D.T3.3.1 REPORT ON THE DESK ANALYSIS OF THE PILOT FEASIBILITY STUDY FOR MAR DEPLOYMENT IN POROUS FLOODPLAIN ALLUVIAL SYSTEMS

(HUNGARY)

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1. Introduction

The DEEPWATER-CE project aims to examine the possibility of improving water supply and increasing the amount of available water, in case of Hungary, especially for irrigation purposes. In this way, sustainable water use can be achieved with regard to agricultural water withdrawal during periods of water scarcity, while the vulnerability of the drinking water aquifers can be decreased. The goal of the Hungarian pilot activity is to select and explore a specific site which is suitable for underground water storage and to study the feasibility of the underground dam MAR solutions in this environment.

A transnational decision support toolbox has been developed within the DEEPWATER-CE project and used to designate potentially suitable MAR locations in Central Europe (output O.T2.1, DEEPWATER-CE 2020a). Using this toolbox, pilot sites with applicable MAR schemes were identified in Hungary (deliverable D.T3.1.2).

This report represents the first step (desk analysis) of a pilot feasibility study by providing an overview of existing data for MAR deployment in porous aquifers located in floodplain alluvial systems in South-East Hungary. Based on this, an outline of further studies for investigating missing data is also provided in this report, in form of a pilot action plan.

In the Toolbox-based MAR pilot sites and aquifers selected (Hungary) D.T3.1.2 report (DEEPWATER-CE 2021) we applied the pre-defined selection criteria to narrow down the investigation area from country level to some potential pilot sites that meet the geological, hydrogeological requirements of constructing an underground dam in Hungary. The results of our general and specific mapping indicated that the Maros alluvial fan was one of the most promising area for further pilot actions, which has been selected as a pilot area. Based on further suitability mapping (specific mapping) in the framework of our project, several potentially suitable areas were delineated and the most applicable final pilot site was selected.

2. Data availability and sources of data

The geological and hydrogeological conditions of the pilot area have been studied intensively in the last 100 years, which has resulted huge amount of information. Most of the data was organized in different databases, maps and GIS datasets. In the following chapter a short overview summarizes the available data and information.

2.1. Previous geological, hydrogeological investigations

The history of scientific research of the Maros alluvial fan dates back to the early 20th century (Cholnoky 1924, Pécsi 1959, Somogyi 1961, Borsy 1987, 1989, Mike 1991, Lovász 2006). Based on these studies evolutionary models have been developed focusing on its morphology and lithology (Mike 1991).

The detailed **geological characterisation of the Maros alluvial fan** was carried out on the basis of geological mapping of the Great Hungarian Plain in the 1960–1970s (Rónai 1983,1985). Analysis of thousands of shallow boreholes (10 m) and fully cored boreholes to a depth between 100 and 1200 m contributed to a better understanding of the Quaternary evolution of the Great Hungarian Plain. This campaign was carried out by the Geological Institute of Hungary between 1964–1991. These boreholes were supplemented by groups of wells screened in different depth intervals, which later also operated as monitoring wells as part of the national groundwater monitor network. Exploration of the shallow (10 m) formations took place in a regular 1 by 1 km network of drillings and contributed greatly to the creation of 1:100 000 scale map series of the Great Hungarian Plain. Results of sedimentary analysis of the borehole material, measurements of the groundwater table and groundwater sampling from the boreholes were published in numerous scientific works (Rónai 1983, 1985, Franyó 1992, Püspöki et al. 2013).

The latest **geomorphological and sedimentological studies (**Sümeghy et al. 2013, Sümeghy 2014) serve with abundant data on close-to-surface lithology and on the evolution history of the Maros alluvial fan. The latter includes the mapping of former riverbeds of the Maros alluvial fan in the Hungarian part. Sümeghy (2014) also suggested these riverbeds may be suitable for subsurface storage of water. In addition, the fluvial forms and processes which played role in the formation of the alluvial fan were also investigated by Katona (2014).

Investigation of the **hydrogeological conditions** of the Maros alluvial fan started with the drilling of the first wells at the end of the 19th century. After the 1960s the number of wells (mainly for drinking water purposes) rapidly increased. Due to the growing water demand a research programme (Drinking Water Reserve Research Programme, 1979-1982) was carried out with the aim of ensuring the future drinking water supply of Békés county and the surrounding area, through the exploration of the Maros alluvial fan and its groundwater sources (Figure 1). This high volume research was performed by different institutions, including research institutes (e.g. MÁFI, ELGI, VITUKI), drilling companies (VIKUV, OFKV) water supply companies, national and regional authorities (VIZIG, OKI, KÖJÁL) and engineering companies as coordinators of the research work (MÉLYÉPTERV, OVIBER). The exploration included drilling activity, geophysical measurements, hydrogeological tests, groundwater modelling (Horváth and Zólyomi 1984). Within the framework of the drilling activity core drillings were done in three sites (Tóthkomlós, Kevermes and Pusztaottlaka) with continuous sampling to the depth of 500 m. Close to the core drillings, groups of wells (including monitoring wells) were drilled where hydrogeological tests were performed. Some supplementary boreholes were created supporting the geophysical interpretations (Draskovits et al. 1982).

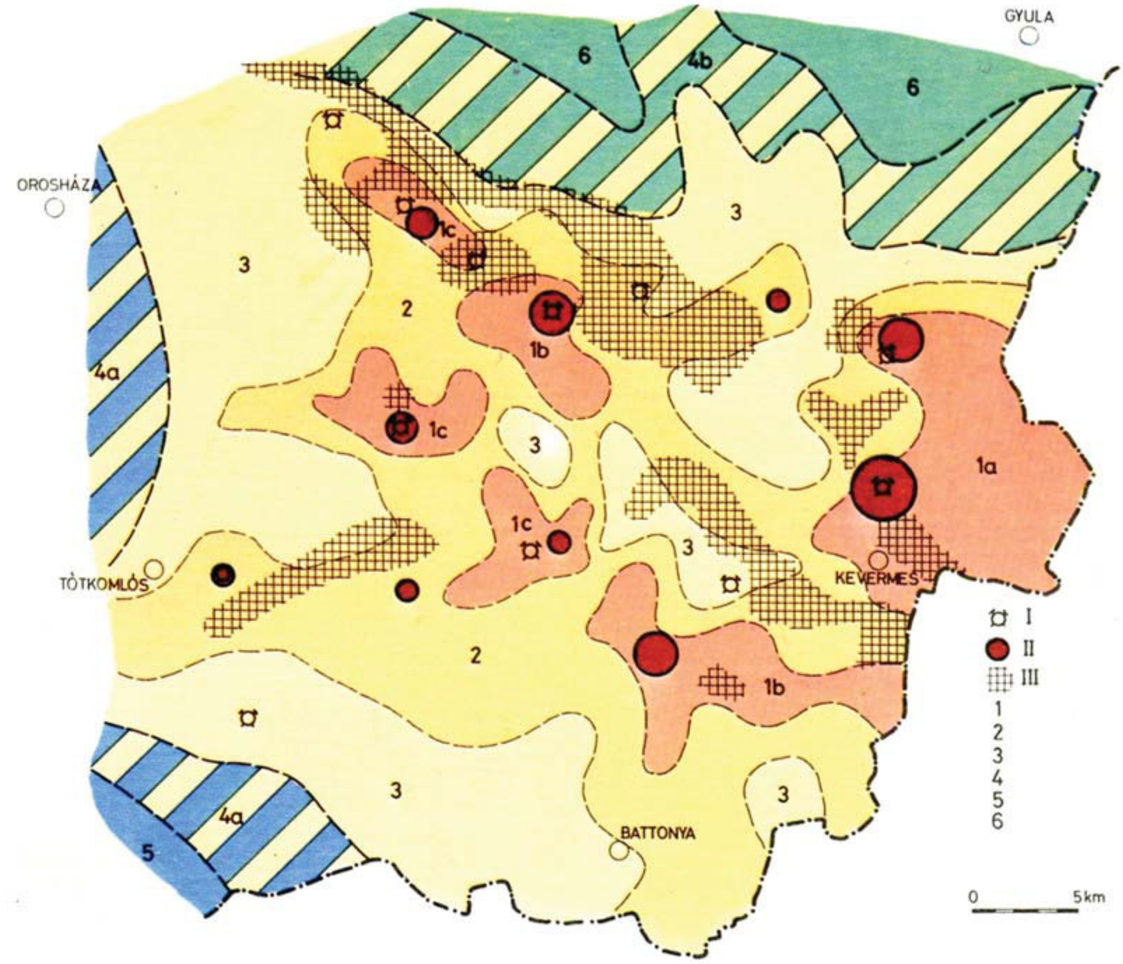

Figure 1: Potential aquifers of the Maros alluvial fan according to the results of the Drinking Water Reserve Research Programme (Bodoky T. and Polcz I. 2016 after Draskovits et al. 1982)

I – Exploration boreholes, II – suggested areas for waterworks, III – zones where infiltration is most likely;
1 – favourable waterworks areas, 2 – good areas, 3 – moderate to poor areas, 4 – peripheral areas of the alluvial fan, 5 – alluvial fan of the Danube River, 6 – alluvial fan of the Körös River

The geophysical investigation (carried out in the frame of Drinking Water Reserve Research Programme) was performed by the Eötvös Loránd Geophysical Institute of Hungary. As the result of this work, the potential zones of groundwater reserves were delineated, where later the regional water supply systems have been built (Figure 1).

Integrated evaluation of geological profiles (established on the basis of boreholes), surface geoelectric surveys combined with special shallow seismic reflection profiles, and borehole geophysical data contributed to the understanding of the geology and hydrogeology of the Maros alluvial fan. Geoelectric investigations involved specific resistivity mapping (Figure 2) based on Vertical Electric Sounding (VES) data with a point density of 1.5 to 2 points/km^2 and construction of geoelectric profiles on the basis of Induced Polarisation (IP) and Artificial Electromagnetic Frequency Sounding (FEM) techniques. The latter two were considered relatively new research methods at that time, but proved to be very useful in identifying the aquifers.

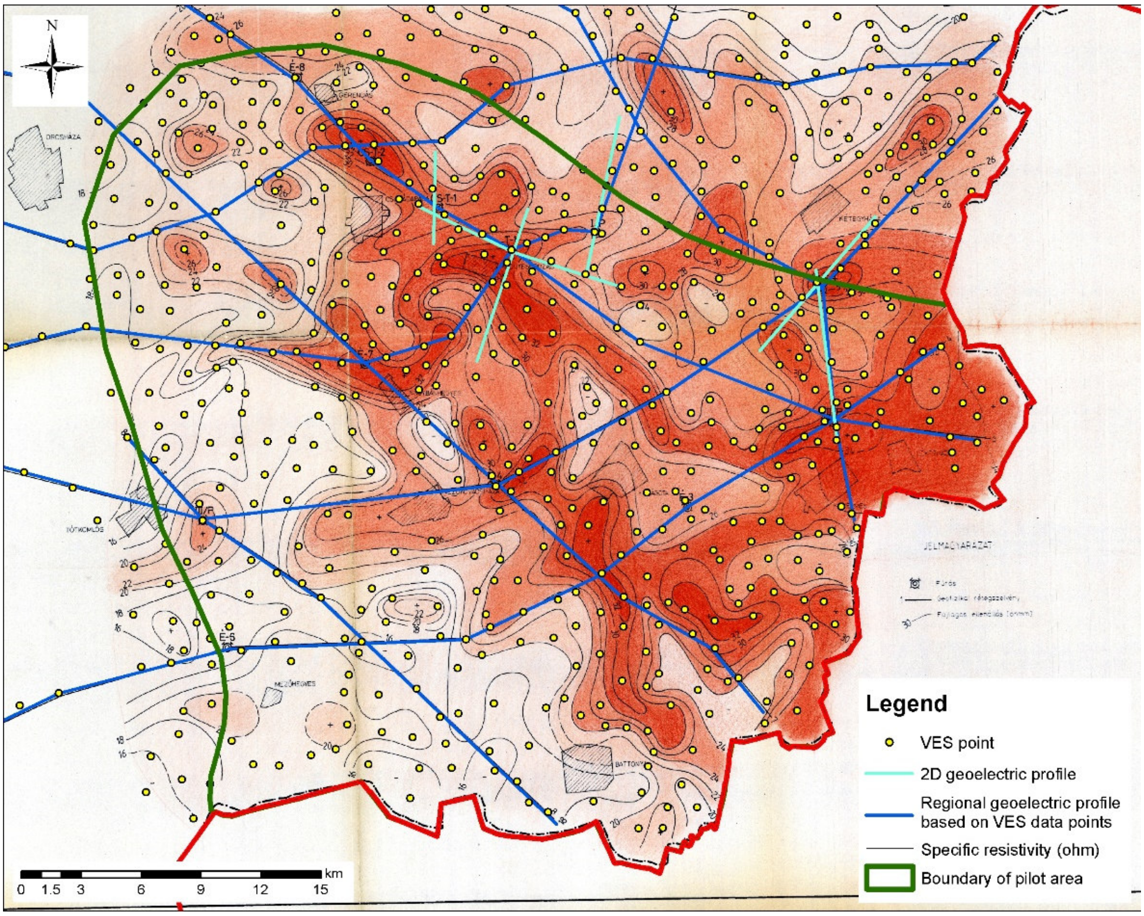

Figure 2: Geophysical measurements of the Eötvös Loránd Geophysical Institute in the area of the Maros alluvial fan (after Draskovits et al. 1982)

The most important results of these geophysical studies were the maps about (1) outlining the vertical and lateral extent of the Maros alluvial fan and characterising its inner structure, and (2) the distribution of coarser grain fluvial sediments appearing as higher resistivity zones on the geoelectric maps and profiles as potential drinking water reservoirs.

In the frame of the Drinking Water Vulnerability Programme of Hungary which started in 1991, the protection areas of the vulnerable drinking water resources were delineated and legal restrictions were officially registered. The delineation processes were carried out based on detailed geological and hydrogeological investigations, which included field measurements, hydraulic tests in wells, monitoring activity, hydro-geochemical studies and development of geological and hydrogeological flow models. These intensive researches provide huge amount of hydrogeological information in the surroundings of drinking water resources. There are 27 vulnerable drinking water resources situated in the Maros alluvial fan (**Figure 3**).

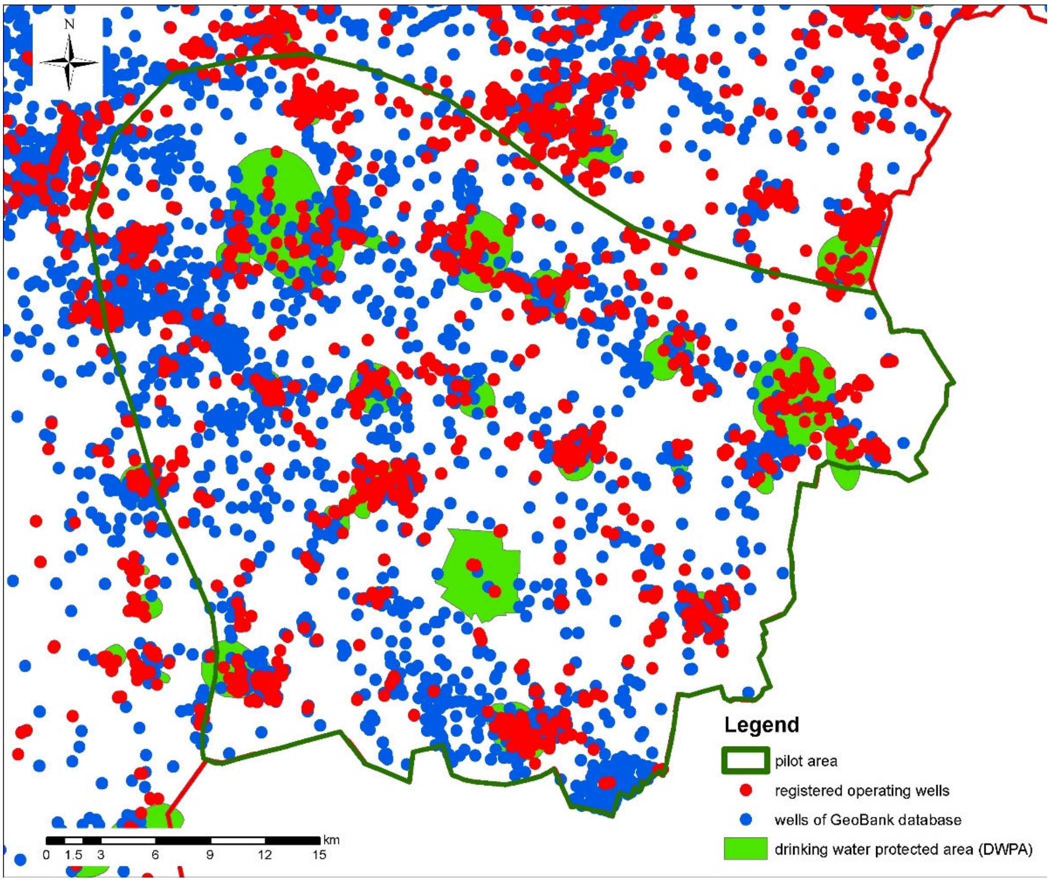

Figure 3. Wells and Drinking Water Protection Areas (DWPAs) situated in the pilot area

2.2. Geological and hydrogeological datasets

There are several national or regional datasets which can provide information for further evaluations.

Groundwater level maps are crucial for the present study. Different maps have been prepared during the last few decades. There are some thematic hydrogeological maps available at regional and country scale, which belong to different map series (e.g. National Atlas of Hungary) or are results of national programmes or regional research projects. The different versions of the map "Depth of the groundwater table below surface" are outcomes of different mapping campaigns of the Great Hungarian Plain. The first version was created by Rónai, the author of the Cadastre of dug wells in the Great Hungarian Plain. The survey of the dug wells was carried out between 1951-1960 (Rónai 1961). Later, in the framework of the 3rd mapping of the Great Hungarian Plain the depth of the groundwater table was measured in most of the boreholes of a regular network. As the mapping process took several years, significant differences were observed in the measurements. Therefore maps display different depth categories of the groundwater table. This categorization was verified by monitoring data of several decades and maps compiled considering average values of longer period time series (Yearbook of the Hydrographical Service of Hungary 2015). These data served as the basis of several further maps (Kuti et al. 2002, Pentelényi and Scharek 2006). Although the methods were different, based on the existing maps, depth of groundwater table could be categorised in the following ranges: 0-2 m; 2-5 m; 5-10 m; >10 m.

Another important data source is the well database. The cadastre of drilled wells was started to be compiled during the 1970s and 1980s by Urbancsek (volume 1–12), which was annually updated by VITUKI (volume 13–36) and later on by MBFSZ (volume 37–43).

Independent of their origin, all the different borehole and well types are included in the so called GeoBank, the borehole database of MBFSZ. The modules of the database contain the basic information of the objects, the geological profiles, and the hydrogeological data of the wells and boreholes (Figure 3).

Recently, a separate database of well logs was developed in MBFSZ (so called Urbancsek database) which can be used for local to regional scale geological and hydrogeological characterisation of a study area and 3D geological, hydrogeological model developments.

Several hydrogeological models have been developed covering the pilot area which can provide information about the hydrogeological conditions and serve as initial data for boundary conditions of further models. The groundwater flow model of the Carpathian Basin, the so called Pannon XL model (Tóth et al. 2010) (Hydrogeological model of the Pannonian Basin developed in the frame of the 3rd River Basin Management Plan) extends beyond the national border. This includes the recharge distribution data of the *NAGiS project* calculated by MBFSZ and groundwater level data of the monitoring wells operated by MBFSZ. This Pannon XL model served so far and could serve in the future as basis for the regional groundwater models.

The first regional numerical model was prepared in the framework of Drinking Water Reserve Research Programme in the 1980s. It described the geological and hydrogeological conditions of the Maros alluvial fan (Csepregi and Nagy 1986). The goal of the cited work was to make predictions and forecasts of the expected changes in pressure- and flow conditions due to increased water extraction at that time. As a result, the delineation of drinking water protection zones at Újkígyós and Medgyesbodzás was performed. For maintaining the quality of groundwater, proposals and restrictive measures were made on activities, according to potential contaminant sources within the area. The research was conducted to help the safe operation of the responsible waterworks. It concluded that increased attention should be paid to aquifer contamination, but did not mention qualitative restrictions (Csepregi and Nagy 1986).

The sand-gravel layers of the Maros alluvial fan represent a significant drinking water production capacity in the Great Plain of Hungary, but for long, it was very uncertain how much water can be abstracted in the area in a sustainable way. Although many researchers and experts have investigated the hydrogeological conditions and water production potential of these layers in the past decades, these works show some contradictions. One of the aims of a hydrogeological modelling performed in 2003 (Völgyesi 2003) was to determine the parameters of the water balance, the impact of water production, taken into account the amount of recharge of the Maros alluvial fan through the analysis of an increasing number of wells, monitoring data and experiences.

In connection with the most recent 3rd River Basin Management Plan (hereinafter 3rd RBMP), according to the status assessments, analysis and tests, hydrogeological modelling was performed for the Maros alluvial fan among other regions. Because several of these sample areas contain transboundary parts, the model relies on the calibrated parameters and cut outs of the so-called large supra-regional *Pannon XL* model. The preliminary report of this newest regional hydraulic model of the Maros alluvial fan was published in 2020, which notes that the first (1980') hydrogeological models were significantly smaller, with no or just partly in transboundary position. The latest model of the area was carried out using a 1x1 km grid resolution, including 10 layers (in the vertical direction), with a total area of 15400 km^2, of which about 30% cross the border (Romania). In the absence of cross-border information on production, the effect of upstream water extraction was not taken into account. The non-permanent scenario of the hydrogeological model simulates the changes in groundwater level through a 38 years period (1981-2018) with a timestep of 1 month. Calibration of the model has begun, but since it is in the first stage, the hydraulic model parameters and detailed results are not yet published. The model is being developed as an integral part of the 3rd RBMP (Csepregi 2020).

3. Pilot site characterization based on existing data

The pilot area is located in the south-eastern part of the Great Hungarian Plain (in Békés County) between the two largest tributaries of River Tisza (Körös and the Maros) along the national border. The pilot area covers the territory of two micro-regions Csanád Ridge and Békés Ridge (Dövényi 2010), and is situated on one of the largest fluvial alluvium in Hungary (**Figure 4**). The special geographical settings (climate exposure, low relief, etc.) determine the land use, water demand and possibilities in water supply.

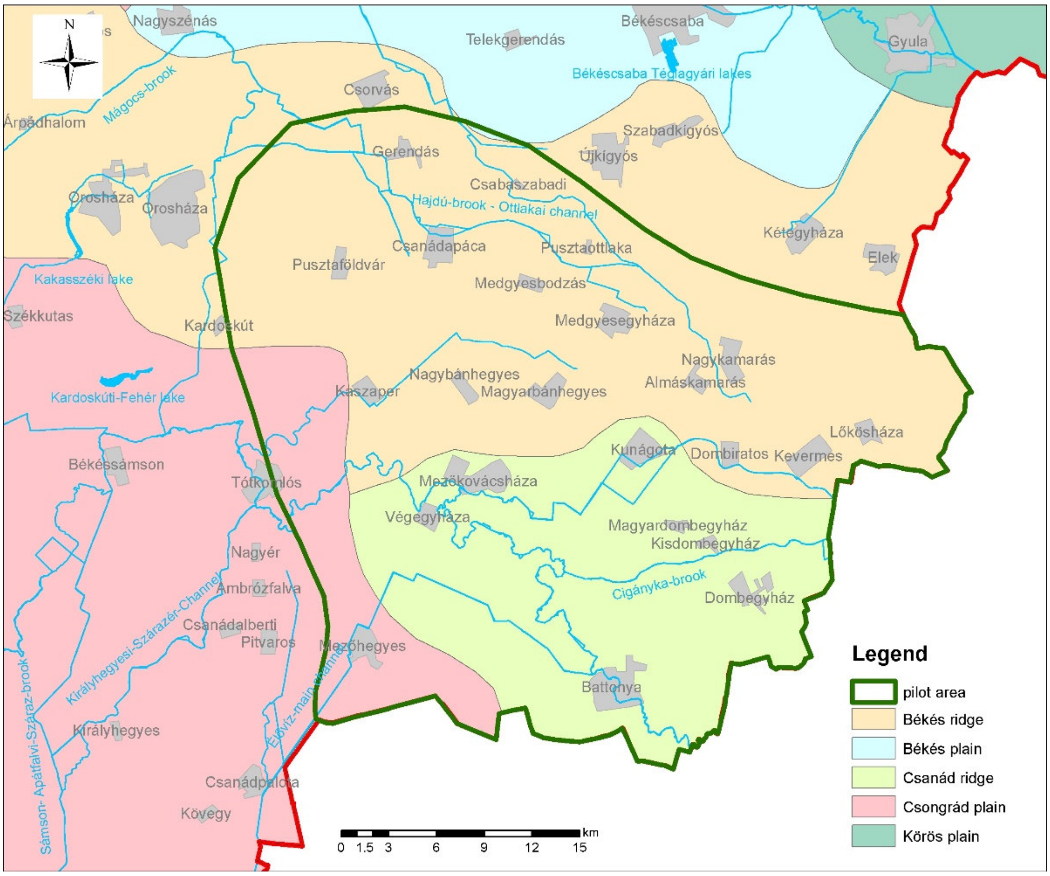

Figure 4: Location of the pilot area

3.1. Geographical settings

3.1.1. Climatic conditions

The climate of the Csanád-ridge microregion (**Figure 4**) is warm-dry, while the Békés-ridge is moderately warm (Dövényi 2010). The number of hours of sunshine per year is varying between 2000-2020 hours, about 810 hours in summer and is about 190 hours in winter. The average annual temperature is 10.3-10.5 °C and the average temperature during the growing season is 17.3-17.5 °C. The average daily temperature exceeds 10 °C from April and falls below 10 °C in October. The frost-free period begins in April and ends in October and lasts 196-198 days. The annual absolute temperature maximum is 34.0 °C, the minimum is between -17.0 °C and -18.0 °C. The annual rainfall varies between 570-580 mm, the average during vegetation period is approx. 340 mm. The maximum precipitation that has ever fallen in 24 hours was measured in Orosháza (147 mm). In winter, the lands are covered with snow for 32-34 days, with an average maximum snow thickness of 17-18 cm. The aridity index in East is 1.20. The most common wind directions are NE and SE; the average wind speed is slightly below 3 m/s (Dövényi 2010).

3.1.2. Surface topography

The region of the Maros alluvial fan forms a flat area emerging a little bit from its surroundings (Figure 5). The Csanád-ridge micro-region, the southern part of the central Maros alluvial fan, is situated between 96.6 m and 106.8 m above sea level. The middle part of the alluvial fan (93-102 m a.s.l.) is almost 36 km long, with a surface slope of 27.4 cm/km. The average relative relief is very small, only 1 m/km^2, reaching values above 2 m/km^2 only in the southern parts.

The Békés-ridge microregion area forms the central and northern part of the Maros alluvial fan and is situated between 82.6 m and 105.5 m a.s.l., sloping slightly to the west-northwest. Its average relative relief is 2.5 m/km^2. Higher values are in the eastern parts of the micro-region, while lower values are in the western ones. The lateral part of the alluvial fan is 22 km (85-93 m a.s.l.) and the surface slope is 37.3 cm/km. The foreground part of the alluvial fan is only 15-18 km long (82-85 m a.s.l.), the surface slope is 8-9 cm/km, its surface shaped by fluvial and aeolian processes (Dövényi 2010).

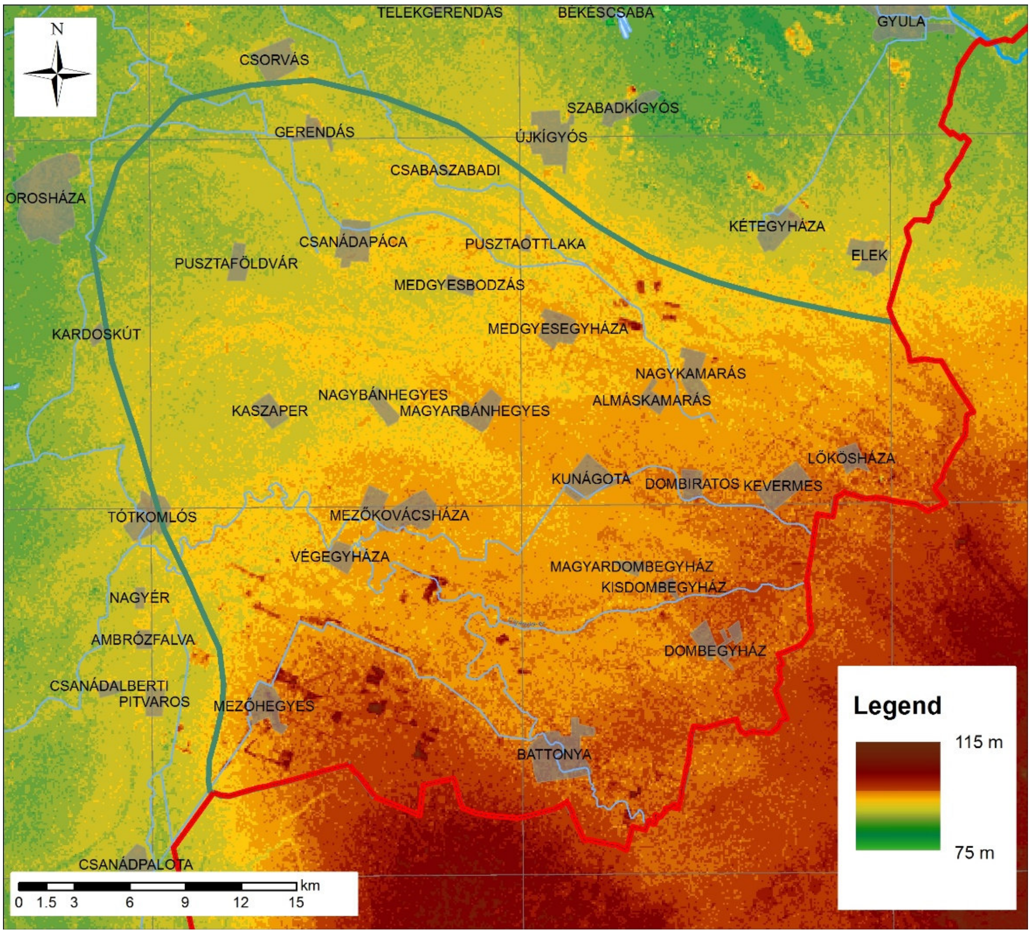

Figure 5. Elevation map of the pilot area (m a.s.l.)

3.1.3. Hydrology

The pilot region has only a few watercourses. In terms of the human impact level, surface water bodies can be further divided into three categories, which are the natural, heavily modified and artificial waters. Most of the watercourses are channels. There are two small lakes (Fehér Lake and Csikóspusztai Lake) outside the pilot area which are naturally formed but shallow and periodic. The most significant surface water of the wider region is the Maros River itself, flowing today outside of the pilot area. All but one of the surface waterbodies flows into the Maros which eventually ends in the Tisza River. The Maros River is the largest tributary of the Tisza River, with a catchment area of approximately 30 000 km^2. The 749 km long river originates in the Eastern-Carpathians and flows between the Apuseni Mountains and the South Carpathians, and enters the Great Hungarian Plain at the Lippa. Although Maros River recently flows outside the pilot area, the Ancient-Maros River crossed this area forming a large alluvial fan.

Despite of the relatively large catchment area, the water network of the Maros alluvial fan is sparse and characterized by low surface runoff. The runoff conditions (especially in the eastern part of the area) are significantly affected by the anthropogenic activities (e.g. spatial planning, channelization) which reduced the amount of available water resources in the Maros alluvial fan (1st RBMP 2010).

After the wet periods, water shortages appear in the summer, which affect most of the region, causing serious damages since the agricultural activity is substantial throughout the whole pilot area. The surface waterbodies could be characterized by small to medium catchment sizes as there are no significant differences in topography. Most of the watercourses are temporary, except those channels which are artificially maintained. The largest lake of the region is the Fehér Lake (at Kardoskút) on the western border of the pilot area which dries out during the dry seasons of the year.

In conclusion, the entire alluvial fan is sparsely networked of surface water bodies and there is water scarcity especially in the growing season. Therefore, in terms of agricultural production the importance of water governance is a top priority. According to the RBMPs due to orographic reasons, it is difficult to supply irrigation water to the northern and eastern parts of the region, which results in crop losses during drought periods.

3.2. Land use

In relation to the Great Hungarian Plain, the pilot area is relatively moderately populated (2 to 3 settlements per 100 km^2, and 67 people per km^2, KSH 2020), but comparing to the average values of Hungary (6 to 7 settlements per 100 km^2, and 105 people per km^2, KSH 2020) the number of municipalities and inhabitants is relatively low. The destruction of settlements during the Turkish occupation (16th century) and the subsequent resettlement play a significant role in this population density and the nature of the actual settlement network. Out of 25 settlements, 3 are towns. These towns are the centres of the microregions. The proportion of the urban population is significantly less than the national average. In addition to their "so-called 'giant villages' with more than 5000 inhabitants, there are several large villages (3000-5000 inhabitants) and medium-sized villages (1000-3000 inhabitants) with smaller populations (Figure 6). Most of the villages exhibit a chessboard pattern. The proportion of the peripheral population is higher than the average.

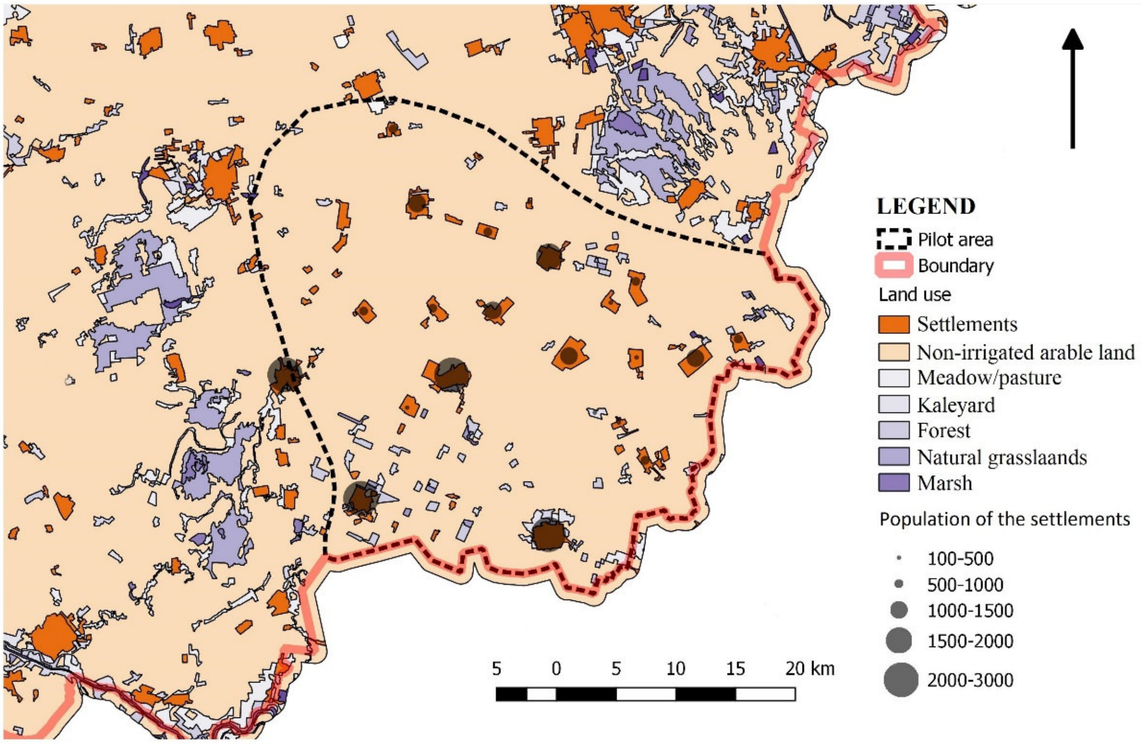

Figure 6. Land use map of the pilot area
(Compiled based on the CORINE database, 2018)

Due to the favourable soil conditions, intensive agricultural activity is taking place in the pilot area. This region has the best productivity in Hungary. According to the land use database (Figure 6, CORINE 2018), 82% of the area is arable land. The second most significant land use types are meadows, pastures and built-up areas which cover 6% of the pilot area. The remaining 6% of the area is made up of forests (3%), wetlands (1%), lakes and rivers (1%) and small gardens (1%). Importance of natural reserves is limited in the Maros alluvial fan. Larger wetlands and Natura2000 sites are located outside the pilot area. These can be linked to different plant associations.

The intensive agricultural land use means a potential diffuse pollution source. Large livestock farms can be significant point sources of pollution for shallow groundwater and surface water, if the manure treatment and storage does not comply with the requirements of Good Agricultural Practice. Pollution from settlements largely depends on the number of residents not connected to the sewage system. In 10 from 23 settlements there is no sewage network system. In the settlements with sewer infrastructure, the amount of households connected to the sewer system varies between 91% and 12% (KSH 2020).

3.3. Geological characteristics

3.3.1. Regional geological settings

Hungary is located in the Pannonian Basin which is one of the largest sedimentary basin in Europe. The Pannonian Basin was formed during the late Early Miocene at the time of thrusting of the Carpathian belt. Due to late Middle Miocene crustal extension resulted in subsidence of the whole Pannonian area and the formation of a large back-arc basin (Royden and Horváth 1988). As a result of the uneven subsidence and subsequent basin inversion the Pannonian Basin was divided into sub-basins filled with several thousand meter thick Neogene sediment series.

In the southern part of the Great Hungarian Plain there are two important depressions: the Békés Basin and the Makó Trough (**Figure 7**). These two basins are separated by the Battonya Basement High, where Neogene sediments have reduced thickness. The pilot area is situated at the western edge of the Békés Basin and the eastern part of the Battonya High.

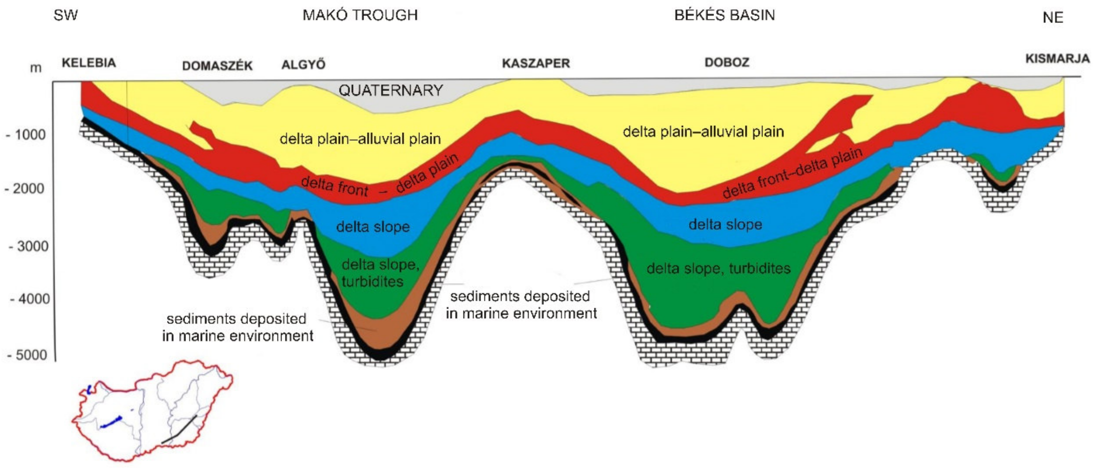

Figure 7. Geological cross section of the Békés Basin and the Makó Trough (Juhász 1998)

The middle Miocene sediments were deposited in water depths of less than 200 m in a marine environment of normal salinity. During the middle Miocene the Pannonian basin was isolated from the Eastern Paratethys system and became a large lake (Lake Pannon) characterized by brackish water. This lake was gradually filled by large shelf margin delta systems during the Late Miocene (Magyar et al. 2013). Delta sediment deposited in the lake prograded from NE, NW directions and a minor delta system from the SE was also identified (Bérczi and Phillips 1985, Pogácsás et al. 1988, Magyar et al. 2013). In the central parts of the Békés Basin, the late middle Miocene shallow water deposits are overlain by these delta sediments with a thickness of about 2500 m. Studies by Késmárky et. al. (1981), Pogácsás (1984), Marton (1985), Mattick et. al. (1985), Horváth and Pogácsás (1988), Pogácsás et al. (1989, 1992a,b, 1994), Pogácsás and Seifert (1991), Juhász (1992), Vakarcs et al. (1992, 1993), Várkonyi et al. (1993) Ujszászi and Vakarcs (1993), Juhász (1998), Sztanó et al. (2013), Magyar et al. (2013) and Csató et al. (2015) indicate that the Late Miocene open water marls (Endrőd Fm.), and turbidites (Szolnok Fm.) are conformably overlain by a series of prograding sediment wedges composed of sediments deposited in “delta slope” (Algyő Fm.), delta front (Újfalu Fm.), delta plain and fluvial (Zagyva Fm.) environments. The formations are time transgressive in the Pannonian Basin as they are related to the progradation of the morphological shelf of Lake Pannon, which was built by the large delta complexes during the late Miocene and Pliocene (Pannonian stage). The upper part of these strata is deposited in fluvial plain environment).

Since the rate of accumulation exceeded subsidence, the Lake Pannon was infilled by the Late Pliocene and finally formations of a paludal to terrestrial environment were deposited (Jámbor 1989; Juhász 1994; Magyar et al. 1999, Magyar et al. 2013).

Due to the tectonic extension of the Pannonian Basin, uplift of the marginal flanks and subsidence in different parts of the basin occurred. This resulted in areas of continuous fluvial sedimentation during the Quaternary. Rivers discharging from the uplifting areas were drawn towards the subsiding depressions, which served as local base level and a new drainage system was developed. Detailed study of Quaternary sediments in these depressions, Urbancsek (1960, 1965) pointed out that the subsidence was a multi-phase process where changes in subsidence rates in space and time resulted in the evolution of a complex drainage pattern (Gábris and Nádor 2007).

During the Pleistocene the basin of the Great Hungarian Plain was infilled by alluvial fans prograding from the uplifting margins. The thickness of the sedimentary layers varies between 700-800 m in the deepest parts of the depressions, 150-350 m above the basement highs.

3.3.2. Special characteristics of the (Maros) alluvial fan

Alluvial fans (Figure 8) can be divided into upper/proximal, middle/central, and peripheral/distal parts (Rachocki 1981, Kochel 1990, Lecce 1990, Murkerji 1990, Gómez-Villar and Garcia-Ruiz 2000, Yuste et al. 2004). The division is based on their longitudinal section, the running direction of the beds (Basu and Sarkar 1990), and the grain size distribution of the sediment (Yuste et al. 2004). The inflection band is the part of the alluvial fan where the incised main channel merges with the surface of the alluvial plain (Lecce 1990; Harvey 1996). The apex of the alluvial fan is the highest point of the alluvial fan from where its branches radially (Nichols 2009). The alluvial plain is formed by the aggregation of several successive alluviums (Lecce 1990, Goswami 2009). Changes in river energy can change the river's eroding capacity and create terraces in the upper and middle parts of the alluvial fan (Harvey 1996). On the surface of the alluvial fan, vigorously incised, deep beds can appear. Alluvial fans are most often crossed by braided channels, characterized by tributaries and bars (Harvey 1990, Stanistreet and McCarthy 1993). They may also have meandering and anastomosing sections (Stanistreet and McCarthy 1993). Higher water flows increase the rate of sediment accumulation in the riverbed. As a result, the watercourse responds with gradual lateral migration or avulsion (Nichols 2009). This is the way how secondary beds are created, which occur on the sections with the largest falls. Their characteristic is that the beds are constantly separated and reunited (Rachocki 1981).

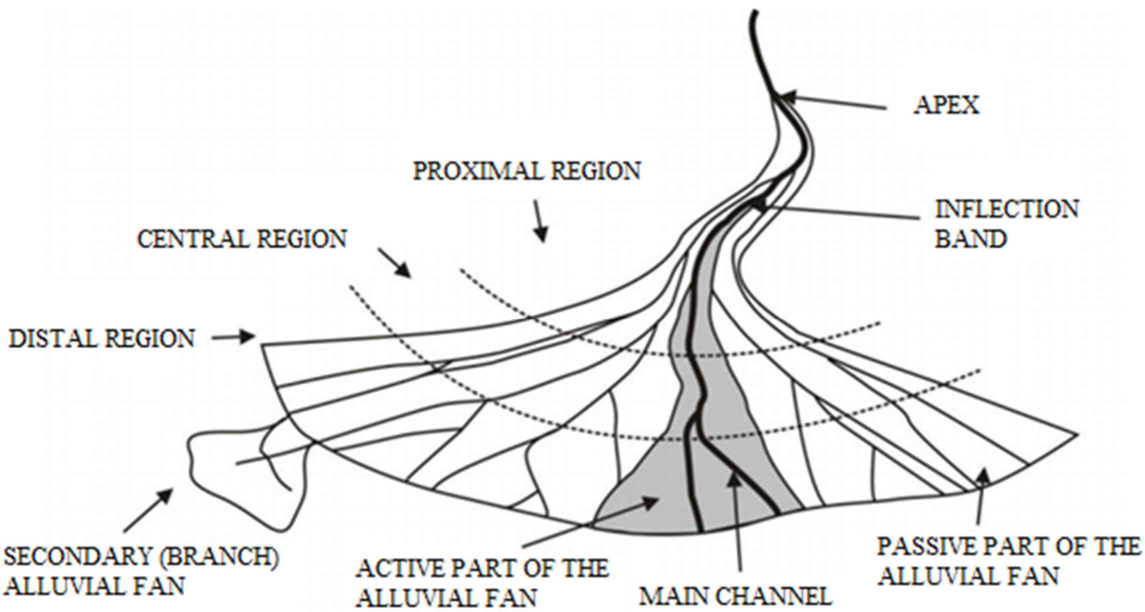

Figure 8. General characterization of alluvial fan (Sümeghy 2014)

The Maros River has played an important role in filling up the south-eastern part of the Great Hungarian Plain. The Maros alluvial fan extends beyond the borders of Hungary with an area of ca. 8300 km^2, (Fiala and Juhász 2015) and a radius of 80-100 km (Figure 9). The alluvial fan is shared by Hungary (35%), Romania (50%), and Serbia (15%). The proximal part of the alluvium is situated in the territory of Romania and most of the distal part is situated in Hungary representing our pilot area. The present-day Maros River is located within the E–W axis of the alluvial fan. To the north of this axis, the alluvial fan is more elongated than on its southern part. The Maros alluvial fan is built up from sediments of the Eastern and Southern Carpathians.

Both differential tectonic movements and climate change in the Quaternary has played an important role in the evolution of the alluvial fan. Surrounding floodplain (Makó Trough and Körös Basin) were sinking areas. The Battonya-Pusztaföldvár High to the S-SE is an uplifting block, while the Békés Basin and Makó Trough are sinking basins during the Quaternary (Joó et al. 2000, Nádor et al. 2007a, 2007b), all affecting the run of paleo-river courses, and the nature of sedimentation within the fan. Similarly to the other vast alluvial fans of the Pannonian Basin, the Maros alluvial fan developed throughout the Quaternary period (Borsy 1989, 1990, Mike 1991, Gábris and Nádor 2007). Entering the "gate" between Lökösháza and Battonya, the Ancient River Maros deposited gravel, coarse-grained sand, and fine-grained floodplain sediments on its alluvial fan. From the apex to the western margin of the alluvial fan (where it connected to the Ancient-Danube alluvial formations) the thickness of the sedimentary body increases from 100 to 500–700 m (Borsy 1989).

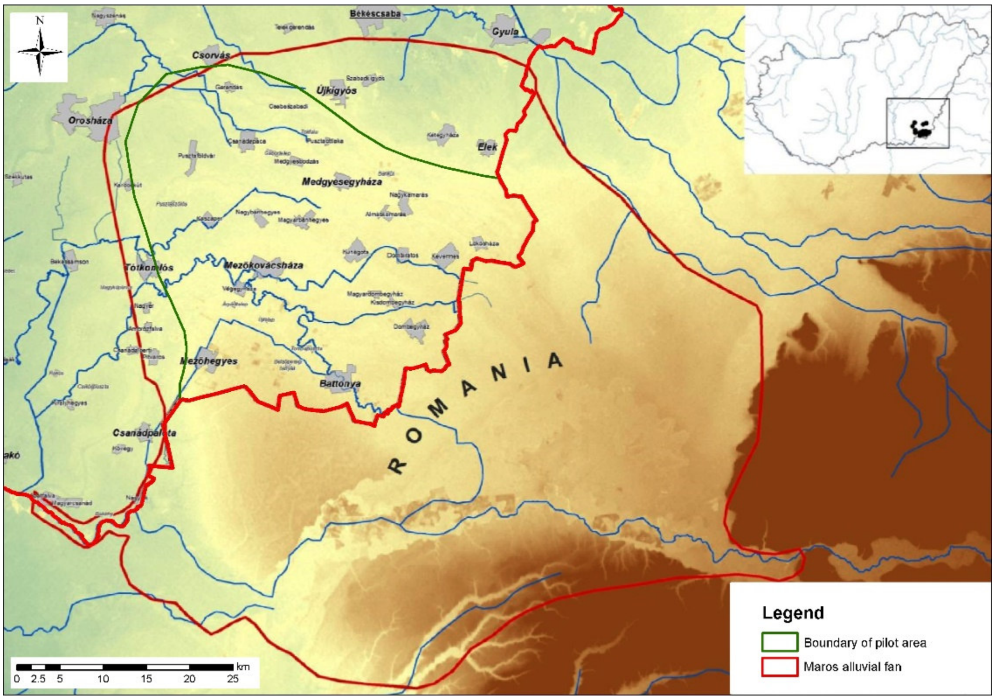

Figure 9. Location of the Maros alluvial fan (Fiala and Juhász 2015)

3.3.3. Fluvial sequences of the Maros alluvial fan

The uppermost 200 m of the Quaternary strata of the Maros alluvial fan can be further subdivided by using geophysical maps, well and borehole data. Applying fluvial sequence stratigraphic approach (cf. Püspöki et al. 2013), lithological information and geophysical logs (natural gamma, SP and resistivity) from 196 boreholes were organized to a database in the framework of this project, to construct regional geological profiles and set up a regional hydrogeological model of the area. Altogether, 8 regional key profiles, completed with 25 supplementary profiles were constructed to show the main lithological boundaries (fluvial sequence boundaries) and the facies changes in each investigated sequence (Figure 10). An example profile running from the village of Végegyháza to the town of Medgyegyháza is shown in **Figure 11**. Only boreholes deeper than 50 m were used in the analysis as geophysical logs are available in these wells, and the characteristic thickness of the fluvial sequences is 20 to 50 m. Based on susceptibility measurements, the base of the Quaternary was also defined and interpreted from borehole to borehole. The depth of this horizon was in agreement with the result of geoelectric measurements.

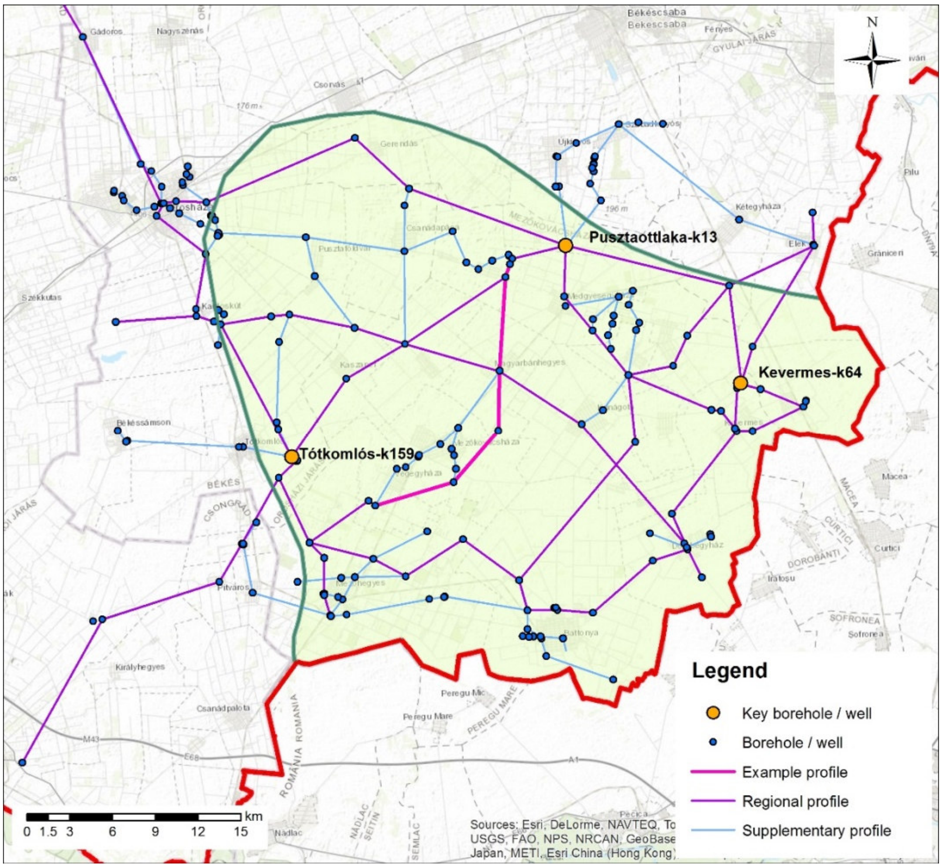

Figure 10: Boreholes and profiles used for the fluvial sequence stratigraphic analysis of the Maros alluvial fan

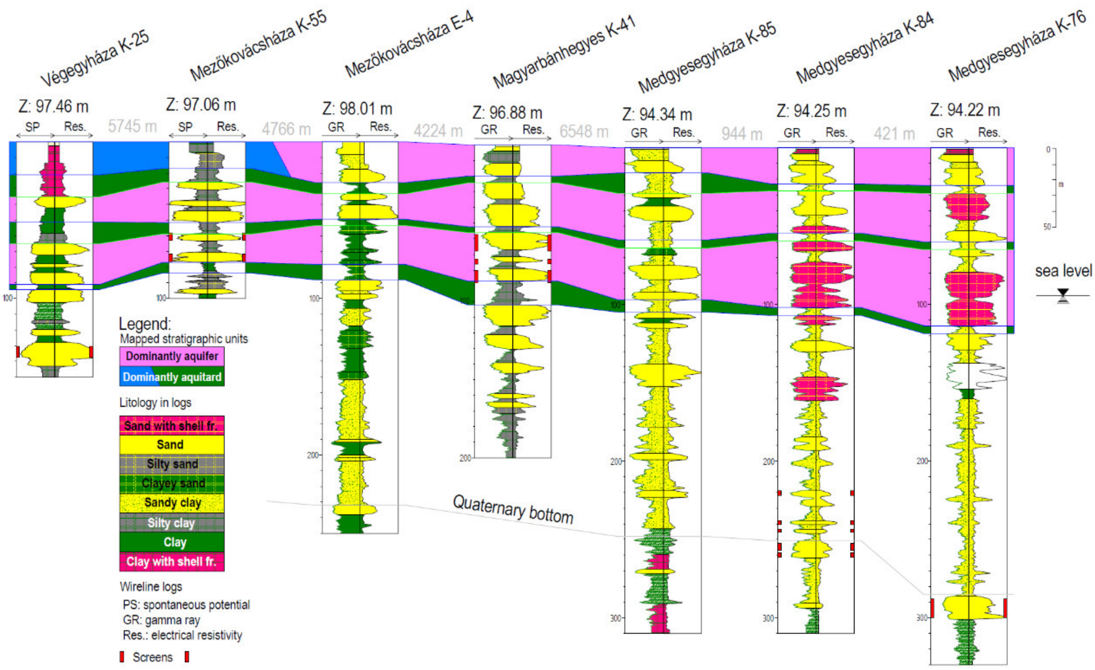

Figure 11. Example profile to show the correlation of fluvial sequences between Végegyháza and Medgyesbodzás

The section line is illustrated at Figure 10

Boundaries between fluvial sequences were defined along facies changes related to the shift from low- to a high-accumulation setting in the fluvial system. These changes cause characteristic deviations in the log curves that can be correlated between boreholes with the aid of preliminary depositional models (**Figure 12**). To reduce errors from the large distances between boreholes, the borehole dataset was completed with resistivity maps (Draskovits et al. 1982, Figure 2), found to be appropriate to show proper identification of facies changes for the upper 25 and 250 m. Using the regional cross-sections, the vertical subdivision of the fluvial series was carried out, and the boundaries of the topmost 3 fluvial sequences were interpreted. This core of the interpretation was refined by the use of supplementary profiles connecting certain boreholes of the regional profiles, and providing additional data in between them.

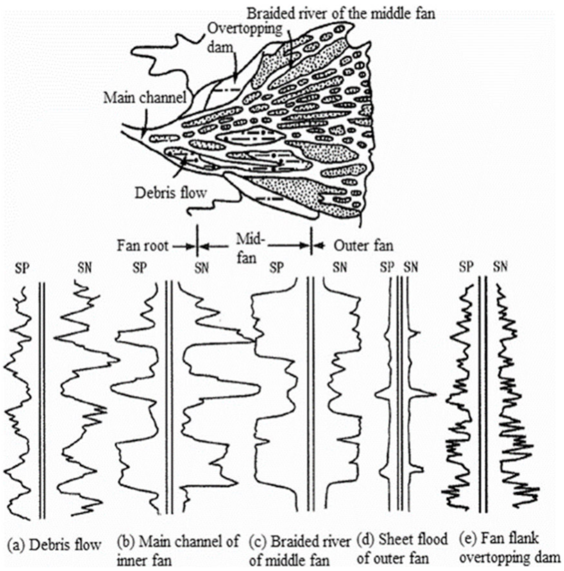

Figure 12. Example borehole log facieses of the alluvial fans (after Yu et al. 2018)

Hydrogeological subdivision of the fluvial sequences was relied on the observation that each interpreted sequence starts with a fine grained sedimentary unit - considered as an aquitard, while the sand ratio in the sequence is normally increasing, and these coarser grain sediments represent potential aquifers. Above each sequence boundary, the beginning of the following sequence is either marked by fine grained fluvial sediments or in ideal conditions paleo-soil horizons. In this work, the boundary between the above mentioned two sub-units was defined as the base of the first dominant sandy group of layers that has a thickness exceeding 1.5 m.

The thicknesses and hydraulic properties of the aquitards delineated are variable in space, and their permeability strongly depends on the facies distribution provided by the fluvial system.

The surface of the pilot area is covered by the variation of loess, river sediments, and clays and siltstones and formed by fluvial and aeolian process (Figure 13). As a result of the continuous fluvial surface formation, slightly undulating plains were formed. Aeolian surface formation created only a few landforms, but also played a significant role in shaping the topography of the area. Aeolian sediments usually deposited in fluvial environment and the mixture of these sediments near the surface resulted high quality soils. The surface of the extensive Maros alluvial fan is densely (0.78 km/km^2) covered by palaeo-channels. Some of them are currently covered by thin younger sediments, mostly by loess, sandy loess, and clayey–silty overbank deposits (Sümegi et al. 1999). The variation of these formations is displayed in the 1:100 000 scale surface geological map (Figure 13, Gyalog and Síkhegyi 2005).

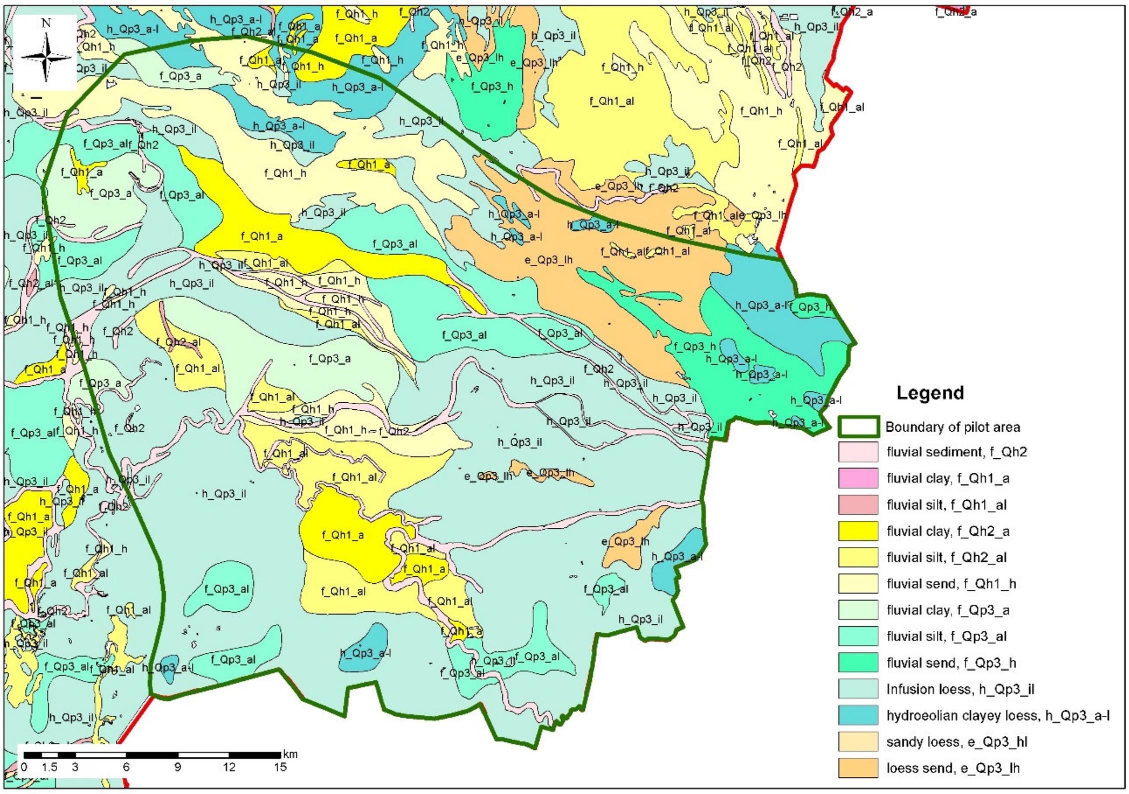

Figure 13. Surface geological map of the pilot area 1:100 000 (Gyalog and Síkhegyi 2005)

3.4. Hydrogeological conditions

3.4.1. Characterisation of the aquifers

The geological settings of the alluvial fan built by the Ancient Maros River determine the hydrogeological conditions of the pilot area. The fluvial sediments deposited in channels, point bars, islands, and incised valleys of the fan act as aquifers, while fine grain silts and clays and formations derive from floodplain environments represent the aquitard layers.

Due to their relatively high silt content, aquitards of the Maros alluvial fan are not aquiclude, therefore hydraulic communication between neighbouring aquifer layers is possible. As a result of the semi-permeable behaviour and lenticular appearance of the aquitards the whole alluvium forms a hydraulically connected aquifer system. Although there is no regional aquiclude layer that is able to constrain regional vertical flow, however, based on fluvial facies analysis (described in Chapter 3.3.3), some aquitard layers with larger extent can be identified. These layers partially separate different groups of aquifers, which therefore form local sub-systems within the regional groundwater flow system.

Aquifers can be identified as the upper parts of the individual fluvial sequences, where the number or thickness of sand layers is usually higher and the sand to silt ratio is increasing in the upper part of the fluvial sequences. These aquifers are mostly related to lithofacies of incised valleys, point bars and islands in the proximal or middle region of the fan. They are often confined by younger flood plain sediments acting as aquitards, while in other locations where the covering fine grain sediments are missing the system may become unconfined. This can typically happen at places, where the base of the topmost sequence is eroded by the activity of river channels of the youngest fluvial sequence.

Using facies analysis and fluvial sequence stratigraphy, the properties and thickness of the sandy upper part of the youngest fluvial sequence was interpreted. The effective thickness of the aquifer layers varies between 3-30 m with an average value of 15 m. The first impermeable layer (the silty lower part of the topmost fluvial sequence) is situated in the 6-41 m depth interval with the average depth of 25 m (DEEPWATER-CE 2021).

The aquifers were characterized by a factor based on the sand to silt ratio and the general thickness of the sand bodies revealed by borehole logs. This factor showed good correlation with surface specific resistivity values of geophysical data, and therefore proved to be very useful in the calibration of resistivity maps (Draskovits et al. 1982) to show lithological changes.

Based on the lithological profiles of wells and boreholes the percentage of coarse sand or sandy gravel is generally higher in the upper 100 m, and lower and less frequent in the deeper aquifers, however, significant trends could not be detected (Horvath and Zólyomi 1984). The hydraulic conductivity is in the range of 5-60 m/d (Ferenc 1986, MÉLYÉPTERV 1983) and the yields of the wells are approximately 400-1250 m^3/d. The values of the hydraulic conductivity show some heterogeneity with increasing values from West to East (e.g. at Tótkomlós 12-36 m/d, at Medgyesbodzás 12-36 m/d, at Kevermes 17-68 m/d). Wells screened in the first aquifer (until the depth of 30 m) can yield 280-350 m^3/d.

3.4.2. Inland excess water and groundwater flooding

The formation of inland excess water is a characteristic phenomenon of the Great Hungarian Plain. Inland excess water can form by rainwater accumulation, extremely high groundwater table or even by upward seeping groundwater from deeper aquifers under pressure. In the Hungarian lowlands these inland waters endanger the agricultural production by flooding croplands and making them inaccessible. As MAR systems are often operating in shallow aquifers, this phenomenon represents an extra risk to the system, and could cause temporal or long-term failure of a MAR facility.

“Groundwater flooding” is a special form of inland excess waters that is unique phenomenon in SE Hungary. It also appears at our pilot area, thus has to be considered during the feasibility study as a potential natural risk for shallow MAR installations. During ”groundwater flooding” water can upraise from shallow aquifers that has become pressurized after a period of extremely wet and cold period. According to Pálfai (2000) the phenomenon has a return time of 10 to 15 years, and it is related to both local precipitation anomalies and increased groundwater flow caused by the extra recharge of precipitation. In the case of the Maros alluvial fan, Körösparti and Bozán (2008) showed that groundwater dynamics and the increased hydraulic pressures causing “groundwater flooding” could be correlated along some observation wells, describing a zone with an elevated groundwater table in the northern half of the pilot area. According to their statistical analysis, this zone runs in SE-NW direction, connecting Nagykamarás, Megyesbodzás, Pusztaföldvár and Orosháza, where it turns to the south, and continues until the southern borders of Hungary.

Based on field observations, upraising (discharging) waters occur mostly at those places where the confined aquifers with increased hydraulic heads become unconfined, and the hydraulic conductivity of the surface formation is relatively high (Rónai, 1985). In the area of the Maros alluvial fan these places show high correlations with the position of buried paleo-river beds, forming elongated narrow zones (**Figure 14**).

High connectivity along the paleo-channel system - that was proven in connection to the “groundwater flooding” events - does not only represent a risk for MAR projects, but also indicates that an underground dam can have effect on larger scale on groundwater level. In addition, “groundwater flooding” zones represent local discharge of the complex alluvial aquifer system in the case of extreme climatic events. Currently the appearance of this phenomenon can be controlled by the existing artificial drainage system.

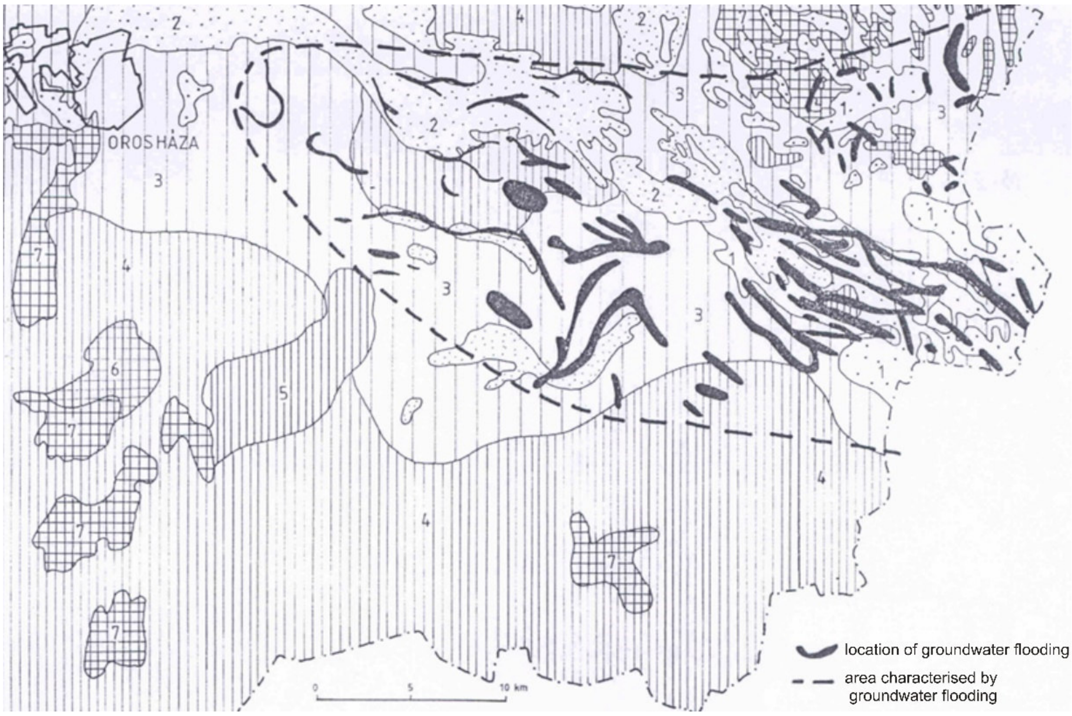

Figure 14: Occurrence of groundwater flooding in the Maros alluvial fan, 1979.
1. Fluvial sand, 2. Sand with loess, 3. Sandy loess, 4. Infusion Loess, 5. Silty loess, 6. Clay, 7. Saline clay, Groundwater upraise zones marked by black (after Pálfai 1986)

3.4.3. Groundwater flow system and hydro-geochemical conditions

The regional recharge area is situated in the hilly and mountainous region outside the national border. Some local recharge can be considered through areas covered by sandy formations on the surface. However, the ratio of regional and local recharge is still uncertain.

The groundwater table is hosted by the youngest (mostly Holocene) sediments of the fluvial series. Originally its depth varied between 2-5 m, but recently it is at 3-6 m which can be influenced by the several factors including drainage effect of the artificial channel system. Groundwater table can be either confined or unconfined depending on the lithology of the surface formations.

The main drinking water aquifers are situated between 50-400 m below surface. Recently, the utilization of aquifers in shallower depth is limited, and the more protected deeper aquifers are in the focus of abstractions. The additional horizontal flow through the interconnected aquifer system (recharged in distant areas) is significant at this depth.

These aquifer layers also get some ascending groundwater from the deeper part of the alluvium as part of the regional groundwater flow system. The horizontal component of the regional groundwater flow is from SE to NW in the whole alluvium body (**Figure 15**). This horizontal component is dominant throughout the entire alluvium.

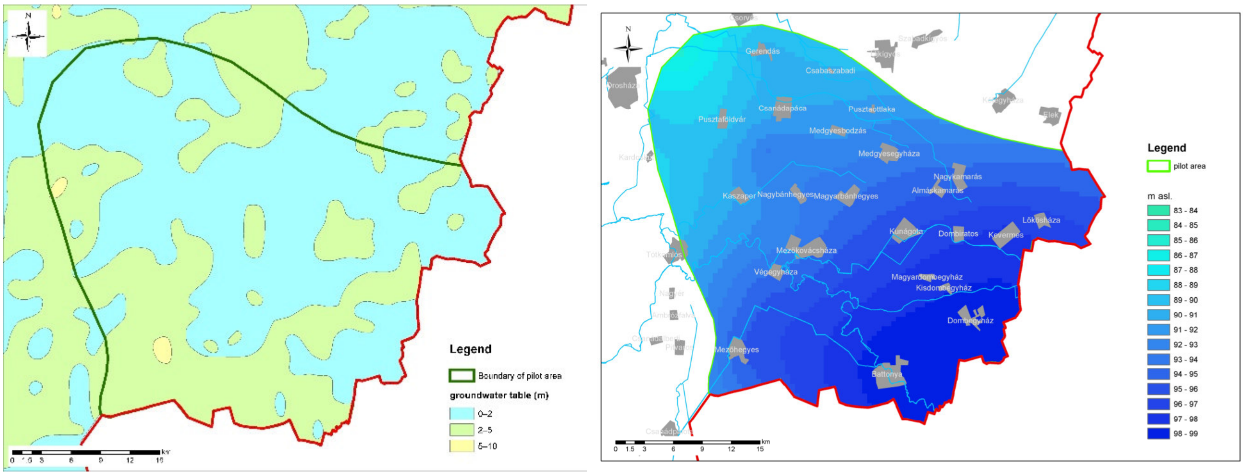

Figure 15. Position of the groundwater table below the surface (left) and above sea level (right)
(Based on Scharek and Pentelényi 2006 and average groundwater level measurements (1961-2009) in monitoring wells)

The discharge area of the regional flow system is situated further, along the rivers of Körös and mainly Tisza. **Figure 16** illustrates the schematic model of the groundwater flow system.

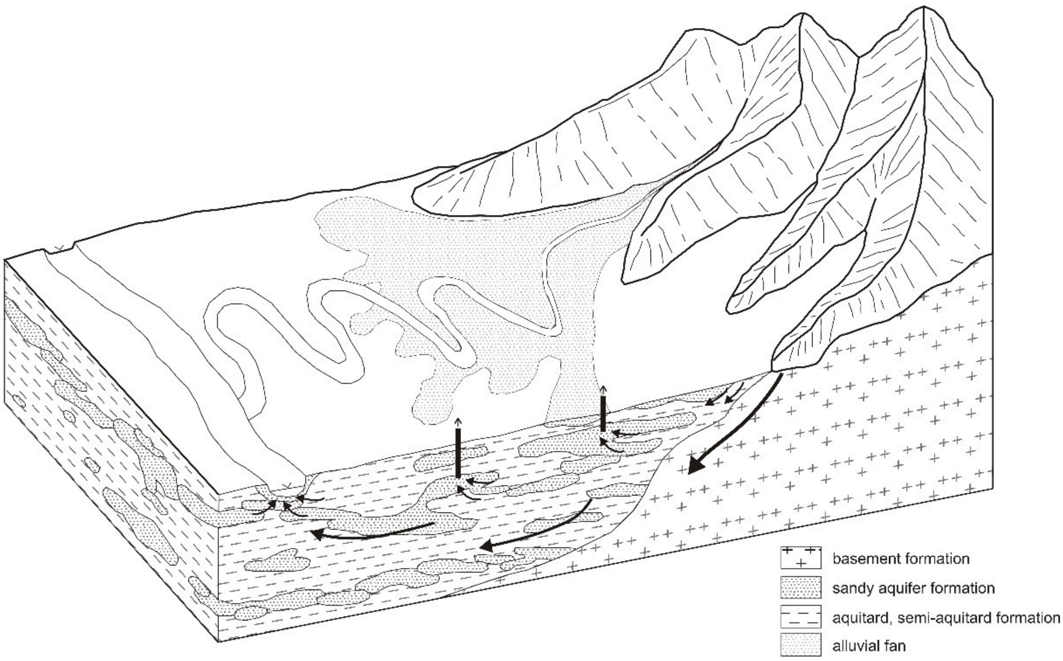

Figure 16. Schematic model of the groundwater flow system of the Maros alluvial fan

The hydro-geochemical composition of groundwater indicates groundwater flow conditions. The water chemistry of the shallow groundwater close to the groundwater table reflects the surface geological settings and the effects of anthropological activities. Areas with unconfined groundwater table and sandy sediments on the surface are usually characterized by $Ca\text{-}Mg\text{-}HCO_3$ waters, with low TDS values. The presence of NO_3 indicates oxidative environment. Higher NO_3 concentrations indicate anthropogenic pollution. In areas where clay or silty layers cover the surface, and confined groundwater table exists, $Na\text{-}HCO_3$ type groundwater dominate, with significant Cl and SO_4 content and relatively high TDS values, sometimes exceeding 1000 mg/l. The presence of higher NH_4 concentrations can be detected in reductive environment (Geological Institute of Hungary 1969-1991). According to the hydro-geochemical investigations carried out in the framework of the National Drinking Water Protection Programme in the deeper layers the Ca and Mg ratio is higher, while the TDS has lower values. In the deeper aquifers the NH_4 content is often higher than the drinking water standard due to natural origin. The high (sometimes higher than 10µg/l) As content has also geogenic origin in the Maros alluvial fan aquifer. The ratio of Na, K and Cl increases along the groundwater flow paths in the deeper aquifers.

3.4.4. Groundwater abstraction

In the pilot area, most of the groundwater abstractions are related to drinking water supply. There are 6 main sites and some additional standby sites, where drinking water is abstracted from the alluvium of the ancient Maros River. Alföldvíz Zrt. (the responsible regional waterworks) provides drinking water from these sites into the regional pipe system (BMRV), which supplies 73 settlements. Only a few settlements have local drinking water reserves (own abstraction sites). Although most of the aquifers are situated between 100-400 m below surface, shallower aquifers (<100 m) are considered too. Drinking water protection areas are delineated based on detailed hydrogeological evaluation and groundwater flow modelling. Within the protected areas certain activities are restricted (Figure 3). Altogether approximately 3352 wells were drilled and licenced, out of which 1481 are still active (**Figure 3**).

The pilot region is characterized with rural land use, therefore, there is a great need for irrigation water. Since the river network is very sparse, 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. According to experiences, unregistered wells are commonly used for irrigation purposes. On a country level, only about 1% of farmers have a water right permit for irrigation in average. This is despite the fact that the costs of using water for irrigation are negligibly low for farmers (the Ministry of the Interior estimates an average of 5000 HUF / hectare / year, which means cc. 15 Euro/hectare/year). These wells are usually drilled without considering any regulations and technological guidelines. Therefore they can endanger the drinking water aquifers by potentially polluting them or abstracting valuable high quality groundwater from the same aquifers. Considering this situation, the application of MAR systems for irrigation would provide significant environmental benefits, which could make these systems (cost-)efficient even if being more expensive than drilling a number of wells.

Due to decreasing groundwater levels and as the recharge area of the groundwater is outside of the national border, groundwater resources are at risk according to the 2nd River Basin Management Plan of Hungary. Therefore groundwater utilization for irrigation purposes is limited by law (groundwater abstraction contingents are determined for irrigation).

Groundwater abstraction for industrial purposes is negligible in this region.

3.4.5. Groundwater budget of the Maros alluvium

In the framework of the drinking water research project (MÉLYÉPTERV 1983) the total amount of groundwater flow in the alluvium was determined as 70000 m^3/d. The horizontally moving groundwater was estimated as 2000 $m^3/d/km$. The vertical upward flow from deeper layers was determined approximately as 5 $m^3/d/km^2$, while direct recharge from the groundwater table to the aquifers below had the value of $15 m^3/d/km^2$ (which means about 30 mm/year direct recharge).

Later water balance calculations (Völgyesi 2003) included some information from the southern part of the Maros alluvial fan, outside the national border. For the year 1991, 1 747 457 m^3/d total water flow was calculated by groundwater flow modelling, having mostly direct recharge water origin and only 10% derived from horizontal flow. A significant discharge process was evapotranspiration, 14.9% was abstracted and only 4% left the region with underground flow. In contrast, the model from 1999 shows a decrease in loss by production (6.4%). In order to predict the impact of long-term abstractions, a groundwater level drop of a maximum of 50 cm was set for both calibrated models (in the Hungarian part of the Maros alluvial fan). The study highlights the fact that the location of watershed areas contribute significantly to the amount of groundwater. However, it makes no mention of any additional anthropogenic effects such as channelization or other water management activities in the area (Völgyesi 2003).

New water balance calculations (new regional groundwater flow model) are currently in progress in the framework of the 3rd RBMP. Although the above mentioned estimations used all the available information, the results have significant uncertainties due to the additional horizontal groundwater flow from outside the country which is decisive for the estimation.

According to the regional and national groundwater flow models some decrease in the groundwater levels have been identified. In the case of the groundwater table only mild decline could be observed, which did not exceed 1 m. In the deeper aquifers 2-4 m decline of the groundwater levels were calculated, which draws the attention to the importance of groundwater management. Considering the impact of climate change more intensive groundwater level depletion was predicted. According to the models, by 2027 the groundwater table will decrease 2-4 m, while this value could reach 6 m in the deeper part of the aquifer (Pannon XL model of 3rd RBMP).

4. Final site selection

Within the 3rd Work package of the DEEPWATER-CE project we carry out a MAR suitability mapping to find the best suitable places for the construction of an underground dam in Hungary. Based on mapping different limiting parameters as constraints, like some geological-hydrogeological criteria (slope, depth of the groundwater table, lithology of the shallowest aquifers), climate exposure, and need for sustainable source of water, the Maros alluvial fan was selected as a pilot area (DEEPWATER-CE 2020a). The selection of a specific pilot site, where we can perform a preliminary MAR feasibility study is a crucial step of the DEEPWATER-CE project. To find the appropriate place, we have carried out a preliminary suitability mapping based on the 8 selection criteria specified within the 2nd Work package of the project (DEEPWATER-CE 2021). This mapping process highlighted several sites within the Maros alluvial fan, characterized by high suitability. To make a choice on the final location, additional data was required, which can be collected by field observations and measurements.

Based on the results of suitability mapping and considering available and re-evaluated data, a two-day long field visit was carried out to collect information on the two most promising areas with high suitability, determined in the deliverable D.T3.1.2 (Figure 17).

(A) Area between Csanádapáca and Medgyesbodzás

(B) Area bounded by Nagybánhegyes-Kunágota-Mezőkovácsháza

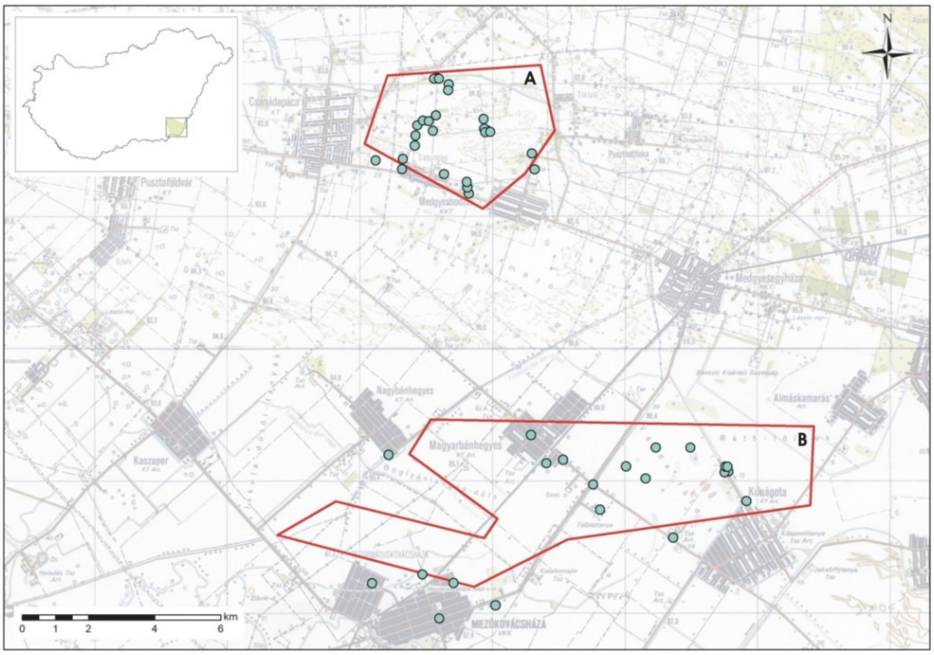

Figure 17: The two most promising sites and the observation points of the preliminary field work

During the field visit we searched for:

- Suitable areas to perform geophysical measurements (e.g. geophysical data acquisition)
- Existing monitoring or pumping wells within or close to the selected area that can be used for hydrogeological field studies (along with updating the institutional well database)
- Wells in which monitoring instruments (e.g. water level recording data logger) can be installed
- Wells, lakes and channels that are appropriate for water sampling

We made observations, took photos and gathered information on:

- Local vegetation type and density
- Surface water coverage, irrigation/drainage systems and channels
- Land use
- Potential pollution sources

We conducted some field measurements on:

- The local depth of the groundwater table
- Electric conductivity and temperature of surface waters

4.1. Preliminary field visit

In the frame of the hydrogeological survey, about 25 wells were visited which could potentially be used for hydrogeological studies and might be suitable to perform water sampling or to install monitoring devices. More than 200 field photos were taken at 46 observation points.

We also made contact with some of the locals and farmers, who shared their information about the occurrence of droughts and inland excess waters, the methods of irrigations used in the area, and provided assistance in finding some wells in the vicinity of their farmlands.

Some local pollution sources were identified. In the northern site a reclaimed landfill was observed with 4 monitoring wells in operation on its each corner. Both sites are affected by diffuse pollution due to intensive agricultural land use and point source pollution originated from nearby livestock farms.

Electric conductivity measurements were carried out in surface water at two sites and the depth of the groundwater table was measured in 17 wells. This provided a rough overview on the state of the groundwater table in the autumn season.

Field report, measurements and the related coordinates were organized into an ArcGIS database and the possible locations of geophysical profiles were identified.

Since the entire area is part of the Great Hungarian Plain, the relief is very low. This is favourable for the planned geophysical measurements. Practically the whole pilot area is an agricultural region with a large network of fairly straight dirt roads separating crop fields. We found that most of these roads are suitable for measurements (Figure 18).


Figure 18: Landscapes of the sites selected for field visit.
Left: Area between Csanádapáca and Medgyesbodzás; Right: Area in the vicinity of Mezőkovácsháza

4.2. Geophysical test measurements

Based on field experiences, the location of two few km long geophysical profiles (ERT-1 and ERT-2) has been designated in order to support the final site selection process and to check the efficiency of geoelectric surveys in the two visited sites. Profiles were marked out perpendicular to the assumed paleo riverbeds of the Ancient Maros River in each site. At the southern site the orientation of ERT-1 section was NW to SE, and the profile run parallel to the main road 4439, while in the northern site, ERT 2 section is oriented N to S from the road 4432 to the north, to the residential area of Gábortelep, a small settlement between Csanádaapáca and Medgyesbodzás (Figure 19).

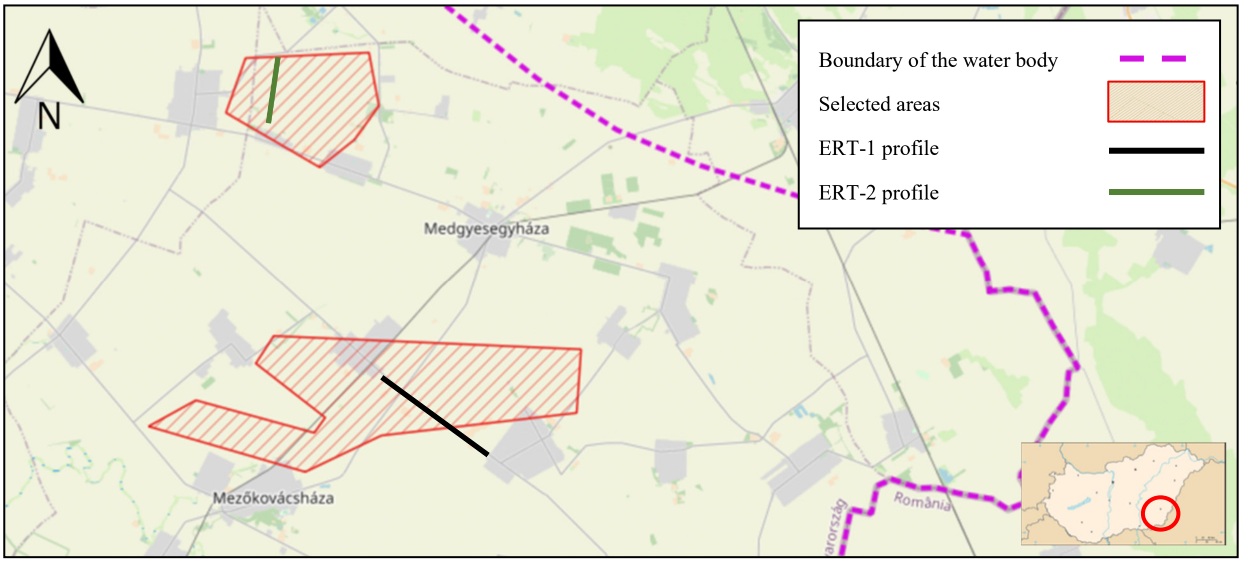

Figure 19. The location of the profiles of the preliminary geophysical (ERT) measurements used for final site selection

The applied geophysical method of investigation was Electrical Resistivity Tomography (ERT), a cost effective near-surface direct current geophysical imaging method frequently applied in groundwater research (see e.g. Loke 2004, Loke et al. 2013, Marsan et al. 2017). Upon injecting electric current into the ground via some electrodes, this method creates an electrical potential field in the surface that allows the mapping of subsurface specific resistivity distribution in rocks and sediments. The measured resistivity depends on many parameters, most importantly on rock components (for example clay content, salinity), water saturation, dissolved ions, etc. ERT is a multi-node system in which dozens of electrodes are connected to an instrument, automatically measuring specific resistivity for large number of subsurface points. Identification of rock types and geological formations is based on the resistivity pattern calculated via geophysical inversion (see e.g. Loke 2004). During the measurements, the reciprocal Wenner-Schlumberger electrode array, with an electrode spacing of 5 m, was applied. This allowed fast multichannel data acquisition with acceptable vertical and horizontal resolutions for the uppermost 50 m. Preliminary geophysical measurements showed basically 3 layers in both sites.

In case of the southern site, the ERT-1 profile had to be split into two lines (ERT-1 and ERT-1', Figure 20 and Figure 21) due to the main road that crosses the planned section in N to S direction. In both parts of the profile, we can see an approximately 8 to 15 m thick top layer showing high electrical resistivity values of 100-300 Ωm. This is followed by a low resistivity (5-20 Ωm) layer separating the third moderate resistivity layer (20-100 Ωm) from the top one. These resistivity values confirm our hypothesis about the geoelectric response of buried riverbeds and other aquifers in the area. The very high resistivity values at the top can be interpreted as coarse grain material (sands of different size and gravel) related to paleo-riverbeds (target of the underground dam). The low resistivity layer is an aquitard with higher clay or silt content and a thickness of 20 to 30 m. Below this clayish layer the moderate resistivity values indicate a second aquifer most probably fully saturated with water.

ERT-2 shows very similar settings (Figure 22), but with higher resistivity contrasts and therefore more clear contours of the different hydrogeological layers. The top layer here has a resistivity up to 500 Ωm and a thickness of 8 to 10 m. The aquitard layer is a bit thinner than in case of the southern site, having a thickness of approximately 10 m, while the deeper aquifer is defined by the 50 to 80 Ωm resistivity domain.

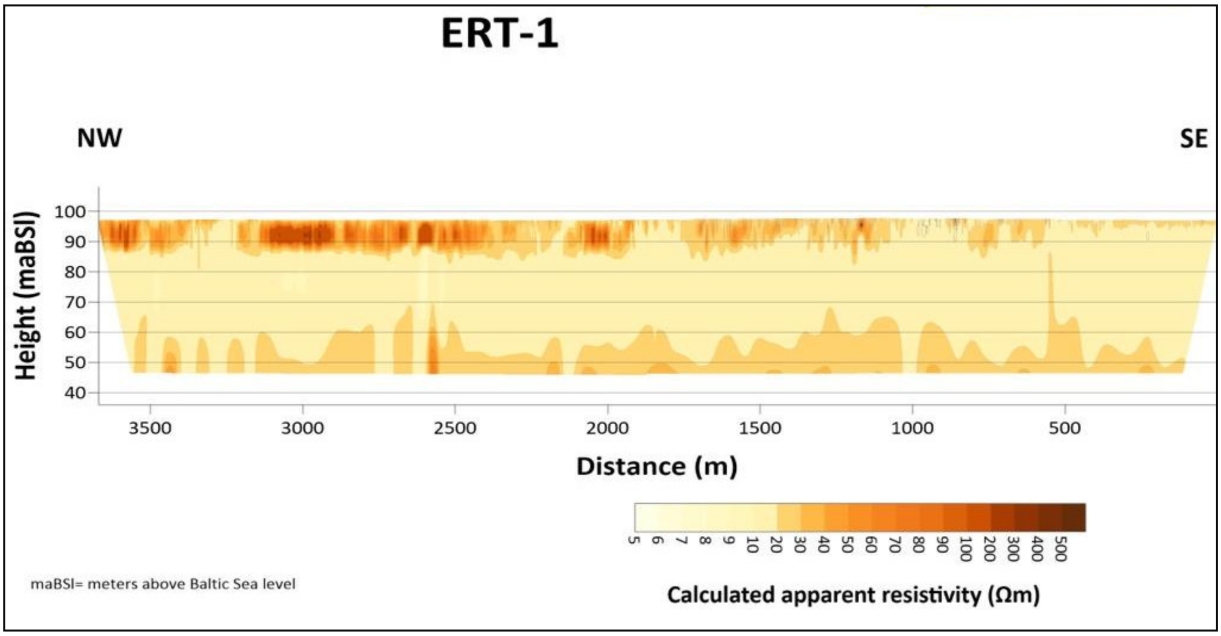

Figure 20: ERT profile in the vicinity of Kunágota, southern potential pilot site.

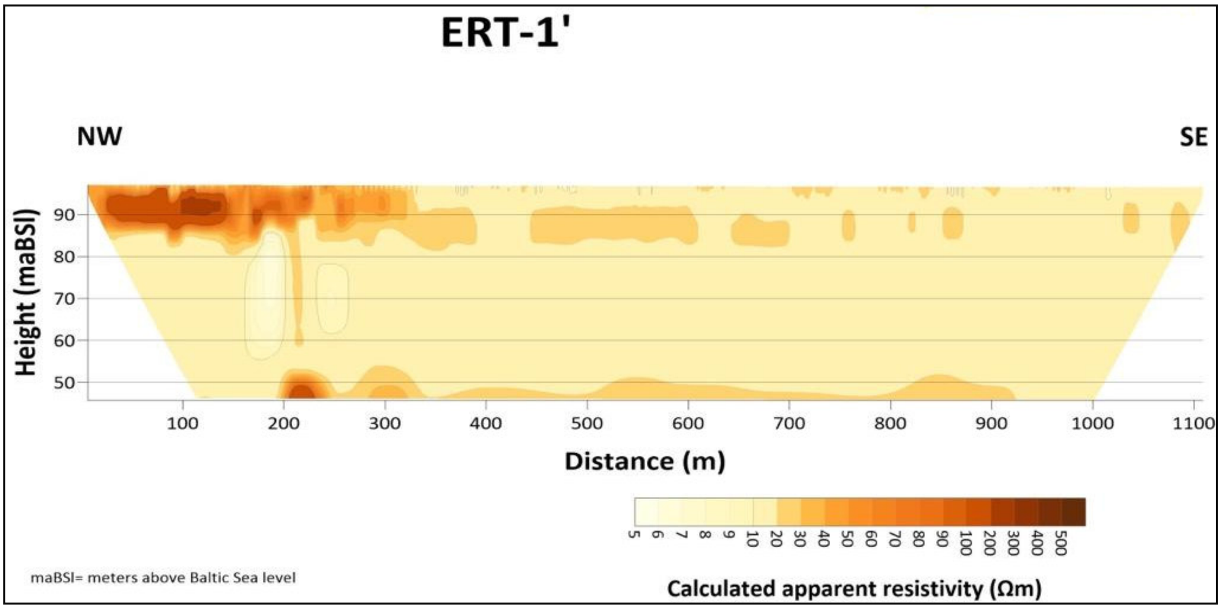

Figure 21: ERT profile in the vicinity of Magyarbánhegyes, southern potential pilot site

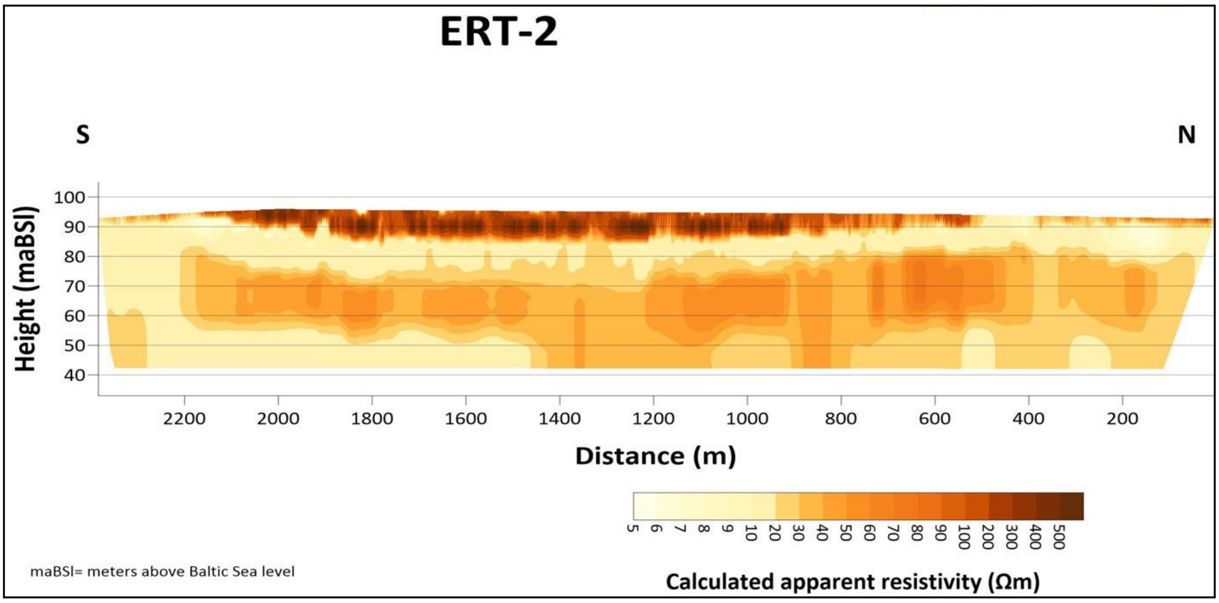

Figure 22: ERT profile between Medgyesbodzás and Csanádapáca, northern potential pilot site

Based on these test ERT profiles, we can say that both selected sites were found to be very promising for geoelectric investigation, and represent very similar hydrogeological settings with regard to the construction of an underground dam. However, the accessibility, as well as the obtained resistivity contrast during the geophysical survey, offers some preference towards the northern pilot site at Medgyesbodzás. For this site, we also have more archive geophysical data, and useful documentations from previous water resource studies. A deep monitoring well Medgyesbodzás K-54 (a former parameter borehole Csa-T1) in the middle of the northern site offers great potential for hydrogeological investigations too. In addition, this site can be very well defined both in geographic and hydraulic sense, as it is bounded by two artificial channels on its northern and southern sides. Following these advantages, the site at Csanádapáca-Medgyesbodzás was selected for the further investigations, and to carry out a demonstrative feasibility study.

5. Pilot action plan

5.1. Aims of the pilot action

In the framework of the project, the aim of the Hungarian pilot action is to examine the possibility of increasing the amount of available irrigation water by applying a MAR technology. In this way, sustainable water use can be achieved, especially during periods of water scarcity and vulnerability of the drinking water aquifers can be decreased.

Our goal is to collect information for the feasibility study of an underground MAR scheme and complete available archive data with in situ measurements.

According to the conceptual model, the task of the field investigation is to explore some well-defined paleo-channels, which are suitable for groundwater retention and storage. A paleo-channel is usually suitable for an underground dam MAR scheme if it is relatively isolated at its sides and has significant amount of groundwater supply through lateral recharge of groundwater as part of the regional flow system. The presence of an impermeable base layer separating the near surface paleo-channels from the underlying drinking water aquifer layers is also a critical factor (DEEPWATER-CE 2021).

Based on the integrated data evaluation, the feasibility of the underground dam MAR scheme will be tested by hydraulic model simulation.

The following sub-chapters describe the methodology of the detailed investigation of the selected site.

5.2. Plan of the detailed field work

The planned fieldwork includes electric resistivity surveys, special probe tests (modified Cone Penetration Tests or CPT), monitoring of groundwater levels, groundwater sampling and hydro-geochemical analysis.

5.2.1. Geophysical measurements

Electric resistivity measurements will follow the methodology described in Chapter 4. These electric resistivity data will provide an overview on the local geological, hydrogeological settings, including the location of paleo-channels and a hydrogeological framework for the hydraulic models. Geophysical sections are planned perpendicular with the paleo-channel beds derived from topographic maps (Sümeghy et al. 2013) and archive geophysical investigation (Draskovits et al. 1982). This survey geometry maximizes the chance of specifying the shape, thickness and boundaries of river beds (Figure 23).

Figure 23: The planned ERT profiles at the pilot site

5.2.2. Probe tests

In addition to geophysical profiles special probe tests (modified CPT test) will be carried out at 6 selected sites. These probe tests will be planned based on the resistivity survey to calibrate geophysical data with lithological/facies information. These tests will investigate and hopefully will also justify the presence of buried ancient paleo-channels of the Maros River, and provide data on the near-surface sediments, geological and hydrogeological conditions including parameters for the hydrogeological model. During the probe tests the vertical changes of peak resistance, mantle friction, specific resistance, natural gamma activity, neutron porosity and rock density of the media will be measured. The total length of the 6 probe tests is planned as 180 m, while the maximum penetration depth is planned for 30 m in each testing location.

5.2.3. Hydro-geochemical investigation

The hydro-geochemical investigation will provide information on the chemical composition of groundwater and characteristics of the groundwater flow system. Water samples will be collected from monitoring wells and temporarily established sampling sites from 3-4 different depth intervals.

The planned groundwater sampling will be carried out by the accredited sampling group of the Mining and Geological Survey of Hungary (MBFSZ) in two sampling campaigns (March-April 2021 and May-June 2021). The cited CPT test design refers to a technique called Khafagi probe procedure where temporary water sampling sites can be set up for selected depth ranges based on the results of the CPT measurements. After the water sampling the holes will be reclaimed.

The water samples need to be preserved and transported (according to the requirements of the planned analytical method) to the laboratory, where main components, trace elements and isotope analyses ($\delta^{18}O$, δD, $^{3}H/^{3}He$, ^{3}H, ^{14}C, $\delta^{13}C$, ^{39}Ar) will be performed. Main components and trace elements will be analysed by the laboratory of MBFSZ, while the isotope analysis is performed by Isotoptech Zrt.

Besides, precipitation samples are collected in the pilot area at Mezőhegyes on a monthly basis for six months to provide additional information on the recharge process. Analytical measurements will be performed for the main components and trace elements, and the samples will also be tested for ^{3}H and $\delta^{18}O$-δD isotopes.

5.3. Hydrogeological modelling

The aim of the hydrogeological modelling is to simulate the feasibility of an underground dam and its effect on the natural hydrogeological flow regime. As a starting point, a numeric model will be developed to represent the current situation without the MAR scheme ("zero solution" model according to DEEPWATER-CE 2020b) to incorporate the current knowledge on the hydrogeology of the area. The model area will be determined within the pilot area extending beyond the pilot site. The main frame of the "zero solution" model is provided by a conceptual model built on the results of the geological and hydrogeological evaluation of the archive data and field measurements.

After the calibration of the "zero solution" model, the object representing the underground dam will be added to the system. Different model scenarios will be simulated to visualize the effect of the underground dam with changing its locations and depths.

The different scenarios will help decision-makers and farmers to get information about the feasibility and the potential effect of this MAR scheme on the environment. However, this model serves as a demonstration of a methodology rather than being a step in the planning of an actual underground dam, it can provide basic information on cost benefit analysis to similar MAR investments in the area, too.

6. Summary & Conclusions

The aim of this report was to summarize the available information needed to support the feasibility study for an underground dam located in the Maros alluvial fan, which was selected as the wider pilot area in SE-Hungary. Based on the information gathered, a final pilot site was designated, and a plan was prepared for the field work and subsequent hydrogeological modelling seen as key activities related to the feasibility study.

The Maros alluvial fan has been the target of intensive geoscience research over the last century. Therefore, a huge amount of information and several thematic datasets (well and borehole data, hydrological, geological and hydrogeological maps, data of geophysical surveys, GIS databases and hydrogeological models, etc.) are available.

The low relief and moderately warm and moderately dry climate determine that the land use is dominated by agriculture. The sparse natural surface water network and the predicted trends in climate change models imply that there is an increasing demand for irrigation water in the area. The geological setting is characterized by a thick Quaternary series built up from the alluvial complex of the ancient Maros River. According to the integrated interpretation of borehole logs and geophysical maps, this alluvial fan is built up from several fluvial sequences. In the altering fluvial facies form interconnected aquifers that are part of a unified hydraulic system. The paleo river beds are the best suited shallow aquifers for a potential underground dam. The previously documented near surface paleo-channels have been found to be suitable for an underground dam MAR solution.

Based on suitability mapping several sites have been found promising for installing an underground dam MAR system. After the Toolbox-based site selection two potential sites were investigated. Based on (1) data availability, (2) preliminary field observations and (3) geophysical (ERT) profiles, the pilot site was delineated in the vicinity of Medgyesbodzás and Csanádapáca was selected as the final pilot site. As part of the feasibility study, a detailed plan was created for the fieldwork, to be providing data for the local numerical hydrogeological model. This field work includes a geoelectric survey, special probe tests (CPT), hydro-geochemical investigations and in-situ hydrogeological measurements.

A hydrogeological numerical model will be step up with available and measured data from field work. The model will be used to simulated different scenarios to predict the most suitable approach for installing an underground dam MAR system and estimate its efficiency in the porous floodplain alluvial systems of SE-Hungary. After the calibration of the “zero solution” model, the potential effect and viability of supposed underground dams of various locations and depths will be tested and evaluated through different scenarios.

All these activities will be summarized in the pilot feasibility study which will also contribute to the planned national policy recommendations and action plan for a better adoption of MAR.

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