer in the study area is a slightly curved body of sand, roughly E-W in direction, with a maximum thickness of about 12 m in the central part of the area (Figure 18). The westward continuation of the aquifer delineated in the course of measurements was confirmed during the Csanádapáca aquifer studies, and the aquifer continues in a slightly southward direction in this area. The eastward continuation can initially be identified even in some boreholes at Medgyesegyháza but cannot be clearly traced to the model boundary due to lack of drilling data. In some Medgyesegyháza boreholes (B-62, B-64) near the model boundary, it was observed again with a thickness of about 15 m. Considering the geomorphology of the area, it is possible that this uppermost aquifer found in the study area is connected to the east by a belt of sandy river sediment cycles of more distant areas.

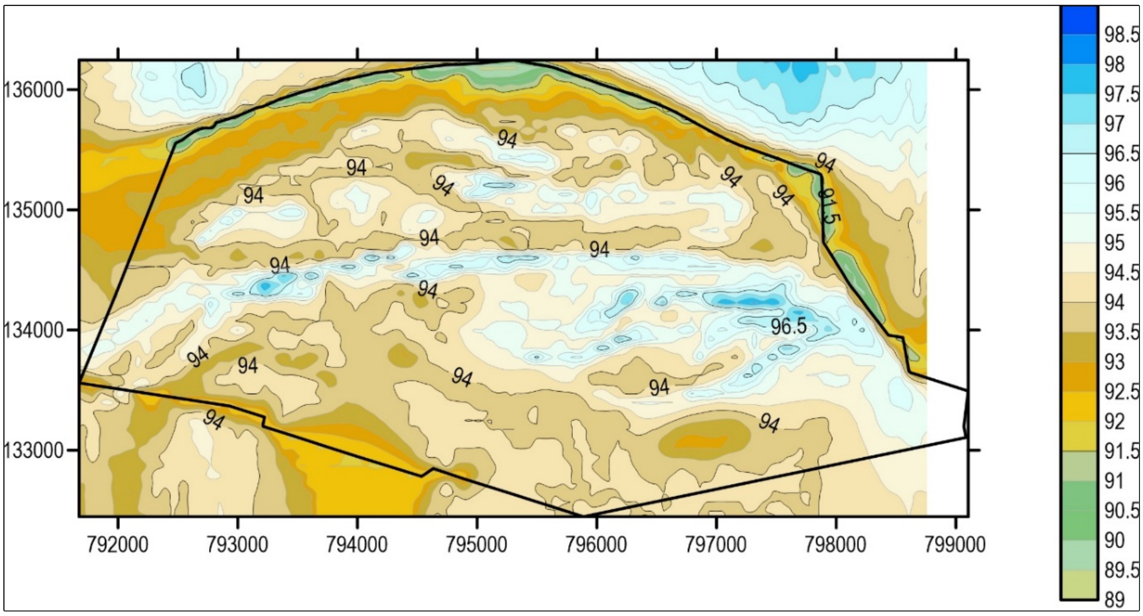


Figure 17. The morphology of the prospect area (m a.s.l.)

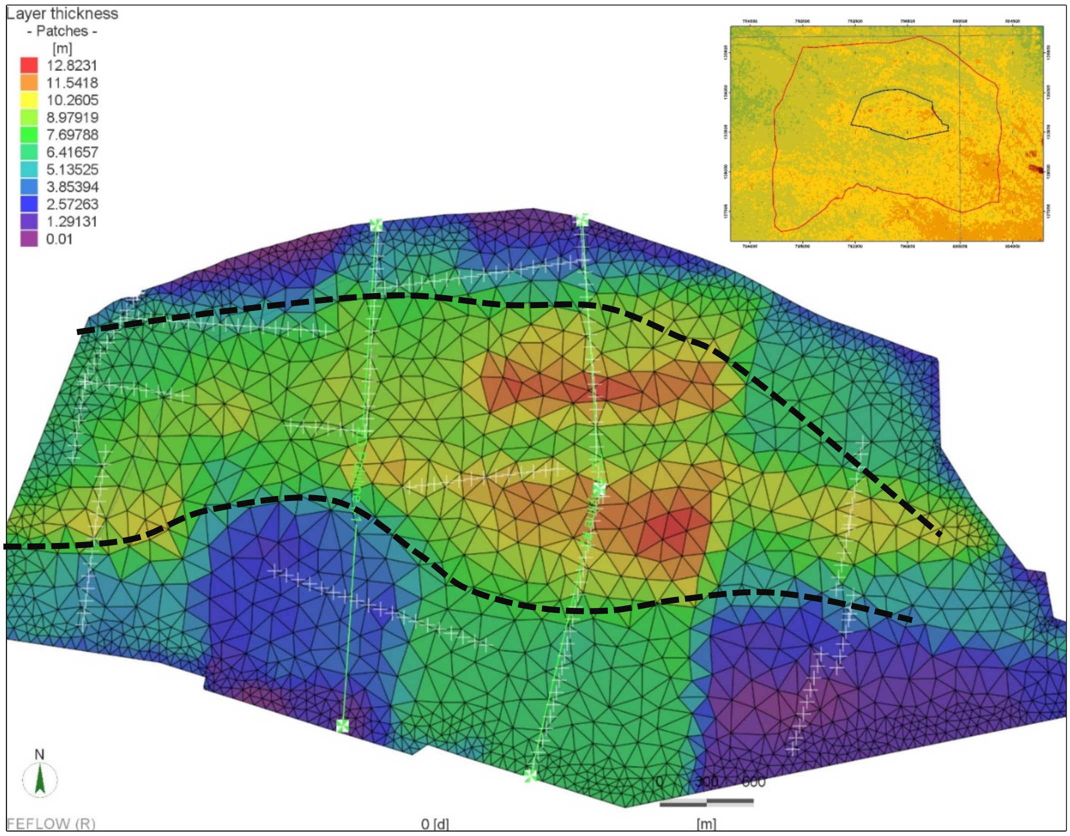


Figure 18. The uppermost aquifer thickness from field measurements

The model domain is vertically divided into 4 distinct layers. Based on the stratigraphy of the area, the modelled volume is characterized by an assemblage of mainly sandy and clayey formations. After data analysis, the thickness distribution for the 4 layers was obtained and is illustrated in the images of Figure 19.

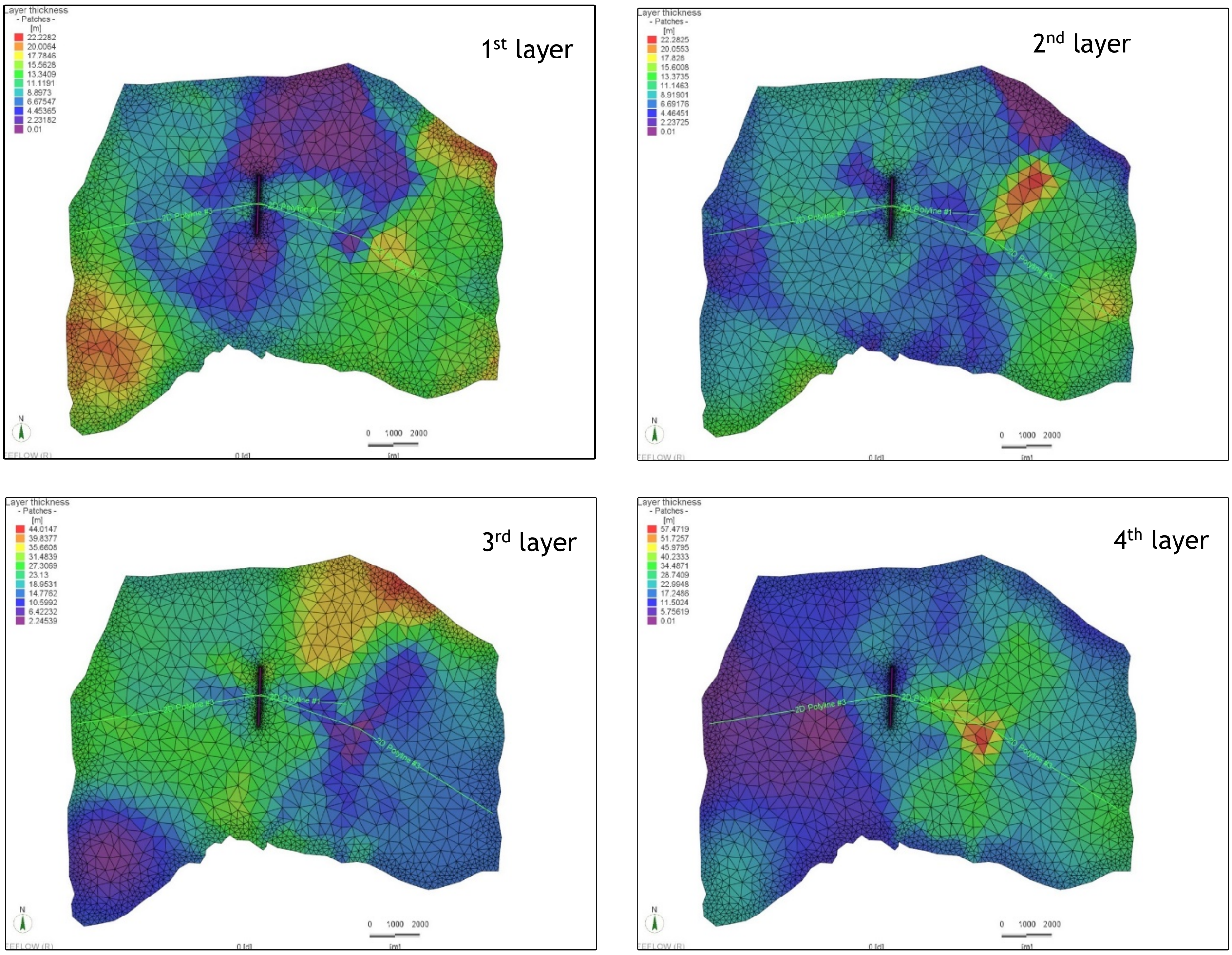
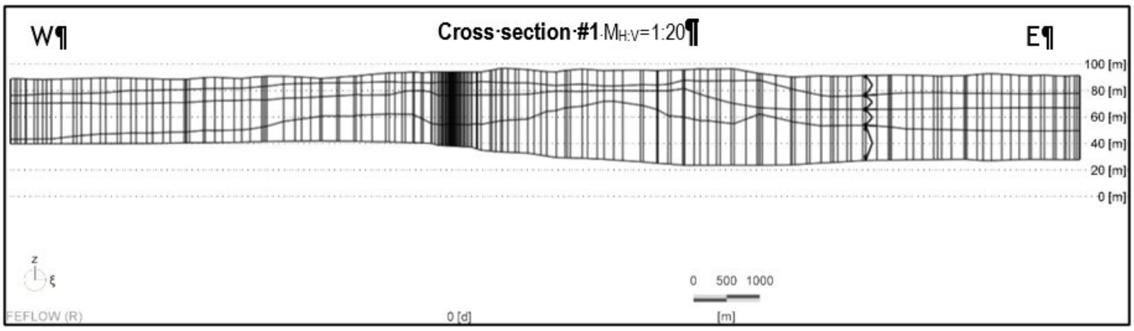


Figure 19. Thickness of the model layers

The layers defined in the modelling were also plotted along sections (Figure 20).


W¶
Cross·section·#1·MH:V=1:20¶
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100 [m]
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z
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0 500 1000
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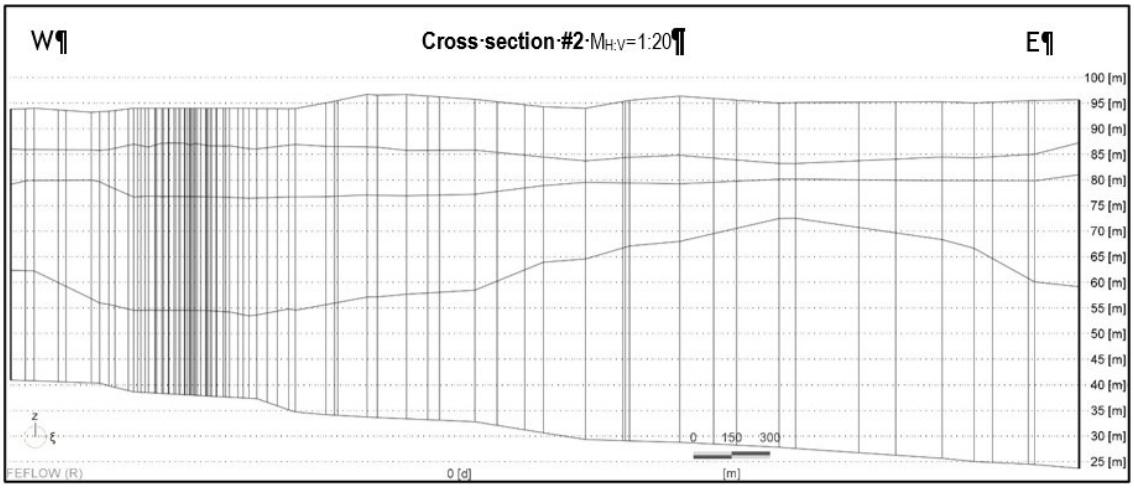
FEFLOW (R)
0 [d]


W¶
Cross·section·#2·MH:V=1:20¶
E¶
100 [m]
95 [m]
90 [m]
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30 [m]
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z
ξ
0 150 300
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FEFLOW (R)
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Figure 20. Layer thicknesses along sections

4.4.1.4. Incorporation of the underground dam in the model

The positioning of the underground dam is based on the geometry of the uppermost aquifer. The E-W sandy bed narrows slightly in the western half of the study area, so the underground dam was placed in this section so that it intersects the aquifer in an approximately N-S direction. The total length of the modelled underground dam is 2292 m. The underground dam was assumed to be perfectly impermeable and therefore had a hydraulic conductivity of 1×10-10 m/s in all directions.

Along the section parallel to the underground dam, it can be seen that the depth of the dam varies as a function of the geometry of the aquifer. Along the studied section the maximum depth of the subsurface dam is expected to be around 85 m a.s.l., which represents a wall approximately 10 m deep maximum (Figure 21).

Figure 21. Relationship of the position of the underground dam and thickness of the aquifer

4.4.1.5. Defining hydraulic conductivities

As mentioned previously, the distribution of the hydraulic conductivity values of the different layers is based on data used in modelling carried out in the framework of previous drinking water protection diagnostic studies (Csanádapáca, Medgyesbodzás). Based on these previous hydraulic tests the conductivity values of the uppermost aquifer vary between 3×10-5 m/s and 1×10-3 m/s. The hydraulic conductivity of the second aquifer has similar values (Diagnostic study of Csanádapáca (2002) and Medgyesbodzás (2000).

In the modelling, the value of the seepage factor was tested in several model versions, so the groundwater flow velocities and directions proven to be different. The used values are indicated for the tested model variants.

Several horizontal and vertical conductivity ratios have been tested during the modelling. The vertical value of the hydraulic conductivity of the layers varied between 1/10 and 1/50 of the horizontal values in the presented models.

The impermeable formations between aquifers were also tested with a range of values (1×10-6 to 1×10-8 m/s).

In the idealized version of the model, a distinct layer of impermeable clay with variable thickness is located between the first and the second aquifers (Figure 22 and Figure 23). However, the geology of the area might suggest that this clay layer can be very thin or even be absent at certain parts between the two aquifers, so there might be a direct hydraulic connection between them. Geophysical measurements confirmed the existence of the upper aquitard in all areas of the study area.

In the deeper layers, this hydraulic connection may also exist, but given the amount of data available, we can only assign areas with high uncertainty. However, these areas are located away from the area of the current intervention, close to the eastern edge of the model.

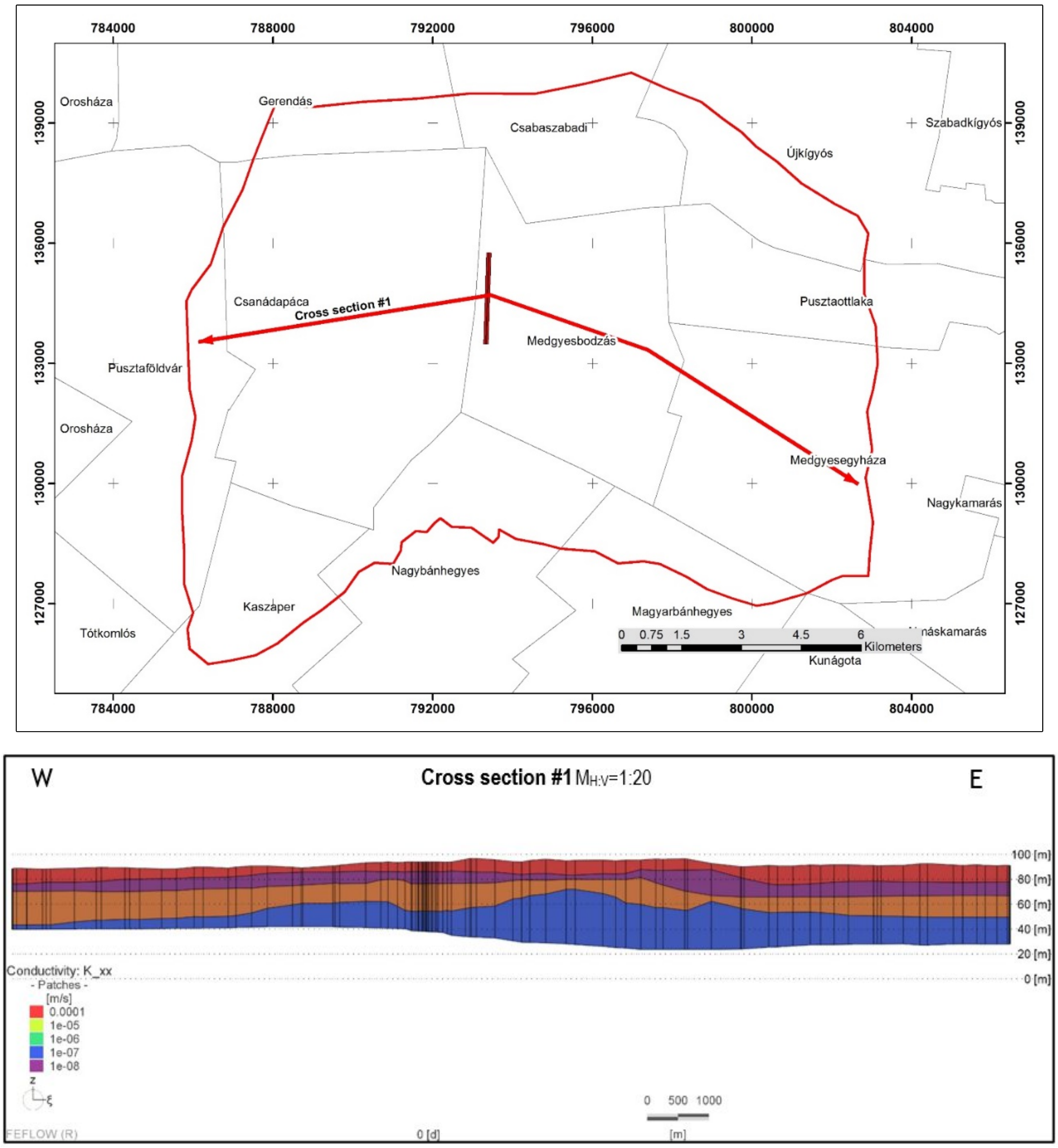

Figure 22. Hydraulic conductivity values used in the model along Section 1.

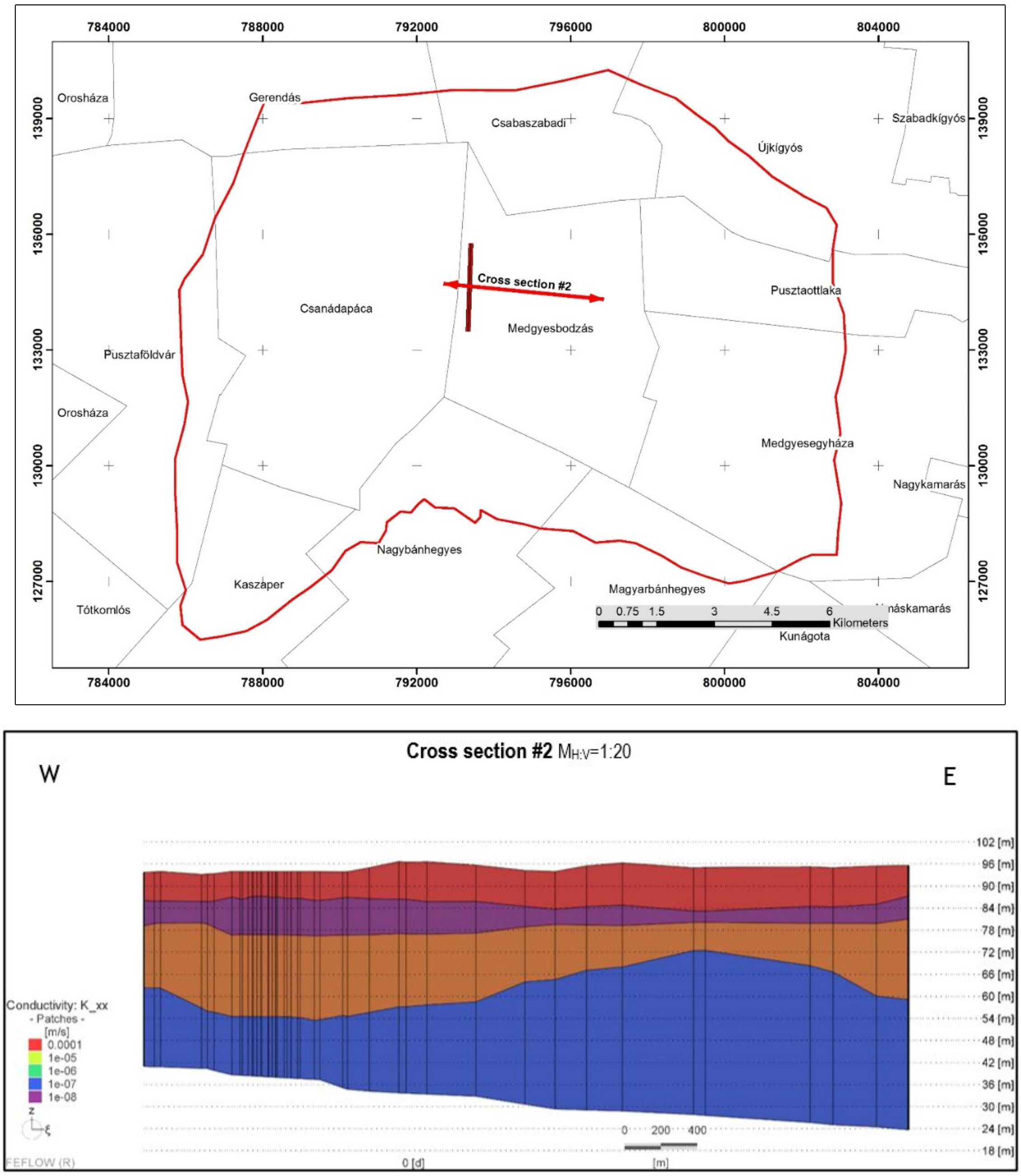

Figure 23. **Hydraulic conductivity values used in the model along Section 2.**

4.4.1.6. Boundary conditions

Groundwater levels at the NW and SE boundaries of the model were determined using a so-called first order (Dirichlet) boundary condition. In the first aquifer, the water levels derived from pressure conditions were 92.0 and 88 m a.s.l., while in the second one, 91.5 and 87.5 m a.s.l. were determined. A ‘no flow’ condition was imposed at the bottom and at the NE and SW boundaries of the model.

The modelling was based on annual average net infiltration (inflow) of 5 and 10 mm for the area (Csepregi, A., 2020).

4.4.1.7. Groundwater levels

To generate the static water level map (Figure 24) of the area, we used the average water level values of several years, constructed from the data of previous measurements. The water levels were obtained from several monitoring wells measured between 2005 and 2009. Unfortunately, none of the monitored wells are located within the model area, so artificially generated water level monitoring points were created from the interpolated values to perform the calibration.

The data of the operating monitoring wells available for the wider area can be affected by groundwater abstraction. These time series indicate that water level fluctuations of about 0.5-1.0 m are observed in the uppermost aquifer, which are influenced by current precipitation and evaporation conditions. Examination of further well data shows that flow conditions in the second aquifer differ only slightly from those measured in the first aquifer.

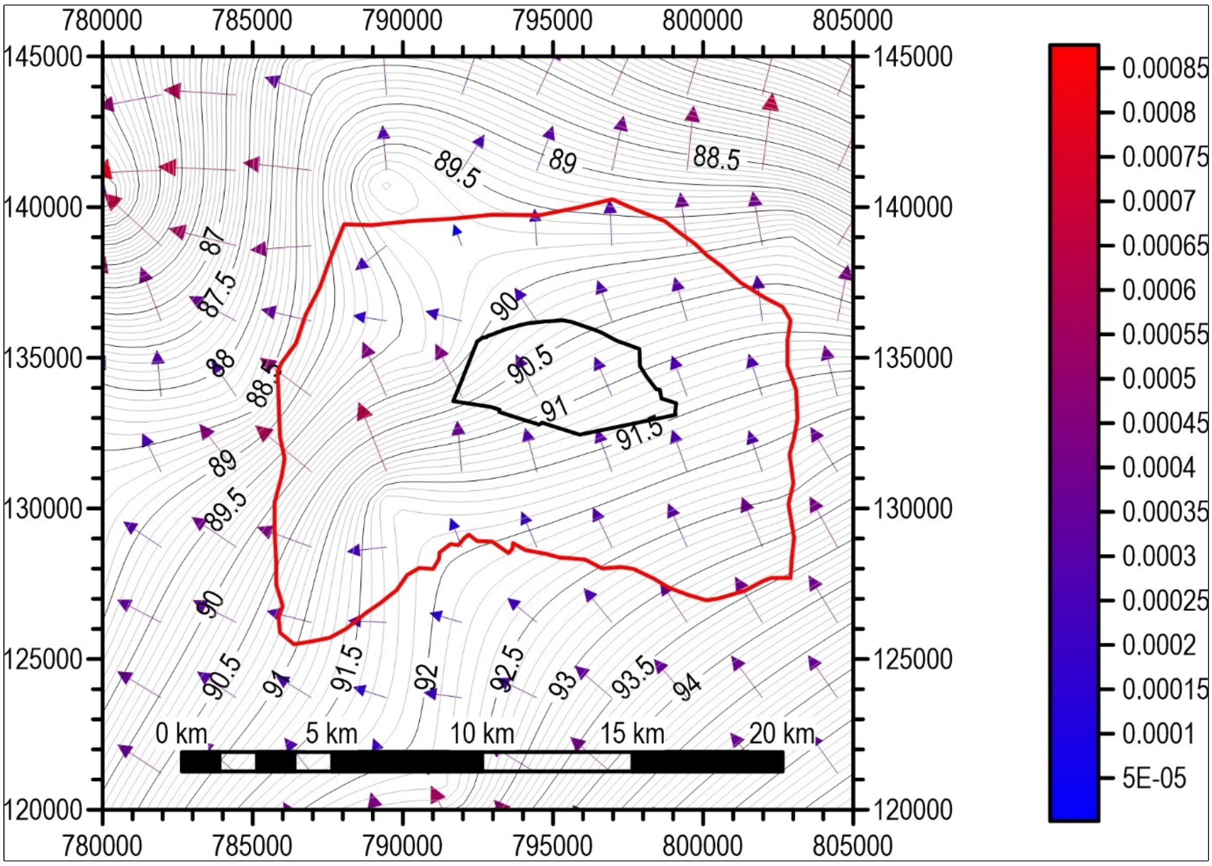

Figure 24. Hydraulic potential and gradient distribution of the static water level (m a.s.l.) used for the modelling

4.4.1.8. Calibration

The results of the numerical simulation are based on geological knowledge of the study area and its surroundings, archive data and previous studies. Any new data that contradicts the assumptions built into the model may require a change in the input parameters and a re-run of the simulation. Acceptable results can only be expected if the available input data are consistent with the current state of knowledge and are free of inconsistencies.

The accuracy of the results is within the limits of what is currently known to be acceptable and is assured by the errors inherent in the simplifications and approximations of the geological, hydrogeological, and numerical methods used.

The model was calibrated to steady state. The completed model must be calibrated to the measured values. Calibration is done by comparing the modelled and measured water level values. To minimize the discrepancy between them, the initial parameters of the model must be changed.

During the modelling process, we had to perform several runs, as our data on the exact structure, hydraulic conductivity and permeability of each layer were inaccurate. Data gaps had to be filled by assumptions, which could only be approximated by lengthy experimentation.

After building the three-dimensional model, the main hydrostratigraphic units with different hydraulic conductivities known in the area were incorporated. By changing the hydraulic conductivities, we further refined the static water levels until an acceptable value for flow directions and velocities was obtained. The final adjustment of the hydraulic parameters was also made at this time. The calibration condition represents a condition free from any artificial interference (e.g. implementation of the underground dam).

The calibrated model is a representation of the layer structure constructed on the basis of the tests carried out during the project and the field conditions found in the prospect area.

The modelling showed a difference of 0.65 m between the initial and calculated hydraulic heads (RMS) (Figure 25).

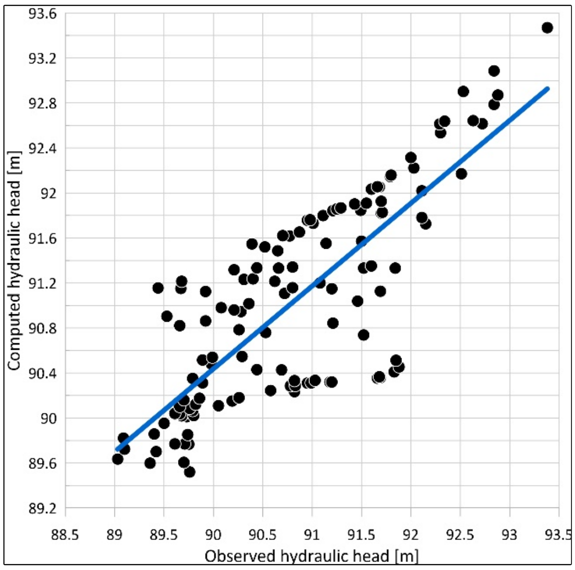

Figure 25. Water levels calculated and observed in the model

4.4.2. Results of the modelling (output data)

The modelled flow directions were similar to those already known, with water levels in the riverbed changing direction slightly to adapt to the morphology of the riverbed (Figure 26).

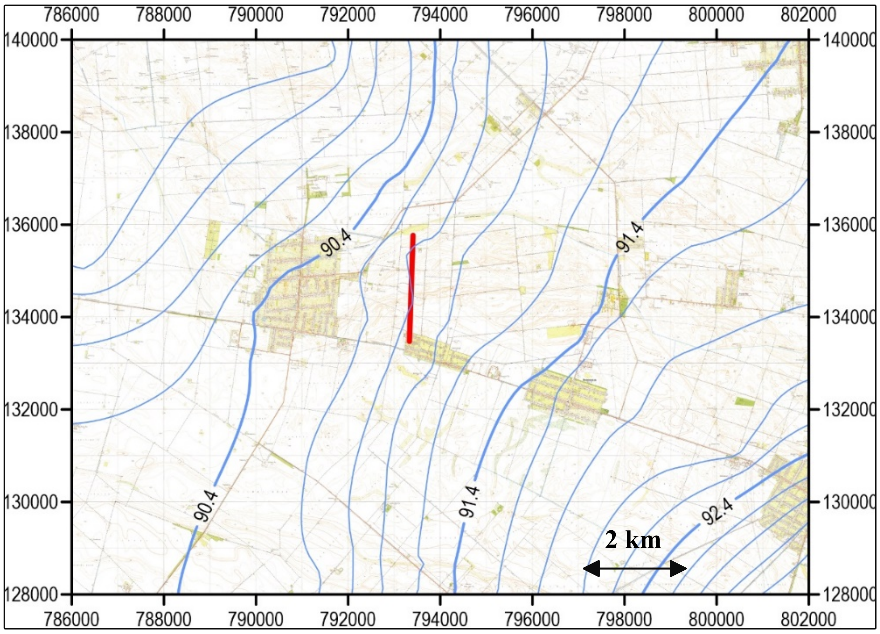

Figure 26. The representation of modelled water levels (m a.s.l.) in the first aquifer (red underground dam)

4.4.2.1. Model scenarios

4.4.2.1.1. Impact of the underground dam in the first aquifer

The modelling was then tested for the condition after the installation of the underground dam. The subsurface dam was placed in the first layer (85 m a.s.l., cca 10 m depth), so that it reached the second layer.

Due to the location of the dam, water levels on the upstream side of the dam rose by 0.3 m (Figure 29), while on the downstream side of the dam they fell by 0.6 m (Figure 30). The size of the backwater area was approximately the same as the area affected by the water level fall. The shape of the area took the form of the zone of better conductivity, and the effect of the wall could be observed at a distance of about 4 km. The backwatered volume was 4 470 824 m^3, which at 20% porosity represented 894 164 m^3 of water.

The direction and gradient of the groundwater flow changed significantly after the emplacement of the underground dam, mainly in its vicinity (Figure 27 and Figure 28).

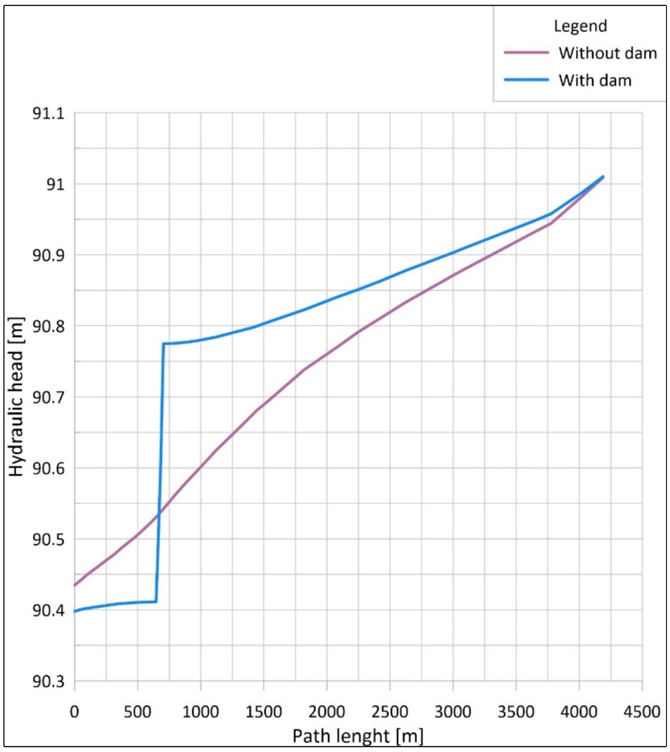

Figure 27. Hydraulic heads as the effect of the emplacement of the underground dam along Section 2.

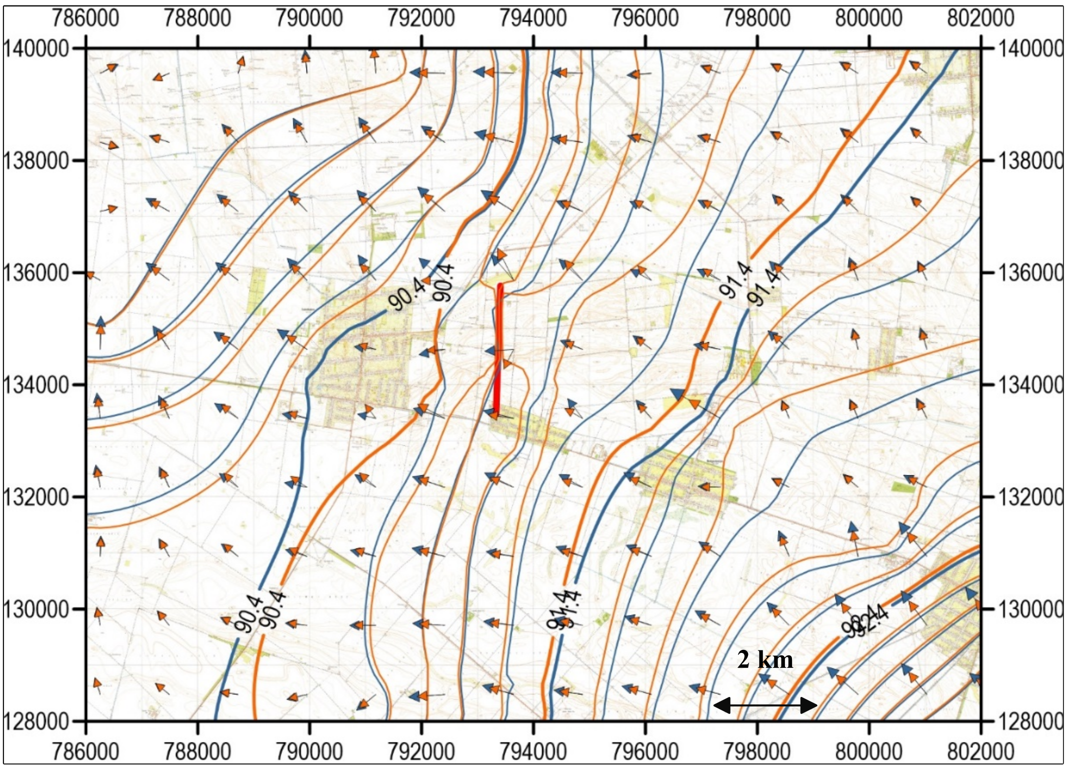

Figure 28. Water levels (m a.s.l.) in the initial state (blue isolines) and in the altered state due to the effect of the dam (red isolines)

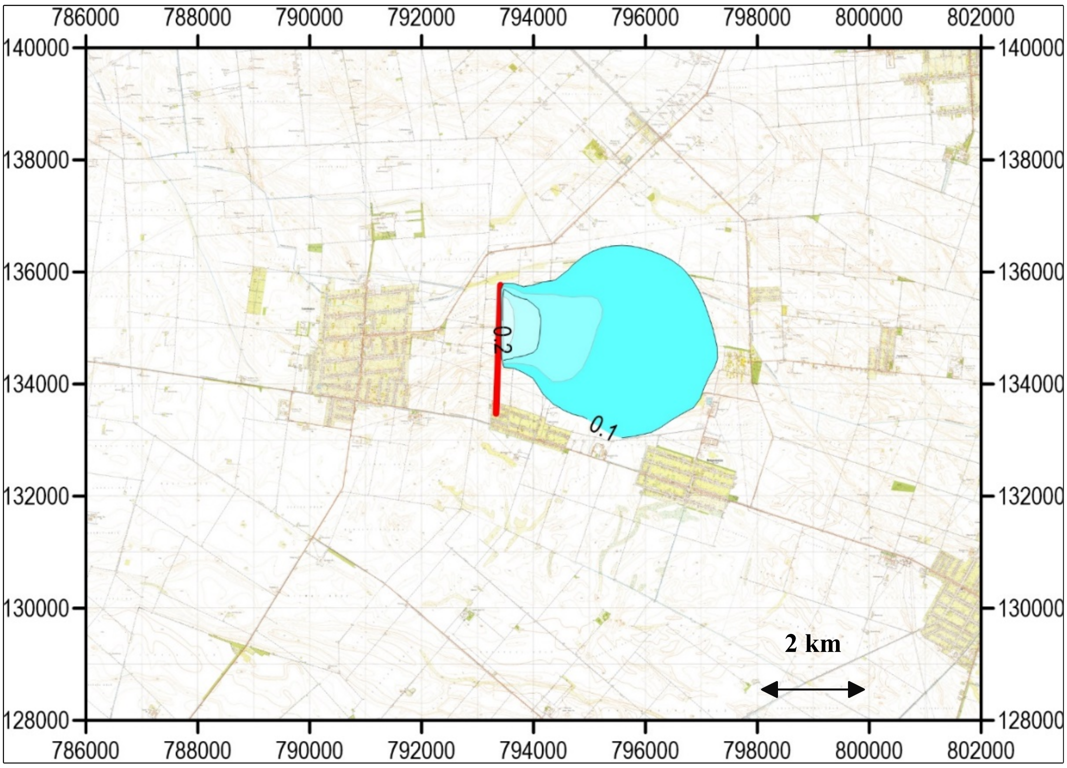

Figure 29. Groundwater level rise (m) due to the effect of the underground dam

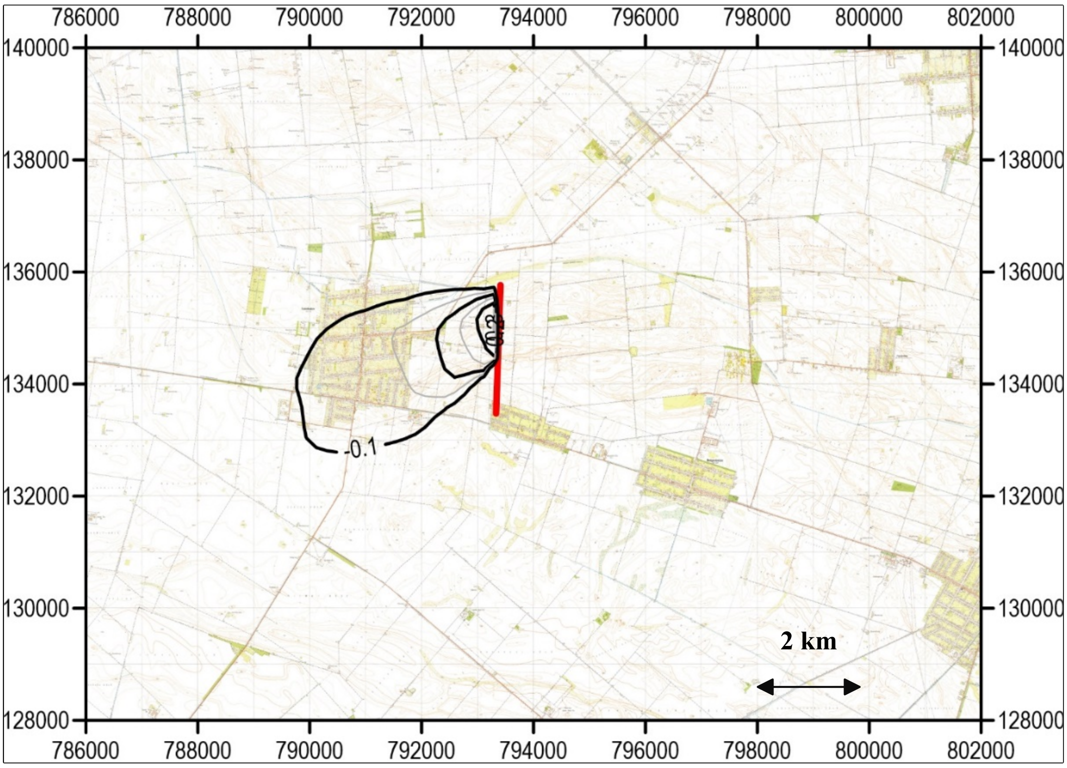

Figure 30. Groundwater level fall (m) due to the effect of the underground dam

4.4.2.1.2. Impact of the underground dam in the second aquifer

The modelling also examined the effect of a deeper subsurface dam located in the second aquifer. The surface location of the underground dam was the same as the previously studied one’s, so only the depth of the dam was changed, with the dam reaching a depth of 50 m a.s.l. at its deepest point. The thickness of the second aquifer in this case was greater than that of the first aquifer. In the tested version, the hydraulic conductivity of the second aquifer was 1×10^{-4} m/s.

The area affected by positive water level changes was a little over 4 km in distance from the dam, while the area affected by groundwater level fall was about 2 km. Due to the impact of this deeper underground dam, water levels rose by 0.35 m on the eastern side the dam (Figure 31 and Figure 32) and fell by 0.35 m on the western side of it (Figure 33). The (backwatered water volume) is 7 850 599 m^3, which, assuming an effective porosity of 20%, represents an increase of 1 570 119 m^3 of water volume.

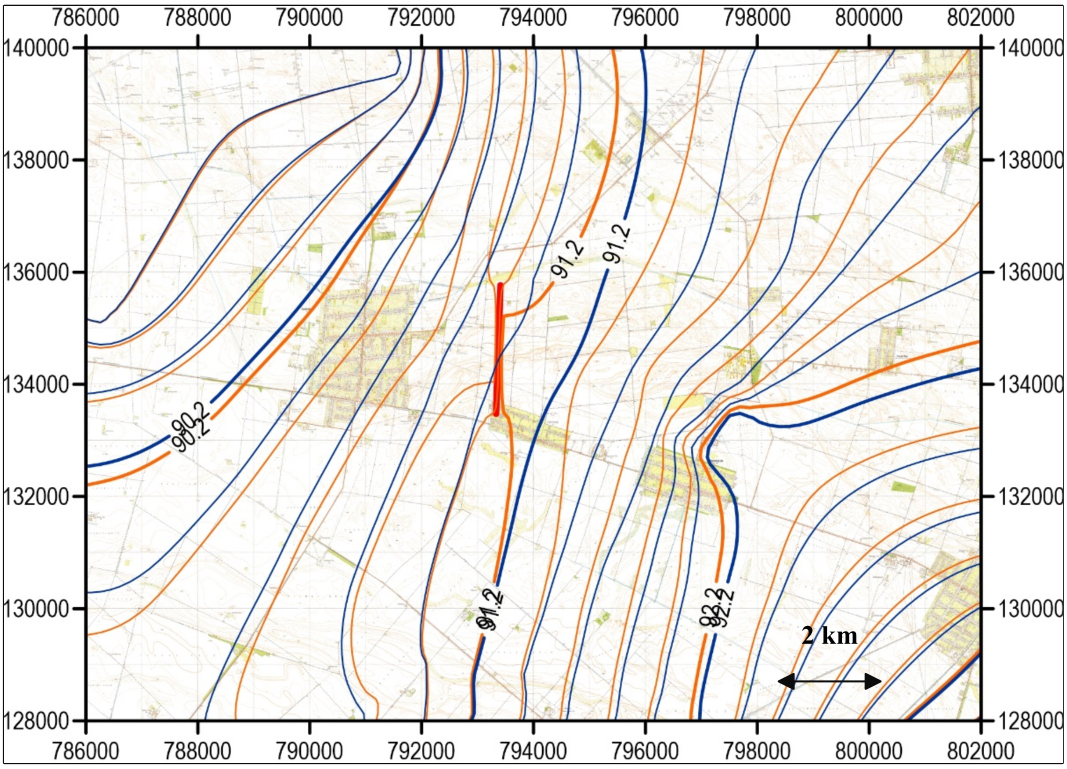

Figure 31. Water levels (m a.s.l.) in the initial state (blue isolines) and in the altered state due to the effect of the dam (red isolines) in the second aquifer.

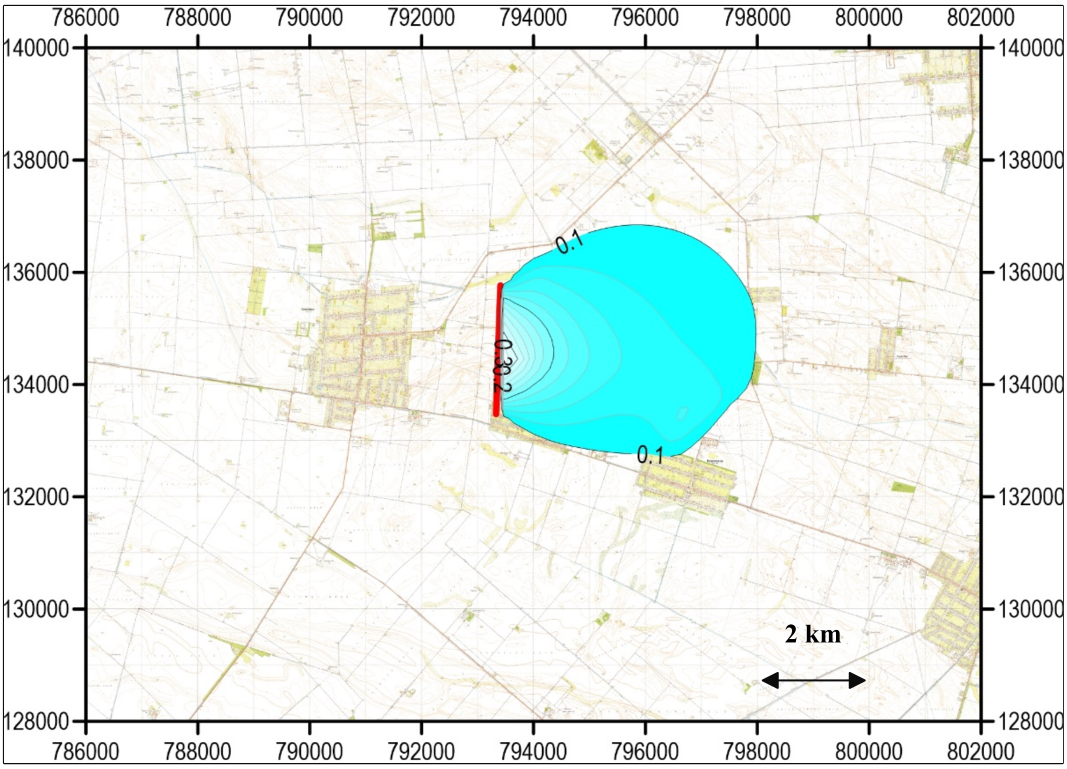

Figure 32. Groundwater level rise (m) in the second aquifer due to the effect of the underground dam

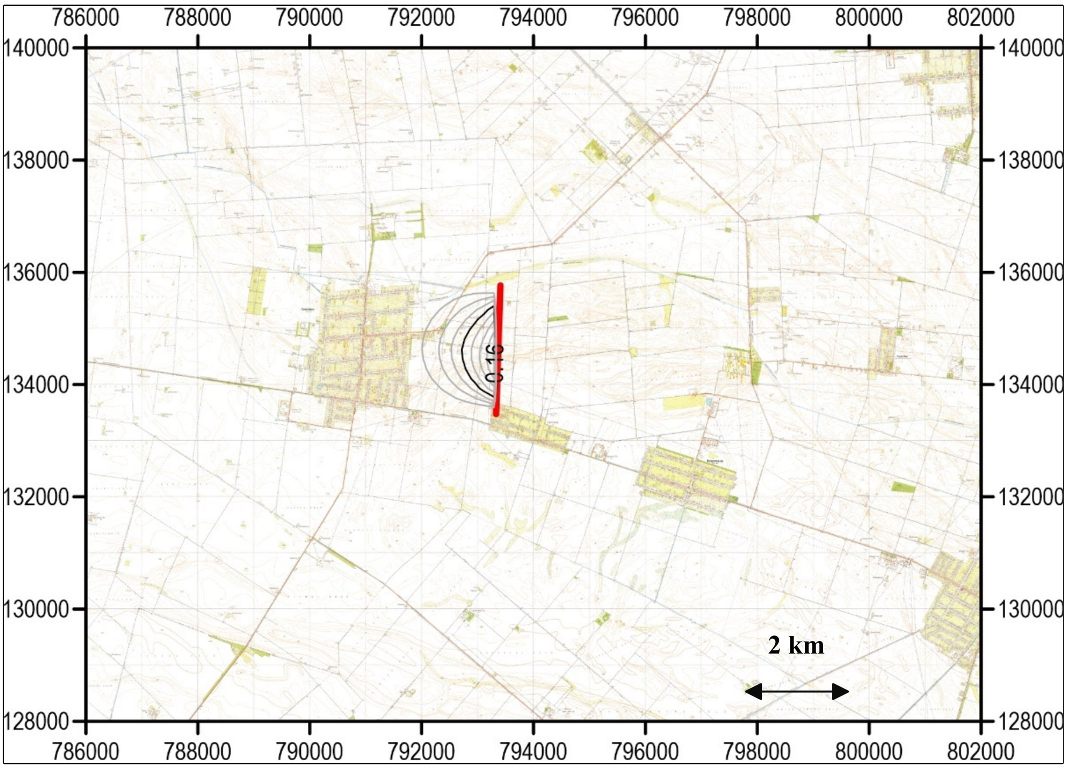

Figure 33. Groundwater level fall (m) in the second aquifer due to the effect of the underground dam

4.4.2.1.3. Modelling the climatic effects

In the modelling, we also investigated the changes that occur when the infiltration effect is reduced. So, the effect of infiltration affects mainly the first aquifer, we only modelled the case when the underground dam is located in the first aquifer.

In the modelling, the infiltration rate was reduced by 10, 25 and 50 %, respectively, to illustrate the reduction in recharge. The results of the tests were as follows (Table 4).

Table 4. Results of the model tests

Model version	Net volume (m^3)	Water vol. (m^3) (n_{eff}=0.2)	Water levels (m)
Underground dam in the first aquifer	4 470 824	894 164	-0.6/+0.3
Underground dam in the second aquifer	7 850 599	1 570 119	-0.35/+0.35
Infiltration rate reduced by 10%	3 511 486	702 297	-0.5/+0.35
Infiltration rate reduced by 25%	3 232 610	646 522	-0.4/+0.22
Infiltration rate reduced by 50%	2 708 871	541 774	-0.28/+0.22

5. Risk management

In the context of risk management, harm can describe an injury or damage to human health, as well as damage to property or the environment. Hazard is the potential source of harm, which can e.g. be a biological, chemical, physical or radioactive agent, and a hazardous event is an event that can cause harm. The combination of probabilities for the identified hazard to occur in a specific time frame and the magnitude of its harm is termed risk (ISO/IEC International Organization for Standardization; International Electrotechnical Commission, 2014; NRMMC-EPHC-AHMC, 2006).

After establishing the scope and context of the evaluation, risk assessment is carried out followed by risk treatment. The risk assessment procedure consists of three steps, i.e. risk identification, risk analysis and risk evaluation. Risk identification is conducted in order to identify and describe hazards that might prevent the achievement of an aim. Factors such as tangible and intangible risks, threats and opportunities as well as consequences and their impact on the aims should be taken into account. Risk analysis describes the likelihood of a hazard or hazardous event by taking into consideration the consequences and sensitivities of these consequences. Risk evaluation intends to identify risks for which actions have to be undertaken such as further analysis, maintenance of existing control structures or risk treatment options (ISO/IEC International Organization for Standardization; International Electrotechnical Commission, 2014; ISO International Organization for Standardization, 2018).

Risk assessment is a step of risk management. Findings of the risk assessment are subsequently used to derive proactive measures in order to handle or reduce risks (risk treatment) within the scope of risk management schemes (EC, 2015; UNISDR, 2009). Risk treatment measures aim to reduce present risks to an acceptable level. Risk treatment options for MAR can comprise pre- and post-treatment of recharge water, adaption of the MAR system design in order to deliver the required functions, the selection of sites that are better suited, an adequate maintenance and operation of the infrastructure or the development of suitable responses to unplanned incidents (NRMMC-EPHC-AHMC, 2006; Pedretti et al., 2012a, 2011).

Several methodologies are frequently applied for MAR-related risk assessment. In the following chapters we describe the methodology we used during the risk assessment process by highlighting the development procedure of the methodology prepared for the target MAR system of the Maros alluvial fan, Southeast Hungary. The results are also summarized in the report D.T3.3.3. (2021).

5.1. The selected risk assessment method

In the process of elaborating the method of risk assessment, multiple different methods were checked resulting finally one composite method for the task. We used a qualitative risk assessment method (which is ideal to be tailored for specific MAR-related hazards, but as a drawback requires detailed input data) together with the possible hazards of an already conducted risk assessment of a MAR system.

As a frame of our risk identification, the structure — so the risk events — of the so-called MAR-RISKAPP Microsoft Excel macro were used. This work is the product of Rodríguez-Escales et al. (2018) which compiles the events of a literature review of 51 MAR facilities. Based on this work, slightly modifying the list for the underground dam MAR type, 82 MAR-system-characteristic possible risks of environmental and human health, technical, social and legislative viewpoints have been differentiated in four phases: non-technical risks during design phase, technical risks during design phase, non-technical risks during the MAR operation and technical risks during operation. There are certain risks, which appear in 2 temporal phases, and it means that even though they are the same risk, they have to be interpreted slightly differently. For example, the risk 'low price of water' — which could imply that a MAR would not be beneficial on a cost-benefit analysis due to the too low prices of other water sources — appears on both design and operation sheets, and they have different likelihood-severity values. The risk 'Low price of water' in design phase must be interpreted in a way that the exact price of water cannot be calculated for the future (so for the whole multiple-decades-life of the MAR) with high precision, though certain financial implications must be considered at that stage as well. But when talking about the 'low price of water' risk in operation phase, at that time a CBA has already been calculated, the financial resources have already been spent for the construction of the MAR, and this way an incidental water price drop will not have that much negative effect on the already built and operating MAR system. Another case could be risk of inadequate water quality, appearing both in design and operation phase. As an example, the risk of elevated metal content in design phase is low, because based on our current knowledge, there are no sources of metal contaminants which would be needed to take into consideration in the time of design. On the other hand, the risk of metal contamination in operation phase must be interpreted more strictly, as the operation would be of decades of lifetime, during which possible contaminant sources could also appear (e.g. new industrial areas). So summed up, every risk event is interpreted independently in the time phase in which they appear, but when appearing in different ones, they have to be interpreted (analysed and evaluated) accordingly. So, regarding risk identification, to best fit the underground dam MAR type, the risks of the MARSOL RIASKAPP application (Rodríguez-Escales et al., 2018) were used, but if needed their names and descriptions have been slightly modified (e.g. instead of water-percolating ditches in the case of an underground dam there are water-distributing ditches).

To assess the possibilities of the defined risks, a qualitative risk assessment method specific for MAR systems was used, which is based on the suggestions of Australian guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009). In this method the likelihood and the severity of a risk is examined and their joint interpretation — based on a risk factor matrix (Figure 34) — shows the total magnitude of a risk. The likelihood of a hazard to occur is identified by the expected recurrence of the hazard (indicated in units of years), and this likelihood is expressed by using a five-step scale. A hazard recurrence interval of 100 years is defined as 'rare' (lowest scale) and a recurrence of several times per year is defined as 'almost certain' (highest scale) (Figure 1). It must be mentioned that this exact timely ranking could not be used in every case. For example, the likelihood of a risk of 'high installation cost' or the risk of 'insufficient technical knowledge' simply cannot be interpreted to happen once in 100 years or several times a year. They might happen or not, with a suspected probability based on the current state of economy, public opinion, number of supporters, etc. Therefore, the likelihood of a risk was more likely interpreted as the predicted possibility of the risk. The severity of the hazard is thereafter assessed with a further five-step scale taking into account the measures of consequences it could cause. According to this scale, a 'catastrophic impact' (highest scale) has to be expected e.g. if human health of a large population is threatened by the hazard, the integrity of regional ecosystems or the life of plant/animal species are endangered. The lowest scale defines an insignificant (or even non-detectable) impact. If both the likelihood and the severity of the hazard are ranked high, the resulting risk is identified to be very high.

Together with every hazard possibility, one or more examples for possible risk treatment methods are suggested. Nevertheless, when the highest risk values become visible, special attention must be paid to elaborate a detailed risk prevention, mitigation and in the case the hazard might take place, a treatment method.

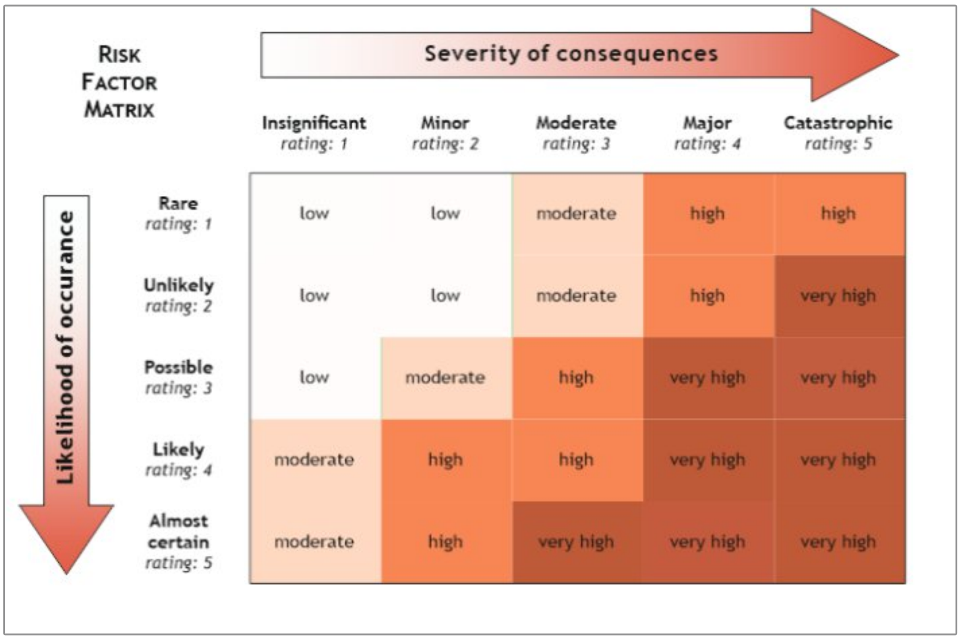

Figure 34. Risk factor score matrix for qualitative risk assessment, relating the likelihood of hazards to the severity of consequences (after Swierz et al. 2005)

In the next pages those assessed risks are listed — together with the likelihood of their occurrence, severity of consequences, risk ratings and some proposed risk treatment methods — which proven to be of moderate, high or very high risk (Table 1-2-3-4). (The whole set of risks with 'low risk' and 'no risk' values are to be found in D.T3.3.3, DEEPWATER-CE 2021d.) Two tables list the possible risks during design phase (non-technical and technical ones), and two tables list the possible risks during operation phase (non-technical and technical ones). Categorization is done by the nature of causes of the possible risks. Values of likelihood and severity range from 1 to 5, five being the most likely/severe. Risk rating is done by the risk factor score matrix of Swierz et al. (2015) (Figure 34).

Table 5. Non-technical risks during design and construction phases

RISKS DURING DESIGN AND CONSTRUCTION OF A MAR FACILITY					
NON-TECHNICAL CONSTRAINTS	**Constraint description**	**Likelihood**	**Severity of consequences**	**Risk rating**	**Suggested risk treatment**
Governance risk					
Lack of coordination	Difficulties in finding the most appropriate and well-qualified owner for the MAR system. Mismanagement of MAR facility by its owners.	3	3	High	Assigning a well-trained management responsible for the supervision of the MAR operation.
Commitment of stakeholders	Joint interest and commitment for a joint MAR project	3	3	High	Information sharing and promotion of MAR systems. Spreading information about the benefits (financial, popularizing effect, etc.) of supporting/operating a MAR system among market investors.
Economic risks					
Macroeconomic constraints	Global factors that can affect entire economies of countries, e.g. the variation in interest rates, inflation rates, and unemployment rates, along with periods of rapid growth or decline. These factors may make MAR unprofitable or significantly increase investment costs.	2	3	Moderate	Elaborating a comprehensive cost-benefit analysis which takes into consideration the most details possible.
Not enough water to recharge due to agricultural use	Not sufficient quantity of water to withdraw at the MAR edifice due to the elevated amount of other water withdrawal facilities (wells, other MAR systems, etc) from the pathway of the groundwater flow for agricultural purposes.	1	3	Moderate	Proper regional regulation of the groundwater use.
Low price of water	The low price of accessible water from other sources makes the proposed MAR facility potentially unviable.	4	3	Very High	Targeted support for the use of MAR facilities in order to promote its financial viability.
High installation cost	High cost of construction related to material prices, workmanship and services.	5	4	Very High	Governmental support, tenders for the design of MAR facilities. Correctly selecting the appropriate size, capacity of MAR system. If the MAR is big enough to be reached by more users/investors, the specific price might be lower. If the MAR system is smaller in capacity, the effective construction costs will be lower.
High maintenance cost / maintenance requirements	Increase in maintenance requirements of MAR facility resulting in increased costs	2	3	Moderate	Allocated separate (full or partial) budget for future maintenance costs which will be included in the effective price of the whole project.
Lack of private /public funding	Underestimation of the project costs, lack of funds at a certain stage of the planned facility implementation.	4	4	Very High	Information sharing and promotion of MAR systems to be able to involve as many investors (private or governmental) as possible.
Social risks (unacceptance)					
Behavioural requirements	Fear that MAR will affect people's daily lives (e.g. longer road to work due to existence of new infiltration ditches, prohibitions and restrictions near MAR site).	3	3	High	Information sharing and promotion of MAR systems to ensure the local population that the edifice of the underground dam is almost completely out of sight and will not bother the daily lives of people after the initial constructions.
Fair distribution of treated water	The possibility that farmers who are closer to water withdrawal points would be gaining more water that the ones further from them.	3	2	Moderate	Appropriate water governance plan, the application of water distributing ditches which run through the lands of multiple owners instead of point-like wells.
Perception of effectiveness by society	Public understanding and awareness of the benefits of MAR solutions.	3	2	Moderate	Information sharing and promotion of MAR systems emphasising the environmental benefits (almost zero evaporation, quasi constant and more predictable recharge, etc.) and water storing possibilities.

Table 6. Non-technical risks during operation phase

RISKS DURING OPERATIONAL PHASE OF MAR					
NON-TECHNICAL CONSTRAINTS	**Constraint description**	**Likelihood**	**Severity of consequences**	**Risk rating**	**Suggested risk treatment**
Legislation risk					
Health legislation	Amendments to regulations related to water intended for human consumption.	3	2	Moderate	
Economic risks					
Not enough water to recharge due to agricultural use	Not sufficient quantity of water to withdraw at the MAR edifice due to the elevated amount of other water withdrawal facilities (wells, other MAR systems, etc) from the pathway of the groundwater flow for agricultural purposes. This phenomenon might bear the possibility of losing the effective working of the whole MAR system.	1	3	Moderate	Proper regional regulation of the groundwater use.
Low price of water	The low price of accessible water from other sources makes the proposed MAR facility potentially unviable. Though this risk will be lower in the operation phase (since by this time the MAR system has already been completed, so the high construction costs have already been spent) but still has to be considered as a high risk as it might menace the effectiveness of the MAR system.	3	3	High	Targeted support for the use of MAR facilities in order to promote its financial viability.
High maintenance cost/maintenance requirements	Increase in maintenance requirements of MAR facility resulting in increased costs	2	3	Moderate	
Social risks (unacceptance)					
Behavioural requirements	Fear that MAR will affect people's daily lives (e.g. longer road to work, due to existence of new infiltration ditches, prohibitions and restrictions near MAR site).	2	3	Moderate	Information sharing and promotion of MAR systems to ensure the local population that the edifice of the underground dam is almost completely out of sight and will not bother the daily lives of people during operation.
Fair distribution of treated water	The possibility that farmers who are closer to water withdrawal points would be gaining more water that the ones further from them.	3	2	Moderate	Appropriate water governance plan, the application of water-distributing ditches which run through the lands of multiple owners instead of point-like wells.

Table 7. Technical risks during design and construction phases

RISKS DURING DESIGN AND CONSTRUCTION OF A MAR FACILITY					
TECHNICAL CONSTRAINTS	Constraint description	Likelihood	Severity of consequences	Risk rating	Suggested risk treatment
Technological constraint					
Construction difficulties	Special requirement of construction due to unusual size or big depth of the building structures.	3	3	High	Detailed site characterization and hydraulic modelling.
Water scarcity risks					
Droughts and rainfall event periodicity (Influence of climate change on water supply)	Not sufficient water available to meet water demand due to periodic droughts/rainfall event.	3	2	Moderate	Designing a robust, regional system with buffer capacities for surplus water. Using alternative water sources.
Changes in water demand and supply	Increased demand and overuses deplete the system or production with higher capacity cannot fulfil requirements.	3	2	Moderate	Designing the system for more capacity than current needs with considering alternative utilizations.
Right of access to water from the national water authorities.	Preparation of a water permit for water use which is accepted by the national water authorities.	2	3	Moderate	Joint work with the national water authorities in order to facilitate the elaboration of water use permits.
Hydraulic and hydrogeological assessment of risks					
Risk of clogging	Presence of at least one type of clogging (physical, chemical, biological) in any part of the MAR system (pipelines, valves, filters, water-transporting ditches, etc.) which reduces the effectiveness of the MAR or leads to the need for renovation work at the MAR facility.	2	3	Moderate	Designing a monitoring system that allows the inspection of the MAR system so that clogging could be detected in time.
Risk of low water storage	Unfavourable aquifer parameters for water storage (e.g. low thickness or extension of aquifer, low values of effective porosity, water storativity etc.)	3	4	Very high	Detailed site characterization (desktop study and field measurements), hydraulic tests and modelling.
Risk of low recharge rate	Unfavourable conditions for infiltration (e.g. low permeability of soils and subsurface sediments, steep slopes, land use and vegetation etc.)	3	3	High	
Hydrogeological setting (hydraulic communication between shallow MAR aquifer and deeper drinking water aquifer)	Determining whether the proposed MAR facility has the significant potential to impact on adjacent groundwater abstraction sites, modify flow directions, water table depths, etc. in terms of regional hydrogeology.	3	3	High	
Lack of infrastructures risks					
Lack of potential available land (lack of approval from landowners to incorporate their lands in the MAR system)	Lack of infrastructure is understood as making the designed MAR investment more expensive due to the problem of land availability or high land purchase or lease prices, lack of technical facilities/solutions to provide water of adequate quantity and quality to the MAR.	3	2	Moderate	Making landowners interested in the application of the MAR system with reduced water prices or other benefits so that their lands could be incorporated within the MAR facility.

Table 8. Technical risks during operation phase

RISKS DURING OPERATIONAL PHASE OF MAR					
TECHNICAL CONSTRAINTS	**Constraint description**	**Likelihood**	**Severity of consequences**	**Risk rating**	**Suggested risk treatment**
Structural damages due to environmental events or human activity (civil work failures)					
Groundwater flooding	Flooding of basements, below-ground cables	2	3	Moderate	Built-in groundwater regulation system and draining ditches (which would also act as water-distributing channels).
Swelling clays	Structural damages occurring to the MAR facility due to the effect of elevated groundwater level on the lifting ability of swelling clays.	3	3	High	Detailed geological and rock mechanic studies prior to planning and construction.
Instrument breakage	Breakdown of any instrument (water-collecting pipe, valves, etc.) in the MAR system may cause the MAR to stop operating.	2	3	Moderate	Installing pressure sensors at certain intervals in the underground pipeline network to get informed in time about failures and to reach damaged parts as soon as possible. Security valves to install for closing damaged parts. Pipelines to run above surface if possible.
Risks of decreased amount of water supplies due to inadequate water quality					
Sanitary/biological restrictions (e.g. due the pathogens)	Recharge water /Water entering the MAR system is contaminated with pathogens or other toxic substances of biological or sanitary origin leading to concentrations in the water exceeding of national and WHO standards.	1	3	Moderate	Monitoring the presence of biological contaminants in the MAR system with regular water sampling procedures and in case their amount exceeds the values specified by regulations for irrigation water, the MAR operation can be paused for the time of remediation.
Metals (e.g. arsenic, manganese)	MAR's recharge water contains too high concentrations of substances which, despite its purification potential, it is unable to reduce to a level consistent with drinking water standards. Contamination may originate from agricultural production, industry (e.g. nutrients, organic pollution, pesticides, metals etc.) or its sources may be geogenic (e.g. aquifer dissolution, changes in chemical composition due to water table fluctuation, redox conditions etc.)	3	3	High	Monitoring the presence of metals, salts, nutrients, organic chemicals and radionuclides in the MAR system with regular water sampling procedures and in case their amount exceeds the values specified by regulations for irrigation water, the MAR operation can be paused for the time of remediation.
Nutrients (nitrogen, phosphorous)		3	3	High	
Organic chemicals (pollutants, EOCs)		2	3	Moderate	
Water scarcity risks					
Droughts and rainfall event periodicity	Not sufficient water available to meet water demand due to periodic droughts/rainfall event.	3	3	High	Proper usage of the underground valves to retain the necessary amount of water. Striving to leave a buffer water quantity in the system by not using up all the reserves.
Changes in water demand and supply	Increased demand and overuses deplete the system or production with higher capacity cannot fulfil requirements.	3	3	High	Designing the system for more capacity than current needs with considering alternative utilizations
Risks connected to unacceptable quality of water at sensitive location					
Nutrients (as the result of inefficient natural attenuation)	Risks associated with insufficient potential of the MAR system to natural attenuation of nutrients.	3	2	Moderate	Monitoring the presence of organic matter, excess nutrients, N-compounds and metals in the MAR system with regular water sampling, and in case their amount exceeds an amount which is harmful for the MAR system, the MAR operation can be paused for the time of remediation.
Nitrogen cycle (NO_2^-, N_2O... as a product of metabolite generation)	Risks associated with insufficient potential of the MAR system to reducing products of nitrogen cycle compounds.	3	2	Moderate	
Specific targets risks					
Risks of the effects on protected drinking water reserves or on their protective blocks.	Any risk associated with the MAR operation's effect on protected drinking water reserves or their protective blocks.	3	3	High	Thorough hydrogeological modelling to minimize the effect of the MAR system on the neighbouring protected drinking water reserves and their regular monitoring (also on their protective blocks).

Water level - groundwater	Risk of any MAR operations leading to negative changes in the position of the groundwater table causing e.g. the local flooding.	2	4	High	Regular monitoring. Built-in groundwater regulation system and water-distributing ditches.

To decrease the possibility and severity of any harm which might cause injury or damage to human health, or damage to property or the environment, a risk management plan has been elaborated for the system of underground dam MAR type.

Our risk analysis methodology is based on suggestions in the Australian guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009), where the likelihood and the severity of a risk is examined and their joint interpretation — based on a risk factor matrix — shows the total magnitude of a risk. Into this system we incorporated the list of risk events of the MAR-specific study of Rodríguez-Escales et al. (2018) which compiles the risk events of literature reviews of 51 MAR facilities. This list was slightly further modified to better fit the underground dam MAR type, resulting a risk identification list of 82 different possible risk events. Risk analysis was carried out in 2 temporal phases, separately for the design and construction, and separately for the time of operation phase of the MAR facility. From the list of possible risks, 46 events are assessed as of low risk, 21 as of moderate risk, 14 as of high risk and 4 as very high risk. 26 events were not applicable for the underground dam MAR system of the target area, therefore they are of 'no risk', nevertheless, they were kept visible, to show all investigated risks. All risk events sum up to 111 which is clearly more than the 82 different possible risk events. This is because certain risks were taken into account both in design and operation phases. In such cases their analysis had to be carried out differently, according to the selected phase they were interpreted in.

Very high risk category was assigned mainly to non-technical (economic) risks in design phase: low price of water, high installation costs and lack of private/public funding. One technical event of very high risk was determined to be the risk of low water storage. High-risk events in design phase could be the lack of coordination, the lack of commitment of stakeholders, fear of behavioural changes of the local society, construction difficulties, risk of low recharge rates, or an improper hydrogeological setting. In operation phase high-risk events are low price of water, the effect of swelling clays, decreased amounts of usable water due to high levels of metal content or nutrients, drought-rainfall periodicity change. Furthermore, significant changes in current water demand and supply, any effect on protected drinking water bases, and the risk of negative changes in the position of the groundwater table due to the MAR operation. As a summary, the design phase of the MAR system is most affected by non-technical risk events, while operation is rather depending on the successful preparation for technical issues.

5.2. Risk treatment

To decrease the possibility of a risk event, some risk treatment methods are suggested for all 111 risks. The ones which would mitigate the possibility of occurrence of very high- and high-risk events are:

- adequate support: Tenders and governmental support may be needed to arouse interest in the investment of MAR applications, to decrease the load on investors, so to open the market for market participant. Targeted support for the use of MAR applications could also promote its usage by keeping its price lower than other sources of water.
- suitable information sharing and education: Raising attention for the traits of MAR systems on social media, video channels, conferences, expos, etc. would expand the knowledge of people and might create a need for a wider usage. Once people know about the benefits, public need could be formed for MAR applications, so decision makers might stand behind the support of MAR facilities. It would increase the number of possible investors and would decrease the risk of

insufficient funding. Letting people know about the MAR methods would also bring them closer to it by dispersing their fear of the unknown.

- thorough preliminary research: By conducting a detailed and precise feasibility study of the area, risks stemming from an inappropriate hydrogeological setting can be decreased (insufficient volume for water storage, presence of swelling clays, connection between different aquifers, etc.). Thorough preparation also means the high-level qualification and right assignation of staff members responsible for the operation of the MAR facility, in order to minimalize the risks due to lack of coordination, insufficient competence and any human failures.
- appropriate monitoring: The importance of monitoring is outstanding in the operation phase. With its appropriate implementation physical and chemical parameters can be observed in real time. In case of any problematic event, it will be instantly detected, and countermeasures can be applied.

It must be mentioned that the risk treatment methods are just a few mentions out of all possible ideas and such as every other aspect of the risk management it also must be tailored specifically to each MAR system. The present document is a checklist for risk management protocol, specific for the MAR scheme of an underground dam in the case of the Maros alluvial fan, Hungary. Therefore, it can be used as a guideline, but the aspects of the target applied MAR system must always be kept in sight.

Among the risk treatment methods of such a subsurface installation as the facility of an underground dam, the role of monitoring must be emphasised. Since nearly all the volume of the facility is found underground, a thoroughly elaborated monitoring plan is the most effective tool of getting information on the subsurface conditions, which enables the operator of the facility to act in case of any unplanned activity, hazardous event.

Risk monitoring activities implement the risk monitoring strategy by gathering information through automated or manual means, alerting or reporting on information relevant to intended purposes for risk monitoring, and providing inputs to ongoing risk assessment and response processes. Depending on risk assumptions, constraints, priorities, and tolerance levels, the set of risk monitoring practices actually implemented at any time may differ from what is documented in the risk monitoring strategy (Gantz et al., 2013). Risk monitoring activities at the various levels of an organization should be coordinated and communicated. This can include sharing risk assessment results that would have an organization-wide impact to risk responses being planned or implemented. The organization should also consider the tools and technologies that will be needed to facilitate monitoring and the frequency necessary for effectively monitoring risks, including the changes that would impact responses to risks (Metheny, 2017).

The proper monitoring of the different objects and processes after the development of a MAR system is crucial during the operation as it is crucial in any kind of intervention to the subsurface and groundwater. By applying monitoring programs, the effectiveness of the risk management system and preventive measures can be ensured (NRMMC-EPHC-AHMC, 2006).

A detailed plan of the monitoring activity is required. The monitoring program is site specific and must contain the monitored environmental element, the frequency of the sampling or measurements, the applied methods. The aim of the monitoring and therefore the activity will be differentiated before, during and after the construction and at the start of the operation. The final utilization purpose (drinking water or irrigation water) of the supplied water must be considered in the monitoring plan. To implement a proper monitoring plan, the granting authority has to be involved as well since they will give the permits and the criteria of the operation.

There is no specific regulation for MAR systems in Hungary, but there are some general regulations about groundwater protection, groundwater management and monitoring activity: Government Regulation 123/1997. (VII.18.) on the protection of vulnerable water supplies concerns their protection measures and the criteria of water protection zones. The Act LVII of 1995 on water management regulates the recharge of aquifers by artificial recharge and reinjection. Accordingly, water users do not have to pay water supply contribution after the amount of water they recharge if artificial recharge is done into the original aquifer from which water was withdrawn. The Government Regulation 219/2004. (VII.21.) on protection of groundwater regulates the artificial recharge and reinjection in order to preserve the quality and quantity of the underground water resources. This regulation also sets out conditions and makes it subject to official water protection authorization. The 30/2004. (XII. 30.) KvVM Decree on rules of monitoring of groundwater regulates the monitoring of quality and quantity status of groundwater bodies. The 201/2001. (X.25.) Government Regulation has a focus on quality requirements of drinking water and regulates respective monitoring. Authorities can determine further monitoring requirements in their permissions.

In the following table (Table 9) monitoring propositions are made only for the relevant 'operational technical' risks. If a MAR system will be built the monitoring activities have to be determined exactly before the start of the operation and the granting authority must be involved.

Table 9. Suggested methods for monitoring activities

5.3. Sensitivity of MAR to climate-induced extreme situations

To assess the sensitivity of the underground dam MAR system sets of selection criteria were collected to extreme situation cases and site-specific cause-effect chain was identified This cause-effect chain evaluation process originates from stimuli (climate extreme events) which induce hazardous events (as the result of natural hazards combined with/superimposed by adverse anthropogenic impacts, and influenced by the local surface and hydrogeological environment). The hazardous events might cause specific negative effects on MAR schemes described in form of cautions to MAR systems as end results of the sensitivity analysis according to the methodology, D.T2.4.3 of DEEPWATER-CE project (DEEPWATER-CE, 2020a). The listed cautions provide suggestions which might be taken into account during MAR schemes implementation. The cautions for both climatic extremes (wet and dry periods) relate to risks of structural damage of MAR infrastructure, water quality and water quantity problems. This MAR specific checklist comprise the relevant criteria which should be taken into consideration in evaluation of sequential and combined effects induced by extreme climatic events on underground dam MAR system, with an ultimate purpose to identify the potential risks posed to them (Table 10). As a summary of the risk analysis DT3.3.3 of DEEPWATER-CE project (DEEPWATER-CE 2021d.), the design phase of the MAR system is most affected by non-technical risk events, while operation is rather depending on the successful preparation for technical issues.

Table 10. Checklist on sensitivity analysis of MAR located in Maros alluvial fan pilot site to extreme climate events

				Dry period	Wet period
UNDERGROUND DAM	Trigger/Stimulus	Climate Extremes		Extremely low amount of precipitation Extremely high temperature/evapotranspiration	Long period of extremely high amount of precipitation
	Hazardous Events	Natural Hazards	Hazard groups	Groundwater drought	"Groundwater flooding"
			Hazard type	Groundwater table depression	Inland excess water Extremely high groundwater table
		Anthropogenic Impacts		Land use (urban/industrial/agricultural) Overexploitation for various uses (e.g. changes in groundwater dynamic) Point pollution (e.g. waste landfills; fuel deposits; waste water treatment plants, agricultural origin, pollution by untreated urban waters, etc.) Mining activity (intensive drainage of surface water and groundwater; pollution leaching, or increasing evaporation from mining lakes resulting further groundwater table decreasing)	Land use (urban/industrial/agricultural) Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric air pollution; etc.) Point pollution (e.g. waste landfills; fuel deposits; waste water treatment plants, agricultural origin, pollution by untreated urban waters, etc.) Mining activity (intensive drainage of groundwater; pollution leaching)

		Surface & Hydrogeological Environment	▪ Soil hydraulic properties (if it is more permeable, the transpiration is quicker and it can influence groundwater recharging) ▪ Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) ▪ Position in the groundwater flow system (in lateral viewpoint - recharge, transitional or discharge area; in vertical viewpoint - order of aquifer in vertical position, its depth and thickness) ▪ Groundwater quality (e.g. high dissolved mineral content, changes in groundwater chemistry)	▪ Soil hydraulic properties (if it is impermeable, the flood is quicker (no possibility for water infiltration in a big area) and therefore more dangerous for infrastructure) ▪ Aquifer type (unconfined, confined, porous, fractured, karst, etc.) ▪ Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) ▪ Position in the groundwater flow system (in lateral viewpoint - recharge, transitional or discharge area; in vertical viewpoint - order of aquifer in vertical position, its depth and thickness)
	Final Impact	Effect on MAR	▪ Wells yield reduction or dry out of abstraction wells due to groundwater table depression ▪ Clogging (by fine particles) or geochemical processes (e.g. evaporation, scaling/calcification) ▪ Intrusion of polluted groundwater or sea water or salt water	▪ Overflowing groundwater ▪ Infiltration of contaminants (biological/chemical/physical) from surface water or artificial channels ▪ Intrusion of polluted groundwater ▪ Mobilization or dissolution of contaminants (biological/chemical/physical)
	MAR sensitivity	Cautions	▪ **Temporary interruption in the operation of the MAR system** (Clogging or geochemical processes; Intrusion of polluted groundwater) ▪ **Water quantity problems** (Clogging or geochemical processes; Wells yield reduction or dry out of wells due to groundwater table depression) ▪ **Water quality problems** (Intrusion of polluted groundwater)	▪ **Temporary interruption in the operation of the MAR system** (Infiltration of contaminants from surface water; Overflowing groundwater; Intrusion of polluted groundwater) ▪ **Structural damage in MAR infrastructure** (Overflowing groundwater) ▪ **Water quality problems** (Infiltration of contaminants from surface water; Mobilization or dissolution of contaminants; Intrusion of polluted groundwater)

6. Economic feasibility (CBA)

Water demand is growing globally, and among economic sectors, agricultural production (especially crop production) is one of the sectors predominantly depending on the accessibility and quality of water. This challenge is overstated by the changing climatic conditions that influence recognizably crop production and lead to increased demand for irrigation water. Thus, water projects gain lots of attention, aiming to address these challenges and guarantee the protection of scarce water resources. Other than hydrogeological considerations and assessment of institutional feasibility, these projects require an economic appraisal, which in most cases points to check whether the net benefit of the project's implementation is positive. To meet this objective economic, efficiency analysis is applied, and more specifically in this report cost-benefit analysis (CBA).

Among promising water management solutions, Managed Aquifer Recharge (MAR) systems have received noticeable attention as they can be used to maintain, enhance, and secure the balance of groundwater systems under stress. Among many benefits that MAR schemes can potentially provide, the major ones include increased water supply (in our study irrigation water) and improved water quality through natural aquifer treatment processes. Despite all advantages that MAR schemes can provide, it is still important to perform an economic evaluation to ascertain that the benefits of the MAR scheme can justify anticipated costs. In this report, we outline the methodology and results of the CBA study for the Hungarian pilot site. This study aims to investigate whether the introduction of an underground dam MAR solution in the pilot area is economically feasible and whether the total economic value of the MAR scheme's extension (which includes both use and non-use benefits of it) meets or exceed the costs of putting this system in place and maintaining it.

Accounting for uncertainty is an integral part of CBA studies. In order to incorporate it in our analysis, we develop scenarios with plausible variations of the main CBA parameters and check how sensible the net present value (NPV) of the MAR scheme is to them. An important section of this report is the assessment of two dimensions of socio-economic risks associated with the MAR scheme: their probability and magnitude of consequences. Based on the conducted analysis we provide policy recommendations for the implementation of the MAR scheme in the Hungarian pilot site from a socio-economic perspective.

It is essential to mention that since today there are no operating underground dams in Hungary, estimates of costs are quite rough with a wide range of possible values. Also, survey results suggest that a noticeable share of individual farmers currently don't normally irrigate crops, thereby direct benefits were estimated under a number of assumptions using very limited data. Thus, obtained CBA results should be treated as more indicative and with a portion of cautiousness.

6.1. Materials and methods

6.1.1. Cost analysis

There are no operating underground dams in Hungary to date. So costs associated with the construction and operation of this MAR scheme are estimates with a quite wide range of possible values. Initial investment costs include investigation costs (among others data collection, hydrogeological modelling, water sampling and analysis, environmental impact assessment), construction and testing costs.

Investigation costs and regulatory and operational testing costs are expected to be realized during the first year, while construction costs along with pre-operational testing costs are planned for the second year.

The expected range of cost values for the main groups of annual operation and maintenance costs (costs of irrigation water distribution, labour costs, amortization and testing costs) are presented in Table 11. (Calculations are based on data provided by DELTA - Dél-Alföldi Talentum Akadémia / DELTA - Southern Great Plain Talent Academy Nonprofit Ltd., Geogold Kárpátia Ltd., LAWAND Ltd., INTERGEO Budapest Ltd.).

Table 11. Costs associated with MAR scheme

Cost group	Units of measurement	Value (range:min-max)
Initial investment-Capital costs		
Investigation costs[1]	mil HUF	35.00-150.00
Construction costs[2]		2 655.00-6 330.00
Pre-operational testing costs[3]		132.75-316.50
Regulatory and operational testing[4]		132.75-316.50
Annual operation and maintenance costs		
Cost of distribution	HUF/m^3	184.00-264.00
Labor costs	mil HUF	30.00-36.60
Amortization costs[5]		33.19-79.13
Regulatory testing costs		0.15-0.25

The cost estimates presented in Table 11 are obtained for the following MAR system design: over of 6 to 10 km long paleo-riverbed section that includes a slurry wall (10 to 20 m deep and 200 to 2000 m long) and several surface and drainage structures allowing regulation and passive abstraction of groundwater.

Minimum values are estimated for the system for the following parameters: a wall of 10 m deep, 200 m long, and a MAR unit of approximately 6 km long, while for the maximum values system's parameters are the following: 2 km long underground dam wall which is 20 m deep on average and a 10 km long MAR storage unit.

6.1.2. Benefit analysis

The main beneficiaries of the MAR scheme under consideration are agricultural producers in the pilot study area. The proposed MAR scheme is expected to provide a source of water that can be legally used to fulfil the need for irrigation water. Moreover, the introduction of the MAR system is envisaged to mitigate the negative effects of unregistered wells that may lead to the contamination of water in the pilot study area.

The pilot study area in Hungary consists of two settlements: Csanádapáca and Medgyesbodzás. The main crops produced there are cereals (corn, wheat, barley) and oilseed crops (sunflower, rape) (Figure 35).

[1] Archive data collection and data purchase; geophysical investigations; CPT probing; well test studies; drilling with sediment and water sampling and analysis; 3D hydrogeological modelling; geodesy; environmental impact study; permits

[2] Calculated with 6 to 10 km underground water storage with 10 to 20 m deep and 200 to 2000 m long slurry wall. Surface structures, drain pipe(s) and the cost of monitoring wells are also taken into account.

[3] Estimated as 5 % of the total construction costs.

[4] Estimated as 5 % of the total construction costs.

[5] Calculated with assumption about average lifespan of 80 years

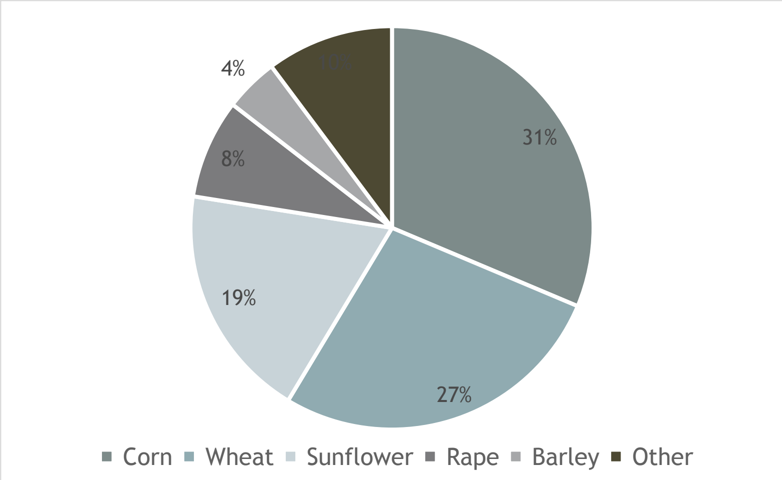

Figure 35. The cultivated area under crops in the pilot study area

Source: Hungarian Central Statistical Service

On the contrary to agricultural companies, as of now the majority of crops grown by individual farmers are rainfed. However, most of the climate projections based on regional climate models expect the climate exposure of the pilot area to amplify which can be followed by the increased irrigation water demand.

An estimate of direct benefits for agricultural producers in the project lifespan period is obtained by multiplying the value of agricultural production in HUF per m^3 by the annual demand for irrigation water from the MAR scheme. Based on the survey data we calculated the average value of crop revenue per volume of applied irrigation water for major crops grown in the pilot study area. Our estimate is as a weighted average using the sowing area under each crop as weights (Table 12; *Source:* Expert estimations based on data for Békés County).

Table 12. Calculation of direct benefits

Indicator	Unit of measurement	Value
Annual irrigation water demand	m^3	300,000
The weighted mean of crop revenue	HUF per m^3	1,122.36
The annual direct benefit	mil HUF	336.7

It is important to highlight here that the obtained estimate may suffer from a major limitation: it is based on survey data with a low number of observations on irrigated crops. This is the only estimate that is feasible to get given data limitations.

6.1.3. Net present value

Following the CBA literature, we use the net present value (NPV) 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):

$$NPV = -k + \sum_{t=1}^{T} \frac{NCF_p}{\left(1 + r_f\right)^t} + \sum_{t=1}^{T} \frac{NCF_s}{\left(1 + r_s\right)^t}$$

where k: initial investment cost,
t: time
NCF_p: private net cash flow,
NCF_s: socio-environmental net cash flow,
r_f: financial discount rate,
r_s: social discount rate

So NPV is the sum of the discounted value of the stream of benefits minus the present value of future costs and initial capital costs. Calculation of NPV requires defining the following parameters: project horizon, financial and social discount rates.

According to the literature, in MAR case studies 30-years horizon for assessment is frequently used (Ross and Hasnain, 2018; Dashora et al., 2019; Arschad et al. 2014). Thus, for our study project lifespan is defined to be 30 years. Values of discounts rates were selected following the European Commission's benchmark, namely the financial discount rate of 4% in real terms for 30 years reference period for water supply projects and the social discount rate of 5%.

6.2. Details on survey design and implementation

Aiming to estimate both use and non-use (socio-environmental) benefits, we surveyed local farmers and agricultural producers to find out the maximum amount of money that they are willing to pay (WTP) to have a stable supply of irrigation water, ensuring its quality and improvement of the ecological status of the water body.

The design of the survey is partially based on the paper by Damigos et al. (2017), in which the authors aimed to reveal the economic value of managed aquifer recharge via a contingent valuation study in Italy.

The developed questionnaire for irrigation water MAR system is in line with the concept of "general specific", i.e. it starts with general questions on the state of the environment. In particular, the first section of the questionnaire is on current local environmental conditions and existing problems associated with irrigation practices. It includes questions on how typical recurring droughts and periods with inland excess water for the area are amounts of applied irrigation water, awareness of problems related to groundwater quality and quantity, self-assessed impact on groundwater. Also, this section includes a part aimed to reveal the profile of crop production, including types of crops produced, sowing area, total harvest, crop revenue, the volume of irrigation water applied and its cost. These data are used in the calculation of the expected direct benefit of the MAR scheme.

Questions gradually become more specific in the second part of the questionnaire, which deals with the willingness to pay for the proposed MAR scheme. This section starts with a brief description of the MAR project, outlining its objectives, main benefits for agricultural producers and need for financial contributions to put the MAR scheme in place. The description is followed by questions on the preferred way of funding the proposed plan and the maximum amount respondent would be willing to pay per month per hectare. Options of these maximum amounts were proposed in the questionnaire based on average irrigation water prices. On the one hand, if the respondent selects not to contribute to the proposed plan, he or she is asked to choose the reason for such a decision. On the other hand, if the maximum amount of financial support is provided, the respondent is asked to distribute it to the distinct categories of benefits that the MAR scheme yields (use and non-use benefits). The concluding part contains questions on the farmer's or agricultural company's characteristics, namely area of cultivated land, annual profit, irrigation technology. Appendix of the A.T3.2 contains a full version of the questionnaire.

The survey was conducted via personal interviews with farmers and representatives of agricultural companies.

6.3. Results of the survey and assessment of socio-economic risks

6.3.1. Survey results

In the Hungarian pilot study, both individual farmers and representatives of agricultural companies were surveyed to reveal the willingness to pay for the MAR scheme as a source of irrigation water.

The total number of responses obtained is 25 with 21 coming from farmers and 4 from agricultural companies (the total population of agricultural companies operating in the pilot area is 9). Starting from surveyed individual farmers, more than 70% of them do not normally irrigate crops, while more than half have used groundwater for irrigation purposes (the A.T3.2). Among farmers, 38% have used drilled wells for irrigation purposes with 5% of them haven't had an opportunity to consider regulation and technological guidelines while drilling the wells (B10).

As for the problems related to groundwater quality and quantity in the pilot study area, 57% of surveyed farmers have heard of them (B3). Pollution from pesticides and fertilizers, over-pumping and water scarcity/deep water table in wells during drought periods are main farmers' concerns with regards to groundwater problems (B4). Almost five-sixths of farmers stated that recurring droughts are typical for their area to a moderate or great extent (B5) while more than 70% of them are concerned with the negative consequences of climate change to a moderate or great extent (B7).

Among surveyed farmers only one mentioned a non-zero amount that he is willing to pay to support financially MAR scheme (B11), all other farmers stated that they would not like to make financial contribution mainly because they consider it to be governmental responsibility and they already pay enough taxes (B13).

When it comes to surveyed agricultural companies, the majority of them (three out of four) acknowledge their impact on groundwater quality and/or quantity (B23), normally irrigate crops and have used groundwater for irrigation purposes (B18). Their main concern related to groundwater problems is water scarcity/deep water table in wells during drought periods (B20). Again one company out of 4 expressed non-zero WTP for the MAR scheme (B24). Among the main reasons not to contribute to the implementation of the MAR system are considered to be the government's responsibility and profit level that does not allow them to afford financial support of the MAR scheme (B26).

6.3.2. Assessment of socio-economic risks

Economic risks along with health, environmental, technical and management risks can incur by the implementation of MAR schemes. Primary economic risks of MAR are related to the financing of MAR projects and benefit's realization over time. One of the core discrepancies in the financing of water projects is that water users (primary stakeholders, who benefit from them) often have an insufficient amount of financial sources to support these projects (Maliva, 2014). Moreover, there is a time lag between construction costs and the realization of benefits. Burdens associated with the financial constraints of MAR schemes' implementation may lead the main beneficiaries to consider the investment in the MAR system infeasible in terms of costs and benefits. Thus, governmental support through subsidies is often considered to be justified in such cases, though subsidies may sometimes create incentives that induce water inefficient behaviours (Maliva, 2014).

To capture non-use values (existence, bequest and altruistic) of water use contingent valuation techniques are commonly applied to reveal the WTP for MAR systems. However, they may sometimes struggle from several potential biases (Boardman et al., 1996) due to the hypothetical nature of respondents' answers as their statement of WTP does not imply conversion into the actual payment obligation (Maliva, 2014). Thus, there may be a high risk that realization of these biases (more severely in case of improper survey design) will result in overestimation of potential benefits, which in turn will inflate NPV values and affect the decision regarding the economic feasibility of MAR.

Failure to meet performance objectives is also considered to be the principal risk and source of uncertainty associated with MAR schemes (Maliva, 2014). Despite common adverse results being mainly related to technical and health risks, they may translate to economic ones. An example of such a transmission mechanism is when the problem of excessive well clogging is remedied by pre-treating the recharge water at a cost of additional expenses. At the same time, the expectation that adequate pretreatment would mitigate clogging is not always true, as clogging during recovery may be a consequence of changes in water quality at the storage stage (Nandha et al., 2015). This important operational risk can result in high maintenance costs and consequently lead to unforeseen expenses during the operation stage of MAR schemes.

Finally, another source of economic risk might be revenues lower than anticipated because of not fully realized water demand. Irrigation demand is highly dependent upon climate conditions and the profitability of the MAR scheme may vary noticeably under different climate change scenarios (Rupérez-Moreno, 2017). In addition, MAR systems can be sensitive to extreme climate events.

For the case of the Hungarian MAR scheme, Table 13 presents local experts' assessment of socio-economic risks associated with the MAR scheme. Two main dimensions of expert assessment are the probability of risk realization and its consequences for the MAR scheme in the Hungarian pilot site.

The majority of considered socio-economic risks (two-thirds) are expected to have a low probability of realization. At the same time, experts consider lack of sufficient funding, unplanned additional costs and low price of irrigation water for agricultural producers to be highly probable risks. Lack of funding is not only assessed to be an economic risk with high probability, but also with major consequences for the MAR scheme.

Among risks, consequences of which experts expect to be minor are unplanned costs and such social risks as missing acceptance of local population and insufficient communication. All other considered socio-economic risks are assigned a moderate level of risk consequences by experts (Table 13).

Table 13. Summary table of the socio-economic risk

6.4. Discussion of the socio-economic feasibility

6.4.1. Feasibility of MAR scheme

Obtained WTP survey responses provided useful insights on agricultural production in the pilot area, farmers' knowledge regarding groundwater issues, and their perceptions and concerns. The results suggest that the mode WTP of both individual farmers and agricultural producers is zero. Thus, we calculated net present value accounting only for direct costs and benefits (average values of both). We applied a financial discount rate of 4% to get the discounted value of the stream of direct benefits and the present value of future costs and initial capital costs over 30 years project horizon. Since the operation phase of the extension is expected to start in the 3rd year, values for the first two years are negative, reflecting capital costs (Figure 36).

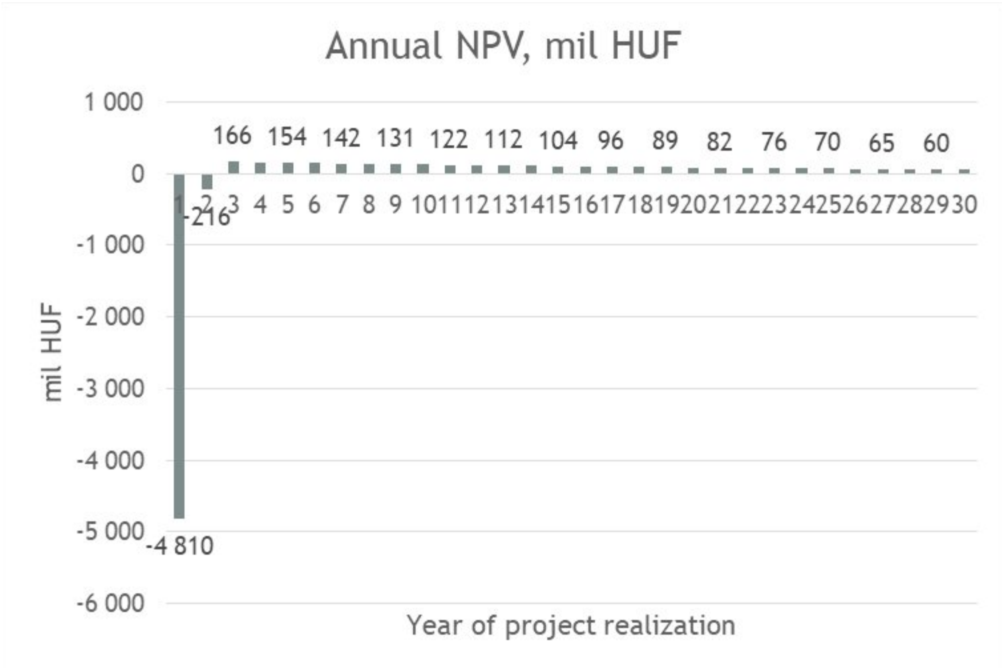

Figure 36. Annual net present value of irrigation water MAR scheme

Obtained positive values of annual net benefits after the launch of the MAR scheme imply that direct benefits cover maintenance and operations costs. However, the expected NPV over 30 years of project lifespan is negative, suggesting that direct benefits are not sufficiently high to cover capital costs. Thus, without budget funding of capital costs, it is not economically feasible to put the MAR scheme in place.

It is crucial to emphasize that obtained results are based on rather limited data and should be treated with caution.

6.4.2. Feasibility of MAR scheme under different scenarios

To incorporate uncertainty in our CBA, we developed three scenarios (maximum, average and minimum) based on the following criteria:

- range of costs associated with MAR scheme;
- crop per drop value: average level of crop revenue per volume of applied irrigation water.

Assumptions that define each scenario are presented in Table 14.

Table 14. Assumptions that define each scenario

Developed scenarios	Assumptions	
	Costs	Benefits (*The level of crop revenue per m3 of irrigation water*)
Maximum	The maximum value of capital and maintenance costs	The Q3: 3,253.00 HUF/m^3
Average	The average value of capital and maintenance costs	The weighted average: 1,122.36 HUF/m^3
Minimum	The minimum value of capital and maintenance costs	The Q1: 795.49 HUF/m^3

We aim to check how sensitive NPV can be to the changes in core parameters as presented in Table 15. NPV over the project's lifespan is positive only under the maximum scenario, in which direct benefits are calculated using the middle value between the median and the maximum value of crop revenue per volume of applied irrigation water (the third quartile). Among irrigated crops in the pilot study area, such a level of crop revenue per drop can be observed for more value-added crops, such as watermelons.

Table 15. NPV under different scenarios

Scenarios	NPV over 30 years, mil HUF
Maximum	5,395.9
Average	-2,144.0
Minimum	-1,031.1

7. Comparison of alternative solutions

Studying the feasibility of the underground MAR type in the pilot site situated in Maros alluvial fan several possible solution were analysed. The different versions were compared by the results of hydrogeological modelling and at the frame of CBA analysis.

The following modelling scenarios were tested:

- natural groundwater flow without underground dam
- underground dam located in the first aquifer layer
- underground dam located in the second aquifer layer
- analysis of climate effect considering different recharge values

CBA analysis compared the cost and benefits with underground dam system to the present situation. Beyond the direct costs it considered the expected changes of water demand, and socio-economic benefits too.

7.1. Conclusions of the modelling

The results of the modelling indicate that changes in the morphology of the buried riverbed in the study area have a major impact on the flow directions. The flow directions in this unit with good hydraulic conductivity change as a function of the unit's shape. Studies on the effect of an underground dam show that the shape of the buried riverbed unit influences the extent of the groundwater level fall area, which is also adapted to the morphology of this zone.

The modelling was used to investigate the boundaries of the buried riverbed, whether it is directly connected to the infiltration area or not. The model response was significantly different in both cases, so this should be considered in modelling approach and further detailed works. The detailed field investigation carried out in the framework of the project which contributed essential data to the hydrogeological model, but further measurements are required and can provide crucial information for detailed study and implementation of construction an underground dam. Additional field work can decrease the uncertainty of the hydrogeological model too.

An attempt was also made to investigate a smaller model area, but the determination of boundary conditions took a long time and without adequate water level data the task proved to be unrealistic.

Based on the currently available water level data, transient modelling cannot be run, although the magnitude of water level fluctuations due to precipitation and evaporation would have a large influence on the flow directions and retention rates.

The modelling did not include canals and small watercourses in the model area.

In the model runs, we investigated the movement of particles starting from the area before the dam and travelling with the groundwater flow. The model runs resulted in reach times of approximately 500-900 days in the first aquifer. These results correlate well with the results from the water age dating studies, which show that the first aquifer has water ages of about 10 years, so that the recharge of the uppermost aquifer is highly dependent on local infiltration from precipitation.

The model scenario with a deeper subsurface dam located in the second aquifer was also examined. Although the effect of groundwater level changes were more favourable and the extra water volume was the double than at the case of the shallower dam variant, implementation of the construction facing technical and financial difficulties.

In all the applied model variants the increase in water volume resulted by the groundwater dam exceeded the required irrigation water amount.

7.2. Conclusion of CBA analysis

Comprehensive assessment of the MAR scheme requires evaluation of its economic feasibility along with hydrological, geological, and institutional considerations. Cost-Benefit Analysis is among the tools, which are widely used to assess the profitability of the MAR scheme. To state whether the MAR system is feasible from an economic perspective, the costs of its construction and maintenance are compared with the system's total economic value, which is the sum of use benefits and non-use values. In order to reveal the latest stated preference techniques, more specifically survey-based contingent valuation method, are widely used in MAR studies.

In our study, we developed a WTP survey, which provided useful insights on agricultural production in the pilot area, farmers' knowledge regarding groundwater issues, their concerns and perceptions. Survey results suggest that the mode WTP of both individual farmers and agricultural producers is zero. Consequently, we make conclusions about the economic feasibility of the MAR scheme based on a comparison of only direct costs and benefits.

In order to address uncertainty in our CBA analysis, we developed scenarios with plausible variations of core parameters, such as cost values and levels of crop revenue per amount of applied irrigation water. Under all scenarios except the maximum one, NPV 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. It is vital to emphasize that since cost estimates are sufficiently rough and benefit values calculation relies on very limited data, obtained CBA results should be treated as more indicative and with a portion of cautiousness.

Uncertainty in this CBA study was indirectly accounted also by incorporating an outline of possible socio-economic risks associated with the MAR scheme in the pilot study and the expert assessment of their probability and consequences. When designing the MAR scheme policymakers should pay sufficient attention to these risks, especially those with a high probability of realization and/or major risk consequences. Based on the assessment of local experts for our pilot study such risks are mainly economic, namely lack of funding, unplanned additional costs, low price of irrigation water for agricultural producers.

Final conclusions, recommendation

The investigated pilot site is situated in one of the climatically most exposed regions to the effects of climate change, situated in the Maros alluvial fan, in the vicinity of Csanádapáca and Medgyesbodzás. As it is an agricultural region without permanent surface water courses, the water demand is expected to increase in the future. Therefore, managed aquifer systems (MAR) can play an important role in water management. Within the preliminary feasibility study of a potential underground dam the following major aspects have been investigated:

1) Consideration of the national regulatory framework,

2) Desktop study of the pilot area,

3) Geological, geophysical and hydrogeological characterization of the pilot site, including the determination of water demand and supply,

4) Risk assessment and management,

5) Cost-Benefit Analysis, and

6) Comparison of alternative solutions.

Based on the archive data, supported by new investigations carried out within the DEEPWATER-CE project, this pilot site is potentially feasible for underground dam MAR scheme considering the followings.

Although, the alluvial environment is characterized by variable geological and hydrogeological conditions, the ancient river channels can be locally favourable for such a MAR scheme. However, detailed field investigations are required to verify the suitability of a selected site.

Combined and complex investigation and interpretation of field surveys can provide a sound 3D conceptual geological-hydrogeological model, also improving the reliability of numerical hydrogeological models.

A hydrogeological model can be a useful tool to test different MAR schemes and to take into account different climate scenarios.

Potential risks have been identified and risk treatment methods have been suggested for all 111 risks.

While the hydrogeological modelling was performed for different scenarios, the cost benefit analysis has been carried out for one option, for underground dam installed in the uppermost aquifer.

The surveys show the local farmers and agricultural companies are not keen in investing their own money, but they expect governmental support.

Although the abstracted amount from unregistered wells is supposed to be significant, only the licensed and abstracted water amounts for settlements in the pilot site are available. Therefore, a rough estimation can be done for the real need for irrigation water.

The results, based on the available data show that an underground dam MAR scheme would be socio-economically feasible only in a long term.

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