O.T3.3 PILOT FEASIBILITY STUDY OF MAR SCHEMES WITH INTEGRATED ENVIRONMENTAL APPROACH IN POROUS GEOLOGICAL CONDITIONS IN SLOVAKIA

Slovakia O.T3.3

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1. Summary

The transnational decision support toolbox was developed on designating potentially suitable MAR locations in Central Europe within the DEEPWATER-CE project (output O.T2.1, DEEPWATER-CE, 2020b). Based on this toolbox, pilot sites with applicable MAR types were identified (deliverables D.T3.3-6.1-5). Furthermore, a common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies (deliverable D.T3.2.5) was proposed which was used in combination with the transnational decision support toolbox to identify the potential of a MAR application. Based on this methodology, to investigate the MAR suitable areas the general screening method was applied in the whole territory of Slovakia. The aim of screening selection criteria was to find suitable areas for a specific type of MAR (i.e. Recharge dam in Slovakia). In the areas which were selected as suitable ones from general screening, the specific selection criteria were applied, i.e. in Žitný Ostrov area, which is the part of Podunajska Lowland.

To reveal possibilities of MAR site construction, the regulatory framework related to MAR sites construction and water usage was summarised. Although similar systems are commonly used for drinking water supply in Slovakia, they are not specified as MAR. Therefore, in Slovakia, in fact there is no legal framework for MAR usage or monitoring. But on the other hand, there is an obligation to respect the rules related to water management established by 2000/60/EC EU Water Framework Directive (WFD). It is transposed to national legislation in Act No. 364/2004 Coll. on Water and amendments of Slovak National Council Act No. 372/1990 Coll. on Offences as amended (Water Act), published in Journal of Laws 153/2004. At national level there are several binding legislative documents related to groundwater replenishment, water abstraction, water quality for irrigation, etc., which are ruled by the State Water Administration Authority, Department of Environment, which is the respective authority at both national and regional levels. It specifies the conditions of water usage in the Permit for Water Usage. Other state institutions involved in water management are the Slovak Water Management Enterprise, state enterprise (SVP, š.p.) which is the administrator of water courses; Slovak Hydrometeorological Institute (SHMU) registers the amounts of abstracted water. The Slovak Environmental Inspectorate is responsible for water quality control at all levels.

The Danube River created an extensive branch system on the territory of the Žitný Ostrov. The natural character of the river was altered by embankments and equalizing parts of the watercourse. The pilot area in Žitný Ostrov is roughly delineated by the towns of Šamorín, Dunajská Streda and Gabčíkovo. It is bordered primary channel S VII (Gabčíkovo-Topoľníky channel) and secondary channels A VII (Vojka-Kračany,) and B VII (Šuľany-Jurová,). The dense network of irrigation channels equipped with technical tools (sluices/gates) for regulation of water flow is a crucial point to create recharge dam MAR type, i.e. accumulation of water between closed sluices. The pilot area is agricultural land. It is located in the Slovak part of the Danube Basin, occurring in north-western part of the Pannonian Basin System. The sedimentary in-fill of the depression is represented by Neogene and Quaternary sediments. The thickness of Neogene sediments in the Gabčíkovo-Győr depression reaches more than 8 500 m (Kilényi &Šefara, 1989; Hrušecký, 1999), and is overlain by up to 320 m thick Quaternary sedimentary cover (Šujan et al., 2018). Benková et al. (2005) estimated the average values of the hydraulic conductivity coefficient Quaternary gravels and sandy gravels in the wider area of the pilot site on $2.91*10^{-3}$ ms^{-1} and the transmissivity coefficient on $2.96*10^{-2}$ m^2s^{-1}. The Quaternary sediments have mostly the phreatic groundwater table. Groundwater in Quaternary sediments of the evaluated area can be generally characterized as fluviogenic water having origin of its chemical composition in infiltrating water from the surface water courses. The main cations are calcium and magnesium, values of iron and manganese contents are often increased. The main anions are bicarbonates and with lower values of sulphates. Presence of nitrites and nitrates indicates the anthropogenic pollution. Groundwater is of middle to high mineralization. The basic distinct $Ca-HCO_3$ and basic non-distinct $Ca-(Mg)-HCO_3$ chemical types prevail.

Groundwater regime from the long-term point of view was influenced by the Gabčíkovo Waterworks, which was constructed on the Danube River between Čuňovo and Gabčíkovo villages, put into operation in 1992. The waterworks consists of the Čuňovo Dam, Hrušov water reservoir (headwater installations) with an area of 40 km^2, the bypass channel (headwater channel and tailwater channel), and the series of locks on the bypass channel (hydropower plants and navigation locks). The Hrušov water reservoir fills left-hand seepage channel, which is the water supply source for channel network of the Žitný Ostrov. The channel network of Žitný Ostrov consists of six main, partially interconnected channels: Gabčíkovo-Topoľníky channel, Chotárny channel, Čalovo-Holiare-Kosihy channel, Aszód-Čergov channel, Čergov-Komárno channel, and Komárňanský channel. The pilot site is located in the sub-basin of Gabčíkovo-Topoľníky channel (S VII) with its sub-channels - Vojka-Kračany (A VII) and Šuľany-Jurová (B VII).

The investigation work in pilot site started by desktop analysis of pilot site area. Within this analysis there were summarised relevant available archive data used for pilot site area characterisation. Main characteristic of the pilot area are geomorphology, climatic conditions, land use, hydrology, geology and hydrogeology. Aspects of existing infrastructure and regulatory limitations were also considered. The information on geology and hydrogeology to characterise the pilot site were collected from archive data of the State Geological Institute of Dionyz Stur. Desktop analysis collected and evaluated archive data in order to plan the field work investigation properly to gain the remaining necessary information/data.

The field measurements aimed at the quantification of infiltrated surface water from recharge dam MAR scheme in order to replenish groundwater resources. The assessment and quantifying the possibilities of aquifer recharge by (i) assessment of lateral range of infiltrated surface water impact on groundwater level based on data of investigated hydraulic conductivity of soil; (ii) modelling the surface water and groundwater interaction and (iii) proposal of scenarios for technical regulation of water flow in channels to ensure groundwater recharge in pilot area. Since long-term measurements were applied, all agricultural seasons were covered, so it was possible to investigate time changes of water demand for crop irrigation. The field measurements and their interpretation were done by PP6 (Water Research Institute) in cooperation with the Slovak University of Technology, Bratislava. Field measurements covered flow measurements in channels, geometry of channels, groundwater table measurements, soil sampling and measurements of soils/rocks hydraulic properties. The latter was done by the auger hole method in the field and the measurement and evaluation of retention curves in laboratory. The soils samples were evaluated in the laboratory in order to get input data to calibrate the numerical models (MODFLOW and HYDRUS-2D).

Representative sites for soil sampling were located in vicinity of adjustable sluice gates, allowing control of the water table level in the channels to perform infiltration tests. Soil samples were measured in laboratory to obtain the data on hydraulic conductivity of water-saturated soil (method of variable hydraulic gradient); soil bulk density and its vertical distribution and soil water retention curves (measurements and calculation). The measured hydraulic conductivity of the surface rocks varies based on content of silty/clayey particles, and in general, the top surface soil is less permeable than deeper parts of Quaternary sandy gravels. The investigation revealed the differences in the hydraulic conductivity distribution in aquifer (350,20 cm/d); sediment in channel (2,88 cm/d) and soil (6,24 cm/d). It is obvious that aquifer is the most permeable and sediment is impervious (compared to aquifer). However, we should notice that due to form sediment in fine particles suspension on the bottom of channels, it is more permeable than expected.

Groundwater level measurements were performed at 3 points using hand-drilled probes at the Jozefov site where groundwater table in 2 probes oscillated in the depth around 1m below surface.

From evaluating the water chemistry of surface water and groundwater and assessing potential risks of pollution by scattered environmental loads and larger potential polluters (the industrial enterprises have their own waste water treatment plants), it was found that they do not pose remarkable threat on water pollution or produce priority substances. Therefore, these are suitable for MAR systems according to the water chemistry as well as according to evaluation of ecological potential of surface waters.

Water demand is growing globally, and among economic sectors, agricultural production (especially crop production) is one that mostly relies on the availability and quality of water. This challenge is exaggerated by the changing climatic conditions that affect noticeably crop production and lead to the increased need for irrigation water. It is essential to mention that due to limited data available for the pilot study area when calculating benefit values, we used data for the reference area – the northern part of Podunajska lowland, which is quite comparable in terms of the number of agricultural producers and hydrogeological conditions. Also, climate conditions in the pilot study area are expected to converge to those in the selected reference area over the project lifespan. Nevertheless, obtained CBA results should be treated as more indicative and with a portion of cautiousness.

Annual operation and maintenance costs depend heavily on the amount of irrigation water demand and water supply by the MAR scheme. Annual level of MAR scheme water supply and projected volume of annual irrigation water demand in 30 years. The level of water supply is estimated under the condition of 3 new sluices/weirs added, in other words, more water can be stored in recharge dams created along the channel in order to increase the infiltrated water amount. The projected water demand in 30 years is evaluated in the range - min 8,699,090 m^3 and max 15,004,000 m^3 while the expected water supply in dry year is 11,967,985 m^3 and in wet year 15,042,745 m^3. The range of values of annual irrigation water demand is estimated taking into account long-term climate forecasts, anticipating that the pilot study area will be vulnerable to droughts. The assumption behind the minimum scenario is that irrigation water demand in 30 years will be 20% higher than the current level in the reference area. When it comes to the maximum expected irrigation water demand, its level is estimated based on a linear trend.

Water supply was assessed by mathematical modelling. The mathematical modelling by MODFLOW enabled to model the potential amount of water infiltrated water into groundwater. A numerical model was developed using the MODFLOW program in the Groundwater Modelling System (GMS) environment, which allows us to use the conceptual model approach. The modelled area was bounded by the left-hand side seepage channel of the supply channel of Gabčíkovo water structure and 13 observation wells of the State Hydrological Network of groundwater quantity monitoring of the Slovak Hydrometeorological Institute. Three hydrological years have been selected for the data analysis, i.e. 2008 as the year which can be characterized as the precipitation normal year; 2010 as the wet year extremely (precipitation above normal); and 2018 with extremely low precipitation totals recorded in April, May, July and October. Then 2 scenarios (prognosis) have been examined on the A VII channel for above mentioned periods 2018 and 2010, i.e. Prognosis 1 – water level corresponded to the maximum levels at each weir when gate slides in the rkm 0.000 and 17.171 were closed; Prognosis 2 – water level corresponded to the maximum levels at each weir when the gate slides on the rkm 0.0 and 17.171 were closed and additional 3 newly proposed weirs in the rkm 2.270, rkm 7.060 and rkm 12.530 were in operation (the height of each gate slide is 1.6 m). Zero variant was the natural conditions – open gates surface water level regime.

The results of modelling showed the potential infiltration amount of surface water to groundwater – in Prognosis 1 it corresponds to 37910 [m^3.d^{-1}] in wet year and 23598 [m^3.d^{-1}] in dry year and in Prognosis 2 it corresponds to 41213 [m^3.d^{-1}] in wet year and 32789 [m^3.d^{-1}] in dry year. It is evident that the amount of water infiltrated into aquifer after operation on existing weirs (Prognosis 1) increased in both investigated years more than 40 % (wet year 2010) and more than 60 % (dry year 2018). The infiltrated water amount into groundwater can be increased by construction of additional three weirs (Prognosis 2) up to more than 50 % (wet year 2010) and more than 75 % (dry year 2018) in comparison with the natural surface water level regime (Zero variant). The present operation on water structures on the S VII channel system by Slovak Water Management Enterprise enables the realisation of managed aquifer recharge.

The model HYDRUS-2D is a mathematical, deterministic model simulating the transport of water, heat and multiple solutes in variably saturated porous media (soil) (Šimunek, et al., 2013). Model HYDRUS can be applied as one dimensional (HYDRUS-1D), as well as two and three dimensional (HYDRUS-2D/3D). As input data to the model hydraulic characteristics of soil (saturated/unsaturated hydraulic conductivities, soil water retention curves, properties of plant canopy and atmospheric characteristics. These characteristic were obtained mainly from fieldwork investigation. Groundwater table level change during aquifer recharge by infiltration from channel can be calculated (by the model HYDRUS 2D). Infiltration of water from channels was assessed in 3 scenarios:

(i) channel is located in upper layer of quaternary sediments (gravel with silt) with different water table level in channel. Modelling episode assumes immediately increase of water table in the channel, by closing sluice gates. During quasi-steady state (QST), the infiltration rate is between 100–350 m^3 km^{-1} day^{-1}.

The length of the channel system in pilot area is 100.86 km, which means, the total inflow into aquifers is in between 10,000 – 35,000 m^3 day^{-1}, which corresponds to the data estimated by simulation model MODFLOW (Šoltész et al., 2021). This is about one tenth of the average daily evapotranspiration. During initial state of infiltration this rate can be up to 25 times higher, than quasi-steady rates, but it is covering narrow strip of soil around channels only. The particular rate of infiltration depends on channel dimensions, hydraulic properties of porous media, channel bottom sediments properties and height of water table in channel. The most important factor influencing inflow rate is the water table level in the channel. Water table when sluices are open is around 0.5 m; the maximum water table is 2.0 m at closed sluices.

(ii) channel in porous media and soil layer above the aquifer. Because soil saturated hydraulic conductivity is significantly lower than the gravel layer, the rate of infiltration is significantly lower than it is in an ideal case. The channels are located in the area covered by relatively impermeable topsoil layer with thickness 1 -2.5 m. The thicker topsoil layer is, the lower rate of infiltration can be expected. The soil layer (i.e. lower hydraulic conductivity than aquifers) can decrease the quasi-steady inflow rate about 10 percent, in comparison to channel without soil layer.

(iii) channel in homogeneous gravel layer with bottom sediments. The aim of modelling was to evaluate quantitatively the role of bottom sediments on infiltration rate of water from channel. The infiltration rate of water is indirectly proportional to the sediment thickness. Bottom sediments in channels are thick 0.5 - 1.0 m (lower value is more frequent). It was observed relatively low significance of the influence to the thickness of the sediments on infiltration rate. The reason is in relatively high hydraulic conductivity of saturated sediments (K_s) in comparison to the soil, or upper layer of aquifer clogged by small particles transported during infiltration of water through bottom sediments. The bottom sediments have low density and their particles are in the state of "floating" in water, i.e. relatively high hydraulic conductivities.

Properly managed water retention in channels and consequent surface water infiltration from channels to the aquifers (MAR), can significantly improve soil-water regime, especially during dry season. In this case, the rate of water infiltration can be expected higher due to higher hydraulic gradient. MAR as a method of groundwater replenishing in Žitný Ostrov can be particularly useful in situation, when water level of Danube river (and discharge as well) will be extremely low, which can be a real situation in near future due to climate change.

The risk assessment of MAR schemes recognized possible risks for the MAR system coming from environmental and human health, technical, socio-economic, governance and legislative risks as well as risks related to the sensitivity of MAR to climate-induced extreme situations.

Risks were assessed by combination of two methods; i.e. risks were identified according to the methodology developed by MARSOL project (Rodrigues-Escalantes et al. 2018). Quantitative risk assessment was done in with risk factor matrix by Swierc et al, 2005 (also mentioned as a method in the Australian guidelines) (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009) where the likelihood and the severity of a risk is interpreted by risk factor matrix. According to MARSOL methodology, there were evaluated quantitative technical and non-technical risks (social, economic, governance & legislation) during design, construction and operational phases.

In Slovakia, the identified risks, i.e. risks related to environment and human health, technique, socio-economic issues, governance, legislation, and risks related to the sensitivity of MAR to climate-induced extreme situations; were evaluated in two phases – (i) design and construction phase; and (ii) operational phase, where technical and non-technical risks were summarised.

As non-technical risks during design and construction phase, the lack of private/public funding was identified as very high risk. Possible treatment is to disseminate and publicize the MAR schemes benefits to be able to involve as many investors as possible. Within this group, two other risks were evaluated as high: low price of water and high installation cost. Low price of water risk was evaluated in operational phase as well. These risks can be overcome by additional support for the use of MAR facilities (state support, private financial sources) in order to promote its financial viability.

Evaluation of technical risks revealed several high probabilities of occurrence during design and construction phase: construction technical difficulties, risk of low water storage, hydrogeological setting. These risks can be treated by preparation of specific technical project, and proper and detailed geological and hydrogeological investigation. During operational phase, high risks are represented by swelling clays, nutrients, droughts and rainfall events periodicity, changes in water demand and supply. To treat this group of risks there considered following issues accordingly: (i) detailed study on geological/rock mechanic conditions of the channels banks; (ii) agricultural pollution can be avoided by applying of Good Agricultural Practice and waste water pollution by centralised sewage system and WWTP; (iii) efficient manipulation with water in channels; (iv) proper regulation of water flow in channels and monitoring of water quantity/quality.

To ensure effective functioning of the MAR system and to be informed about all risks mentioned above in time, the thorough monitoring system of risks should be put into operation. Recognized risks for the MAR system are connected with climate change. It is apparent that there will be still more water needed in the vegetation period for the agricultural plants because of greater differences between precipitation on one side and evapotranspiration on the other, especially in vegetation period.

Economic assessment of projects checks whether the net benefit of the project’s implementation is positive. So, economic efficiency analysis is applied, and more specifically cost-benefit analysis (CBA). An important part of CBA studies is the incorporation of uncertainty in the analysis. To include this element in our analysis, we developed scenarios with plausible variations of the main CBA parameters and checked sensibility of the net present value (NPV) of the MAR scheme to these elements. The report also contains the expert assessment of two dimensions of socio-economic risks associated with the MAR scheme: their probability and magnitude of consequences.

The range of values of annual irrigation water demand is estimated taking into account long-term climate forecasts, anticipating that the pilot study area will be vulnerable to droughts. The assumption behind the minimum scenario is that irrigation water demand in 30 years will be 20% higher than the current level in the reference area. When it comes to the maximum expected irrigation water demand, its level is estimated based on a linear trend.

To estimate both use and non-use (socio-environmental) benefits, a survey was conducted to explore the maximum amount of money that local farmers and agricultural producers 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.

To conclude whether the MAR scheme is economically feasible, we compared direct costs and benefits associated with it. 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. Obtained positive differences between direct costs and benefits suggest that the MAR scheme is economically feasible, having a positive expected NPV over 30 years of project lifespan. Calculations of the NPV over 30 years for 3 scenarios (max, average, min) showed positive results of project feasibility in all cases.

WTP survey results provided useful insights on agricultural production in the pilot area, farmers’ knowledge regarding groundwater issues, and their perceptions. However, since the pilot area is quite small and we obtained only 10 full survey responses, it prevents us from using regression techniques to estimate mean WTP, controlling for farmers’ characteristics. Thus, we do not calculate the expected total economic value of the MAR scheme and make conclusions based on direct costs and benefits comparison. At the same time survey results are helpful for defining policy recommendations.

The pilot area was deemed a suitable site for applying managed aquifer recharge (MAR) in the future to maintain and restore groundwater resources.

2. Introduction

DEEPWATER CE project focuses on developing an integrated implementation framework for Managed Aquifer Recharge (MAR) solutions to facilitate the protection of Central European water resources endangered by climate change and user conflicts.

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, the partners implemented the transnational methodology Managed Aquifer Recharge (MAR) techniques to increase long-term retention of water in aquifers and its subsequent use in drier or increased demand periods. Originating from transnational toolbox for designating potential MAR locations in Central Europe developed in the frame of DEEPWATER CE project (DEEPWATER-CE, 2020a), the MAR pilot sites in the project participating countries were identified, namely in Hungary, Poland, Croatia and Slovakia. Within investigation of 4 pilot areas there were considered geological, hydrogeological, technical, regulatory, socio-economic and human health aspects. Within DEEPWATER CE project the guidance and methodology of the feasibility study of MAR schemes was developed and described in the report (D.T3.2.5, DEEPWATER-CE, 2020b).

Based on above-described methods applied in the territory of Slovakia, the Podunajska Lowland, namely Žitný Ostrov area, was chosen as pilot area for MAR scheme. From climatic models, this area is predicted to be highly exposed to dry periods, from geological viewpoint there are Quaternary sandy-gravel porous aquifers and the area is intensively cultivated. Moreover, there is already existing dense network of functioning irrigation channels with technical tools for water flow regulation. The technical tools (sluices, gates) enable to create recharge dam MAR type, i.e. to store surface water between closed sluices that prolongs the period of surface water infiltration into groundwater. Above mentioned conditions qualified the area as the appropriate pilot area for recharge dam MAR scheme investigation in Slovakia. In the pilot area, roughly delineated by Šamorín, Dunajská Streda and Gabčíkovo towns, fieldwork involving the soil sampling and measurements of soils/rocks hydraulic properties was performed in order to provide input data for mathematical models calibration. The aim of mathematical modelling was to investigate interaction between surface water level and groundwater table as well as calculate the potential infiltrated amounts to groundwater.

This report summarises the work, done by PP6 in cooperation with Slovak University of Technology in Bratislava, at pilot site area in Žitný Ostrov: desk analysis of the pilot feasibility study for MAR deployment in porous aquifers in areas used for agricultural purposes (D.T3.5.1); field work of the pilot feasibility study for MAR (D.T3.5.2); compiled check list for the application of risk management protocol during the field works for MAR (D.T3.5.3); mathematical modelling, comparison of alternative solutions and Cost-Benefit Analysis in Slovak Pilot Site prepared by Technical University in Munich. The overview information on regulations framework was compiled on data from collection of national legislation and policies on MAR.

3. Regulatory framework

In fact, in Slovakia, there is no legal framework for MAR. Rules related to water management are established by 2000/60/EC EU Water Framework Directive (WFD), which is transposed to national legislation in Act No. 364/2004 Coll. on Water and amendments of Slovak National Council Act No. 372/1990 Coll. on Offences as amended (Water Act), published in Journal of Laws 153/2004. The management of water extraction, water sources protection, water quality, payments for water, etc. is controlled by several regulations and decrees as Decree No. 418/2010 Coll. on performance of some clauses of the Water Act as amended by Decree No. 212/2016 Coll., which requires recording of data on amounts and water quality in respective water bodies; Decree No. 247/2017 Coll. on specifics of drinking water quality, control of drinking water quality, monitoring programme and risk management by drinking water supply as amended; Regulation No. 269/2010 Coll., setting up requirements to reach the good water status (in Annex 2); Regulation No. 452/2019 Coll. which amends Regulation No. 282/2010 Coll. on threshold values and list of groundwater bodies; Regulation No. 755/2004 Coll. on amount of non-regulated payments, amount of charges and specifics connected to payment for water use as amended by Decree No. 394/2016 Coll.; Decree of the Regulatory Office for Network Industries No. 21/2017 Coll. on price regulation of production, distribution and supply or drinking water by water supply network and waste water discharge and cleaning by public sewerage as amended by Decree No. 204/2018 Coll.; STN 75 71 43 Water Quality, Irrigation Water; and others.

Related to above mentioned, the conditions for water abstraction are specified under the Water Act (364/2004 Coll.), but not specifically on MAR although, in Slovakia, there are riverbank filtration types of MAR sites. These are used as one of the most common methods to abstract water in the Danube lowland, but also near other big Slovak rivers (Hron, Váh, Hornád). None of the institutions is responsible for the implementation of these types of MAR, since it is considered as a common technical solution to abstract water from river fluvial sediments. The reason why “MAR schemes” i.e. bank filtration are used in Slovakia is to abstract high-quality groundwater for drinking water supply. This definitely shows the necessity to include these solutions into the Slovak legislative framework; improve technical solutions of proper MAR schemes and their financial evaluation; and to prepare the conditions to implement them for various purposes, for instance agriculture, during drought periods within the current climate change conditions.

Specific permission is required for the artificial increase of groundwater amount using the surface water, according to the MAR related content of the National Law. For water quality implications the Water Act requires recording of data on amounts and water quality in respective water bodies including their influencing by human activities in places of artificial increase of groundwater amounts.

Regulation on the prevention and remediation of environmental damage is applied. The operator is liable to prevent the occurrence of environmental damage and imminent threat of environmental damage and need to secure financial coverage of liability for environmental damage throughout the operational cycle.

Separate regulation lays down details on the definition of the river basin district, environmental objectives, economic analysis and water planning. This includes also evaluation of the payback period and analysis of cost effectiveness.

The sewage water and special water containing dangerous compounds are prohibited to be recharged into groundwater. Sewage water or special water containing contaminants which are not dangerous, but potentially risky for groundwater quality, can be released into groundwater body only under specific conditions. Discharging of any kind of water into groundwater must be permitted by the State Water Administration Authority, Department of Environment, which is the respective authority at both national and regional levels. It specifies the conditions of water usage in the Permit for Water Usage. Other state institutions involved in water management are the Slovak Water Management Enterprise, state enterprise (SVP, š.p.) which is the administrator of water courses; Slovak Hydrometeorological Institute (SHMU) registers the amounts of abstracted water. The Slovak Environmental Inspectorate is responsible for WQ control at both national and regional levels.

There are no special national regulations in place concerning operational monitoring of MAR systems. Anyway, existing rules of surface water and groundwater monitoring can be effectively applied for monitoring of MAR system operation.

Surface water and groundwater monitoring is done under EC Directives, particularly the Water Framework Directive (2000/60/EC), Groundwater Directive (2006/118/EC) and Nitrates Directive (91/676/EEC). Surface water monitoring is performed in accordance with Act No 364/2004 Coll (Water Act); Act No 201/2009 Coll. (on state hydrological service and state meteorological service); Act No 7/2010 Coll., (on flood protection) and Government Regulation No 269/2010 Coll (on requirements to achieve good status of waters), Government Regulation No 167/2015 Coll (on environmental quality standards in the field of water policy), Government Regulation No 201/2011 Coll. (on technical specifications concerning chemical analyses and monitoring of water), Government Regulation No 354/2006 Coll. (on drinking water standards) in accordance with Decree No 418/2010 Coll. of the Ministry of Agriculture, Environment and Regional Development of the Slovak Republic (on occurrence, monitoring and assessment of quantity and quality of surface water and groundwater).

Groundwater monitoring relates to item 4 of Collection of Slovak Republic, Act No 364/2004 Coll (Water Act), Act No 201/2009 Coll. (on state hydrological service and state meteorological service), Act No 569/2007 Coll. (Geological Act), Act No 7/2010 Coll. (on flood protection), Government Regulation No 416/2011 Coll (on the assessment of chemical status of groundwater body) and Decree No 418/2010 Coll. of the Ministry of Agriculture, Environment and Regional Development of the Slovak Republic. Surface water and groundwater monitoring data are stored in the Slovak Hydrometeorological Institute.

Surface water monitoring is partially performed by the Slovak Water Management Enterprise and Water Research Institute, other monitoring activities are covered by Slovak Hydrometeorological Institute. Within the River Basin Plan of Slovakia, framework programmes of water monitoring covering 5 years are prepared. The framework programme of water monitoring in Slovakia for the period 2016 – 2021 can be found at:

http://www.vuvh.sk/RSV2/download/02_Dokumenty/26_Ramcovy_program_monitorovania_vod/RPM_2016_2021.pdf

Moreover, there are other documents relevant for water policy in Slovakia such as the (i) Flood Risk Management Plans; (ii) Strategy on climate change adaptation in Slovak Republic (2018); (iii) Water is value – Action plan on drought and water scarcity impacts (2018) and (iv) Slovak Water Policy (2021).

Direction 2011/92/EU Environmental Impact Assessment (EIA) Directive is transposed to Slovak legislation in the Act No. 24/2006 Coll. on environmental impact assessment as amended, published in Journal of Laws 13/2006. The rules on Environmental Impact Assessment stipulate that wells enabling the abstraction of groundwater or artificial groundwater recharge, with a water abstraction capacity of not less than 10 million of m^3/year, are classified as projects that can always have a significant impact on the environment and require an EIA report. On the other hand, wells enabling the abstraction of groundwater or artificial groundwater recharge with a water abstraction capacity from 3 million m^3/year to 10 million m^3/year, are classified as projects that may have potential impacts on the environment and should undertake the process of determining whether the projects shall be made subject assessments.

4. Characterization of pilot sites

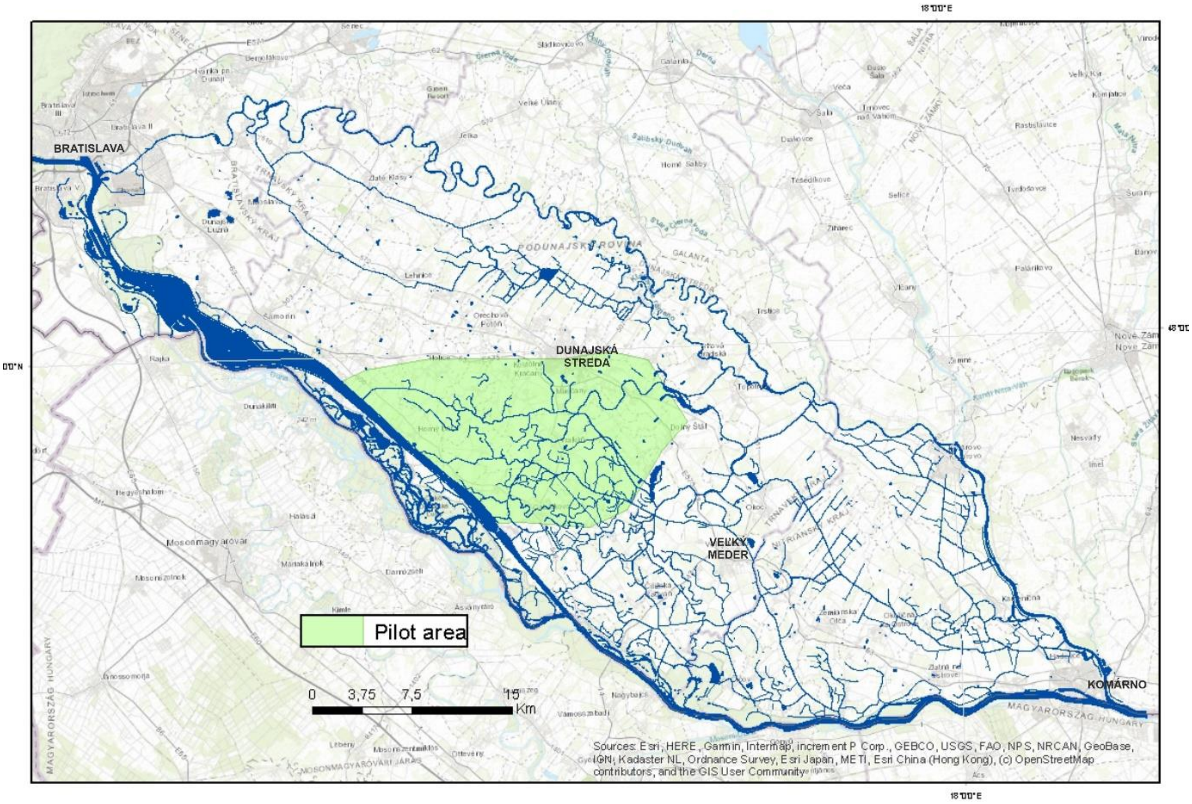
4.1. Pilot site description

4.1.1. Geomorphological and climatic conditions

The Žitný Ostrov area is located in the south-western part of Slovakia, on the border with Hungary. In the south-west, its boundaries are formed by the banks of the Danube, in the north by the branches of the Little Danube, and on a short stretch in the east, it is bounded by the Váh River. The territory belongs geographically to the Podunajska (Danube) Lowland. According to the geomorphologic division (Landscape Atlas of SR, 2002), the pilot area is situated in the geomorphologic unit called Danube Plain (Podunajská rovina) and is a part of Čiližská mokraď sub-unit. The Žitný Ostrov has an elliptical shape, its length is 84 km, the width ranges between 15 and 30 km, and the total area is 1635 km2 (Benková et al.,2005). With its dimensions, the Žitný Ostrov is the largest river island in Europe. The pilot site area is situated in the middle part of the Žitný Ostrov and it covers around 226 km2 (see Fig.1.).

The topography of the pilot site area is similar to the whole Žitný Ostrov, i.e. a lowland area with low slope and small differences between elevations above sea level. The highest point on the Žitný Ostrov area is located near Šamorín (134 m above sea level), and the lowest is the area at Komárno (105 m a.s.l.) (Dušek & Velísková, 2017). The altitude of the terrain in the locality is 110 m a.s.l. up to 122 m a.s.l. The slope in the area is up to 1°.

The most common soil types in the area arechernozems, mollic fluvisols.and fluvisols. According to the texture classification, soils are mostly loamy, clayey - loamy and sandy – loamy (Landscape Atlas of SR, 2002).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Fig.1 Pilot site area in Žitný Ostrov

The climatic conditions of the area are determined primarily by geographical factors, by its latitude, longitude and altitude. According Konček´s climate classification scheme, the Žitný Ostrov area is situated mostly in warm region (Climate Atlas of Slovakia, 2015). Pilot site area is situated in warm, very dry sub-region with mild winter. The average annual air temperature (for the period 1961-2010) is higher than 10°C. During spring and autumn the average air temperature is also higher than 10°C. The average air temperature in summer (April to October) ranges from 19 to 20°C. Total annual precipitation (for the period 1981-2010) vary between 600 – 551 mm in the major part of the pilot area, and between 550 – 522 mm in the southern part of our study area. These amounts are the lowest in Slovakia and are typical for areas in the south of Slovakia. Total precipitation in the summer period (April-October) vary in the range 350 – 307 mm. The lowest values are typical for winter, ranging between 40 and 21 mm. The mean annual potential evapotranspiration (for the period 1961-2010) is higher than 700 mm (Climate Atlas of Slovakia, 2015).

From an agricultural point of view, the district belongs to the suburban region of Bratislava, to the maize agricultural production area and to the lowland warm agricultural natural area (Blažík et al., 2011).

The area is located in the region where climate change in Slovakia has been manifested in recent decades, the climate has changed from warm and dry to warm and very dry compared to the second half of the 20th century (Mello et al., 2010).

4.1.2. Hydrology

The Danube River created an extensive branch system on the territory of the Žitný Ostrov. The natural character of the river was altered by embankments and equalizing parts of the watercourse. This has also changed the natural hydrological conditions: the Danube's branches and meanders were separated from the main stream by the embankments. The current hydrological conditions are strongly affected by building the Gabčíkovo hydro-power water structure (VD Gabčíkovo). The channel network of Žitný Ostrov consists of six main, partially interconnected channels: Gabčíkovo-Topoľníky channel, Chotárny channel, Čalovo-Holiare-Kosihy channel, Aszód-Čergov channel, Čergov-Komárno channel, and Komárňanský channel. The total area covered by the current drainage system is 1469 km^2. The area of drainage with a built-up channel network is 1252 km^2. The total length of the channel network is almost 1000 km. Its density is about 1 km/1.25 km^2. The most important channels in the drainage system are the Chotárny and Gabčíkovo-Topoľníky channels, which flow into the Little Danube (Dušek & Velísková, 2017). The Gabčíkovo-Topoľníky channel, which stretches in our pilot site area is interconnected with the Danube River by an inflow structure and leads to the Klátovský branch of the Little Danube (Malý Dunaj). According to hydrological distribution, the area belongs to the catchment of the Váh River (No.4-21) and sub-catchment of the Little Danube - Malý Dunaj (No.4-21-17, from Čierna voda to estuary). The west- southern boundary of our pilot site area is situated on the border of two catchments: Danube and Váh Rivers, formed by seepage channel on the left side of the Hrusov Reservoir.

According to the SR Government Regulation No 211/2005 Coll. the Gabčíkovo – Topoľníky channel and also its tributaries, channels Vojka – Kračany and Šuľany – Jurová are considered as significant water management watercourses. Based on the second River Basin Management Plans (2016-2021), one artificial surface water body: SKW0023 – P1M - Gabčíkovo-Topoľníky was identified within the pilot site area. Based on evaluation results (monitoring period 2013 – 2018) the water body has moderate ecological potential and does not reach good chemical status. Slovakia has an exception for this water body according to the Article 4(4) for an extension of the deadline to reach good chemical and ecological status beyond 2027.

Pilot site area is a part of Quaternary groundwater body SK1000300P Intergranular groundwater body of Quaternary sediments of the central part of the Danube Basin, which reaches good chemical and quantitative status. Neogene aquifers in the area belong to Pre-Quaternary groundwater body SK2001000P Intergranular groundwater body of the central part of the Danube Basin and its folders and reaches bad chemical (NO_3^-) status with a high degree of reliability, and good quantitative status. The results of groundwater monitoring in 2019 show overcoming of limit concentrations of iron and manganese (compared to limits values in the

Regulation of the Ministry of Health of the Slovak Republic No 247/2017 Coll.). These higher concentrations influence only organoleptic properties of the water and they do not represent any danger for health.

Directive 2007/60/EC on the assessment and management of flood risks (EU Floods Directive, FD) came into force in 2007. The first Flood Risk Management Plan for the Danube River Basin District (2015) assessed the areas of (1) flood hazard and (2) flood risk from several points of view, e.g., population or economic activities. The first preliminary evaluation of the flood risk for Slovakia was done by the Ministry of Environment of the Slovak Republic in 2011, and the updated version was published in December 2018 (Anon, 2018; https://www.minzp.sk/voda/ochrana-pred-povodnami/manazment-povodnovych-rizik).The location of main Slovak streams with flood hazard and flooding scenarios is in Fig. 2.

Fig. 2 Flood Hazard and Flooding Scenarios – Detailed view on Slovakia (Flood Risk Management Plan for the Danube River Basin District, 2015)

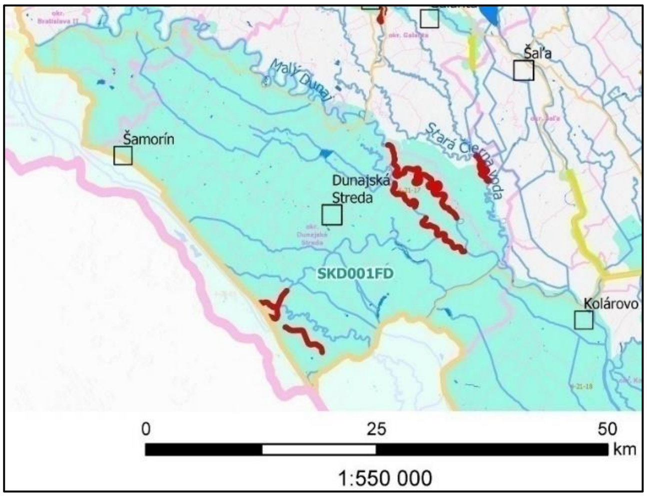


Fig. 3 Territory within the pilot site area with existing important flood risk (Anon, 2018)

Within the pilot site area there exists the area in Baka and Gabčíkovo with important flood risk in the Partial Danube River Basin District (Fig.3). In Baka the length of the river course at risk (4-21-17-554 – Baka-Gabčíkovo) is 2.4 km. In Gabčíkovo the length of the river course at risk (4-21-17-517 – Gabčíkovo-Topoľníky) is 4.4 km. The Gabčíkovo - Topoľníky channel flows in cadastral areas of Gabčíkovo and Baka villages. The floods are the result in long-lasting precipitation, when the groundwater table rises above the ground level.

4.1.3. Recharge dam MAR type in pilot area

Nowadays, after putting Gabčíkovo hydropower plant (GHPP) into operation in 1992, the system of irrigation channels was cut off the Danube River and it is supplied by water from the seepage channel of the GHPP (Fig. 4). This process enabled the second – very important function of the channel – to supply the aquifer as well as supply the unsaturated zone with water by using several irrigation systems (Šoltész et.al, 2021).

The hydrological conditions of pilot are strongly affected by the construction of the Gabčíkovo Water Structure. After construction of the Gabčíkovo Water Structure, a decrease of groundwater levels in the adjacent area of the Danube River was observed and the groundwater regime as well as water levels in drainage channels changed. To improve and control the groundwater regime in the floodplain area, a seepage channel on the left-hand side of the inlet channel of the water structure was constructed. The seepage channel is the primary source of water into an artificial water supplying branch system and consequently into groundwater (Sikora and Slota, 1992; Šoltész, 2002; Červeňanská et al., 2016).

The pilot area is roughly delineated by the towns of Samorin, Dunajska Streda and Gabcikovo. To be more precise, it is bordered primary channel S VII (Gabčíkovo-Topoľníky channel) and secondary channels A VII (Vojka-Kračany,) and B VII (Šuľany-Jurová,) (Fig.4). The dense network of irrigation channels equipped with technical tools (sluices, barriers) for regulation of water flow is a crucial point to create recharge dam MAR type, i.e. accumulation of water between closed sluices. Potentially infiltrated amount of surface water from recharge dam and its storage within the aquifer was investigated by numerical modelling for the subsequent use as irrigation water during dry periods. The pilot area is used for agricultural purposes.

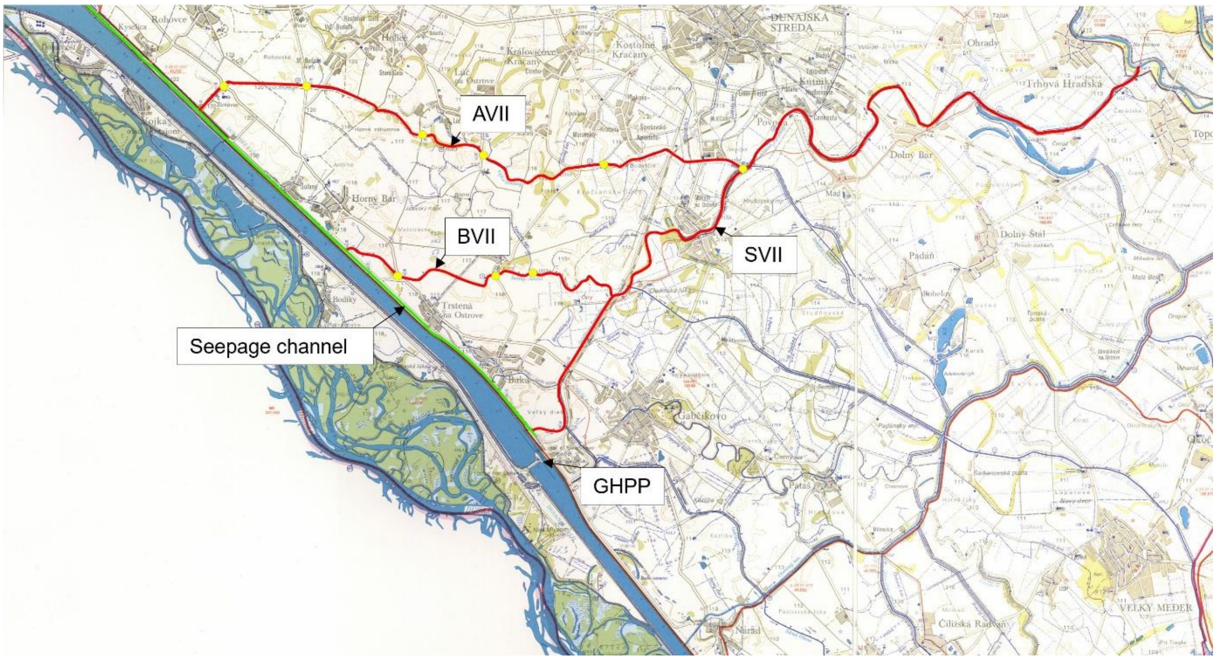


Fig. 4 Illustration of the upper Žitný Ostrov area of interest in Slovakia for MAR purposes

4.2. Geological-hydrogeological characterisation

4.2.1. Geology

The pilot site is located in the Slovak part of the Danube Basin, occurring in north-western part of the Pannonian Basin System. The shape of the Slovak part of the Danube Basin is the result of complex process associated, with polyphase back-arc rifting, post rift thermal subsidence and basin inversion (Šujan et al., 2021). The complicated development manifests itself in several, tectonically different depocenters (depressions). The largest, and deepest of them is the Gabčíkovo-Győr depression, which is tectonically bordered by the Malé Karpaty Mts. in the west, by the Trasdanubian Range in the east and by the Blatné, Rišnovce and Komjatice depressions in the North (Vass, 2002). The Gabčíkovo-Győr depression represents the study area for the pilot site.

The sedimentary in-fill of the depression is represented by Neogene and Quaternary sediments. The thickness of Neogene sediments in the Gabčíkovo-Győr depression reaches more than 8 500 m (Kilényi &Šefara, 1989; Hrušecký, 1999), and is overlain by up to 320 m thick quaternary sedimentary cover (Šujan et al., 2018). In the deep structure of the basin the Neogene sediments discordantly overlie the Palaeozoic granitoid rocks (Fusán et al., 1987), and Neogene intrusive and extrusive volcanic rocks (e.g. the buried Kráľová volcanic field; Hrušecký, 1999) Deposition in the Gabčíkovo-Győr depression started with the late Badenian Báhoň formation, and was associated with the 2nd syn-rift phase. The sediments are represented by inner to outer shelf calcareous mudstones and sandstones of the epicontinental Central Paratethys Sea. The deposition continues with shelf break-slope mudstones and brackish deltaic sandstones of Sarmatian age ranked to the Vráble Formation (3rdsyn-rift). At the end of the Sarmatian a pronounced erosional unconformity is recorded, and most likely connected, with the cessation of marine seaways into the area and onset on the extensive Lake Pennon. This process is most likely controlled by the transition from the 3rd to the 4th and last basin syn-rift phase. Thus, the beginning of the late Miocene (Pannonian), it is still affected by rifting, what resulted into deposition of deep basin calcareous mudstones, turbidite sandstones, and shelf break-slope mudstones of the Ivanka Formation. These are overlain by the sandy deltaic deposits of the Beladice Formation, which include thin lignite layers. The upper Miocene deposition ends with the sedimentation of Volkovce and the Pliocene Kolárovo formations, which mark the onset of thermal subsidence and basin inversion, respectively. These formations are dominated by alluvial mudstones, with rare sand and gravel channel-belt units (Šujan et al., 2016, 2018, 2021) (Fig.5). The upper Miocene and Pliocene sediments are covered by thick accumulation of fluvial Quaternary succession. The lower-Pleistocene sediments (Donau to Günz) are represented by cyclically alternating sandy - gravely layers intercalated by layers of silty clays. Mindel sediments create the basal part of the large fluvial fan of the Danube built by gravels, sandy gravels and sands. The thickness of the sediments reaches up to 100 m in the area of the Gabčíkovo depression. Riss sediments are separated from the Mindel ones by the 3 – 8 m thick, mostly discontinuous layer of clayey-sandy silts representing the Holstein interglacial. The Riss sediments with the thickness up to 50 m are represented by coarse gravels, sandy gravels and coarse-grained sands. The upper-most Pleistocene - Würm sediments have the thickness over 50 m, being built mostly of sandy gravels. The upper-most (Holocene) layer consists of alluvial sediments – silts, silty sands, sandy gravels to gravels (Maglay et al., 2017). The flood silty sediments cover the whole Holocene sedimentary complex. Fluvio-organic, organic and palustric sediments occur in the buried ox-bow fillings. Specific type of sediments are the recent anthropogenic deposits occurring in the urban areas.

4.2.2. Hydrogeology

The pilot site is the part of the hydrogeological rayon (region) *Q 052 Quaternary of the south-western part of the Danube Lowland* (Šuba & Mihálik, 1998). According to the Common Implementation Strategy of the Water Framework Directive (2000/60/EC) a distinction was made between Pre-Quaternary groundwater bodies and overlying Quaternary groundwater bodies in the process of groundwater bodies' delineation in Slovakia. Third layer of geothermal groundwater bodies was also produced from existing hydrogeological data. The upper two layers of groundwater bodies differ from the geothermal one since they contain fresh water.

Due to complicated geological settings in the Danube basin, all three layers of groundwater bodies can be identified within the wider surroundings of the pilot site area. The upper-most groundwater body is the Quaternary groundwater body *SK1000300P Intergranular groundwater body of Quaternary sediments of the central part of the Danube Basin* (Decree of the government No. 282/2010 Coll., time version valid since January 1, 2020) with the area of 1668.112 km^2. Prevailing groundwater aquifers are alluvial and terrace gravels, sandy gravels and sands. Neogene aquifers in the area belong to Pre-Quaternary groundwater body *SK2001000P Intergranular groundwater body of the central part of the Danube Basin and its folders* (Decree of the SR Government No. 282/2010 Coll., time version valid since January 1, 2020) with the area of 6248.370 km^2. Prevailing groundwater aquifers are limno-fluvial sediments, mostly sands, gravels and clays. Agricultural land, including arable land, grassland, pastures and permanent crops plantations, shares 83,38 % of total groundwater body area, rest of groundwater body area land cover is represented by forests, semi-natural land, surface water tables and artificial surfaces. The third layer implies geothermal waters which belong to geothermal groundwater body *SK300240PF Geothermal waters of the Central depression of the Danube Basin* (Decree of the SR Government No. 282/2010 Coll., time version valid since January 1, 2020) covering the area of 3426.870 km^2. The main aquifers of the groundwater body are Neogene sands and gravels.

Hydrogeological situation in the pilot site wider area is conditioned by geological and tectonic structure of the area, morphological, hydrological and climatic conditions. The pilot site area, being located in the Žitný Ostrov, geomorphologically belongs to the Danubian Lowland and geologically to the Gabčíkovo-Győr depression – part of the Danube Basin.

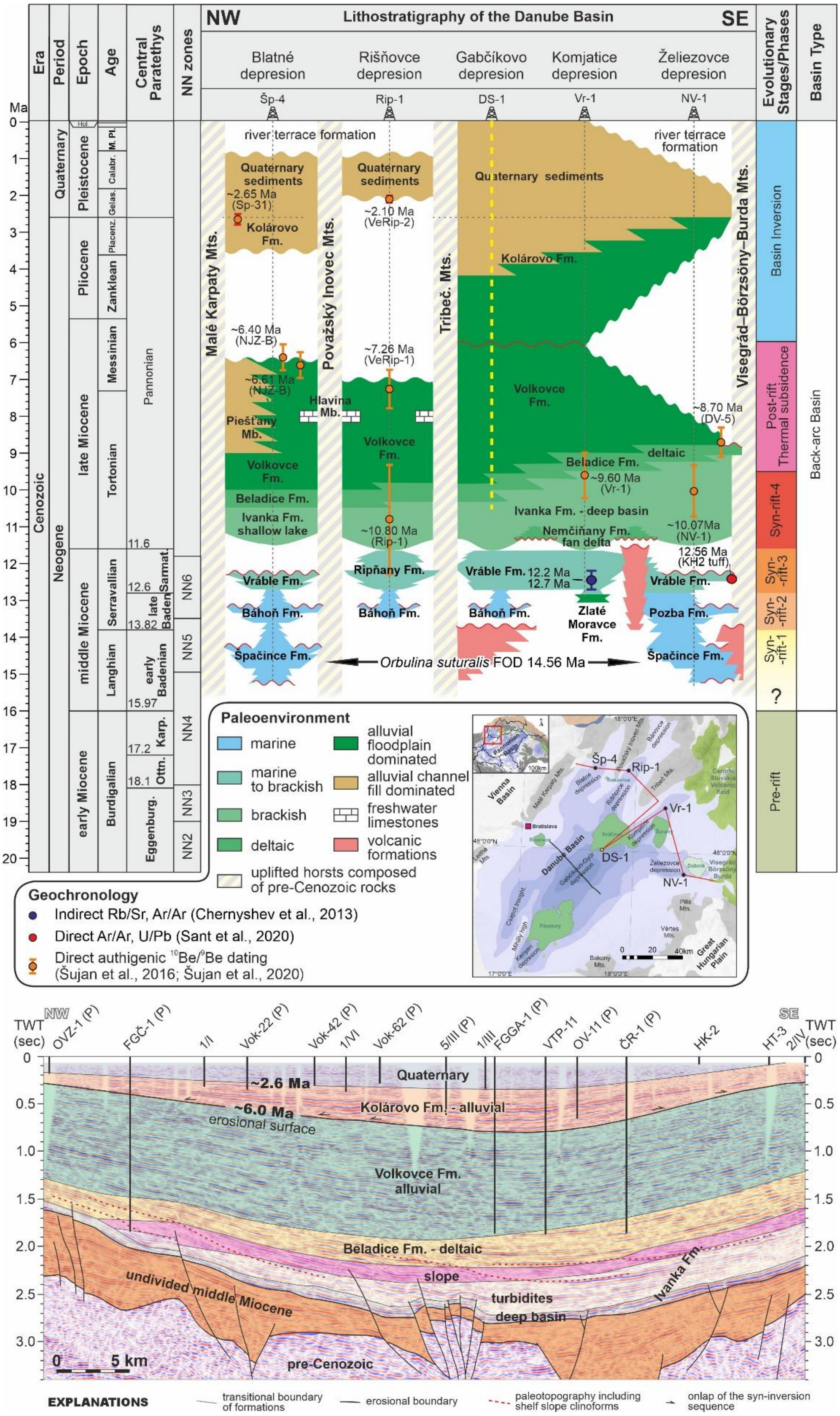


Fig. 5 Lithostratigraphic scheme of the Danube Basin and Seismic line 551/82-83 showing basin fill on the central Gabčíkovo-Győr depression according Šujan et al., 2021

The whole Žitný Ostrov area is covered by Quaternary sediments with the thickness ranging from 12 m to approximately 320 m in the area of the Gabčíkovo depression (Šujan et. al., 2018). Quaternary sediments are lithologically represented mostly by gravels and sandy gravels, locally intercalated by thin layers of clays. The sand content in sandy gravels reaches 50 – 70 %. A layer of flood loams with the variable thickness from 1 up to 3 m covers the underlying gravels. The river sedimentation is irregular and the content of respective facies can change within short distances. Larger thickness of loamy sediments with presence of organic material can be found in buried old river branches - oxbows (Benková et. al., 2005).

Benková et al. (2005) estimated the average values of the hydraulic conductivity coefficient Quaternary gravels and sandy gravels in the wider area of the pilot site on $2.91*10^{-3}$ ms^{-1} and the transmissivity coefficient on $2.96*10^{-2}$ m^2s^{-1}. The Quaternary sediments have mostly the phreatic groundwater table. The same authors also investigated the change in hydraulic conductivity with the depth of the well screen location. They concluded, that increasing depth (0 – 25 m, 25 – 50 m, 50 – 100 m) lowers hydraulic conductivity. Némethyová et al. (2017) estimated the value of the hydraulic conductivity coefficient in well S-1, drilled within the pilot site at Horný Bar village to the depth of 15 m reaching coarse gravel water bearing aquifer. Resulting value was $5.619*10^{-3}$ $m.s^{-1}$, and the value of the transmissivity coefficient was $3.65*10^{-2}$ $m^2.s^{-1}$, values were estimated using the method of grain size distribution curve.

Neogene sediments, mostly gravels, sandy gravels and sands of the Pannonian, Pontian, Dacian and Roman ages belong also to the important groundwater aquifers. They were found in the Žitný Ostrov by more shallow wells (45 – 280 m), but also by deep wells (1000 – 2500 m). Neogene sediments do not occur on the surface, they are not relevant for MAR schemes.

The Pannonian basin is rich in geothermal water, which was found in Gabčíkovo, the well FGGa-1 (Franko et al., 1984). The well is 2582 m deep, Pontian sands form the aquifer. The exploitation interval is at the depth of 1122–1926 m. The free outflow from the well reached 10 $l.s^{-1}$ of Na-HCO_3 chemical type geothermal water with the 52 °C temperature on the wellhead.

Chemical composition of fresh groundwater in the area of Žitný Ostrov generally depends on (Benková et al., 2005):

- Chemical composition of the Danube (initial water)
- Length of infiltration pass of groundwater from the Danube River into Quaternary sediments, place and time of infiltration
- Character and intensity of the Little Danube (Malý Dunaj) and Váh Rivers influence
- Point and diffuse pollution sources, character of the land use
- Sources of iron and manganese in the rock environment
- Degree of bicarbonates content in Quaternary sediments.

Locally, the chemical composition of Quaternary groundwater within the pilot site depends on all mentioned factors, except of the Little Danube and Váh Rivers influence.

Groundwater in Quaternary sediments of the evaluated area can be generally characterized as fluviogenic water having origin of its chemical composition in infiltrating water from the surface water courses. The main cations are calcium and magnesium, values of iron and manganese contents are often increased. The main anions are bicarbonates and with lower values of sulphates. Presence of nitrites and nitrates indicates the anthropogenic pollution. Groundwater is of middle to high mineralization. The basic distinct Ca-HCO_3 and basic non-distinct Ca-(Mg)-HCO_3 chemical types prevail. There are four monitoring wells of the groundwater quality observation situated in the pilot site area: 6032 Gabčíkovo (with 2 observation depth levels), 6033 Mliečany (with 2 observation depth levels labelled), 7312 Kostolné Kračany (with 2 observation depth levels) and 7336 Vrakúň (with 3 observation depth levels). Results of groundwater quality monitoring in the four wells within the period 2017 and 2018 (Ľuptáková et al., 2019) showed good water quality, according to inorganic compounds, over-limit values were measured for organic compounds in Vrakúň (PAU), Mliečany (anthracene) and Gabčíkovo (anthracene) in a few cases.

As an example, results of chemical analysis of groundwater from the well S-1 at Horný Bar sampled in November and December 2017 (Némethyová et al., 2017) are given. Groundwater had weak alkali to alkali reaction with pH value 7.41 to 7.74, increased mineralization of 546 – 590 $mg.l^{-1}$, high electric conductivity of 860 to 862 $\mu S.cm^{-1}$. Groundwater temperature reached 12.9 – 13.0 °C. Chemical type of groundwater was estimated as basic, non-distinct Ca-Mg-HCO_3 to Ca-HCO_3 type (the value of A_2 Palmer index reached 56.93 – 58.17 c.z %), with an increased content of sulphate ions. The content of manganese was also increased. Concentrations of all monitored organic compounds were within the limits of the Resolution of the Ministry of Health of Slovakia No. 247/2017 Coll.

Neogene groundwater can be characterized as groundwater of petrogenic origin - carbonatogenic - of distinct A_2 type with the mineralization between 306.47 and 1059.7 $mg.l^{-1}$, the average value of mineralization makes 530.0 $mg.l^{-1}$. The continuous change in the chemical type of groundwater with the increasing depth was proven - from the Ca-(Mg)-HCO_3 type to Na-HCO_3 type (Bottlik et al., 2013).

The main source for groundwater recharge in the area is the surface water of the Danube River. Water from the Danube infiltrates into the alluvial sediments and flows downward as groundwater through the Danubian Lowland, nearly in parallel with the Danube River. General flow direction is from the northwest to the southeast, even from the west to the east. In the lower part, where the slope of the river and the surrounding area decreases to one quarter of its gradient at Bratislava, the groundwater flows back into the Danube River via its own river branches, the Danube tributaries, and the drainage channels. All this occurs because of the lowered permeability, and lowered aquifer thickness downstream from Gabčíkovo. While the groundwater regime mainly depends on the river water regime, this dissipates with the distance from Danube. The influence of climatic conditions (precipitation, evapotranspiration) on groundwater table fluctuation is not important close to the river bed, however, the influence is more important for Quaternary aquifers in larger distances from the river (central part of the Žitný Ostrov).

Groundwater regime from the long-term point of view was influenced by the Gabčíkovo Waterworks, which was constructed on the Danube River between Čuňovo and Gabčíkovo villages. It was put into operation in 1992. The waterworks consists of the Čuňovo Dam, Hrušov water reservoir (headwater installations) with an area of 40 km^2, the bypass channel (headwater channel and tailwater channel), and the series of locks on the bypass channel (hydropower plants and navigation locks). The Hrušov water reservoir fills left-hand seepage channel, which is the water supply source for channel network of the Žitný Ostrov. There are six main partially interconnected channels, intersected by smaller ones.

Before the Gabčíkovo Waterworks started its operation, the decreasing trend in all groundwater monitoring objects was observed along the Danube River course in the alluvial plain between Bratislava and Medveďovo. The largest decreasing trends of groundwater table were observed in the upper part - between Bratislava and Kalinkovo. The operation of the Gabčíkovo Waterworks changed the decreasing trends into increasing ones in the area of Bratislava, in the upper part of the Žitný Ostrov and in the direction towards the Little Danube. However, the decrease in groundwater table occurred in the area of Gabčíkovo (Mucha et al., 2004). At present, the groundwater depth in the wider surroundings of the pilot area varies between 4.5 – 7.0 m below surface in the upper part of the Žitný Ostrov, in the central part it makes 1.0 – 3.0 m below the surface (Benková et al., 2005).

The infiltration capacity of the rocks surrounding the channels network in pilot area was estimated by mathematical modelling. The potential amount of infiltrated water were calculated by the MODFLOW model.

The huge thickness of permeable Quaternary sediments in the Žitný Ostrov allows to accumulate the largest amounts of groundwater reserves in Slovakia. There are several groundwater sources used for drinking water supply exploiting water from the Quaternary sediments. Among them, the water source Jelka, located in the northern part of Žitný Ostrov, Kalinkovo, Šamorín and Gabčíkovo in the southern part of the Žitný Ostrov are worth mentioning.

The water source Gabčíkovo consists of 13 hydrogeological wells HAŠ-1 to HAŠ 13, which were drilled to the depth of 85 – 90 m during the period 1976 – 1984 (Fatulová, 1976; 1984). The amount of 3000 $l.s^{-1}$ was approved as usable groundwater amount of the water source Gabčíkovo, from which 473.3 $l.s^{-1}$ was used in 2019 (Slivová et al., 2020).

From evaluating the water chemistry of surface water and groundwater and assessing potential risks of pollution by scattered environmental loads and larger potential polluters (the industrial enterprises have their own waste water treatment plants), it was found that they do not pose remarkable threat on water pollution or produce priority substances. Therefore, these are suitable for MAR systems according to the water chemistry as well as according to evaluation of ecological potential of surface waters.

4.2.3. Fieldwork

The archive geological data were supplemented by field measurements. The main goal of the field measurements was to identify the aquifer characteristics in order to provide data for setting up boundary conditions, and providing parameters, for numerical modelling of the surface-groundwater flow interaction. Consequent numerical modelling provided an assessment of the potential volume of infiltrated water into the geologic environment in recharge dam.

The measurements at the pilot area focused on measuring the water flow in channels; water level in channels; geometry of channels; groundwater table in hand-drilled probes; soil sampling to measure geological and hydraulic characteristics of the soil in the zone of water channels and adjacent aquifers; measurements of hydraulic conductivity of saturated soil above the groundwater table in the neighbourhood of channels and measurements of hydraulic conductivity of saturated porous media (below the groundwater table) in the channel infiltration zone using the Auger hole method.

The field measurements of water flow, water table and geometry of the channels were done by the Slovak University of Technology in Bratislava. Surface water flow was measured at 12 measurements points in channel A VII (Vojka – Kračany). Flow measurements and water level measurements in channels took place in two periods, in October 2020 and in May 2021 using ultrasonic FlowTracker instrument.
The position of the water level in channels was measured in front of and behind the closed sluice. Water flow was measured in the sluice neighborhood in a suitable profile (straight and grassless section with a regular shape). Flow rates were determined from the measured velocities at the selected points situated in verticals. Water flow velocities were measured directly in the stream without use of any vessel. Since the conditions for measurements in the AVII channel (Vojka-Kračany) were more suitable, it was measured in detail (Fig.6). Only one flow rate measurement was performed in the BVII channel (Šuľany – Jurová), despite the fact that there are 3 sluices (Fig.6), however the high depth and a dense vegetation overgrowth of this channel did not allow to do more measurements.

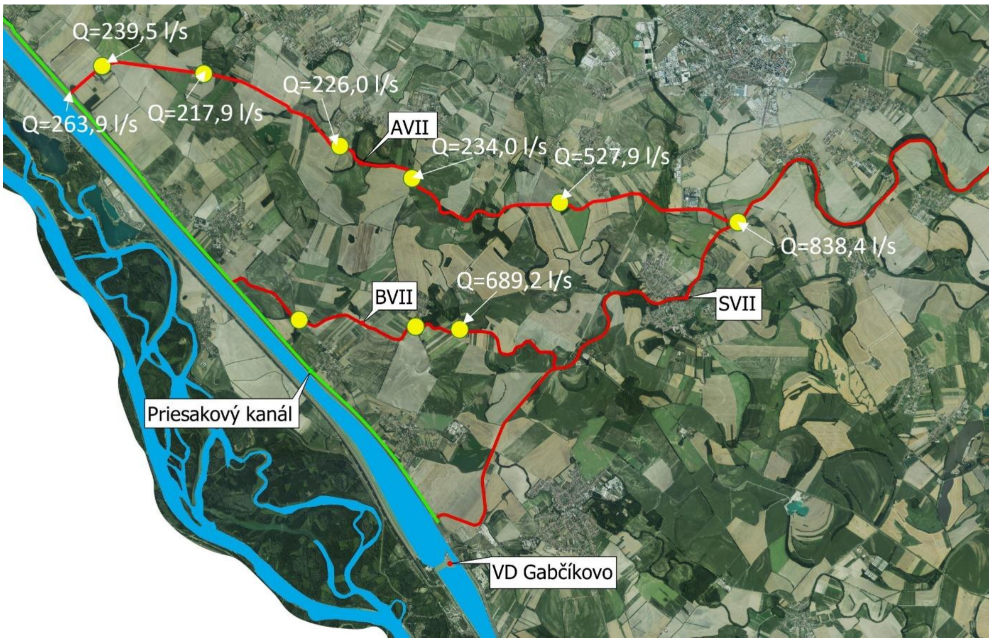


Fig. 6 Flowrates in channel A VII (Vojka-Kračany) and channel B VII (Šuľany-Jurová) measured at 22.10.2020

Groundwater level measurements were performed at 3 points using hand-drilled probes at the Jozefov site (Fig. 7, site L1). Two were drilled at a distance of 1,5 m from the bank line, but in 50 m distance from each other along the channel, and the third one in the forest depression (i.e. about 0,8 m below the surface of the adjacent probes) in the distance 15 m from the channel.

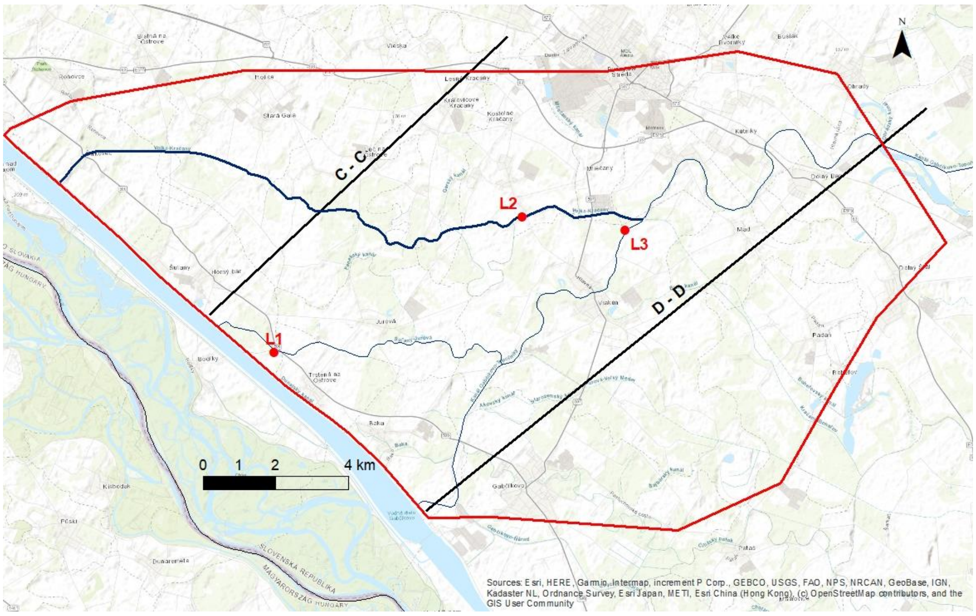


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Fig. 7 Cross sections C-C, (Horný Bar – Veľké Blahovo) and D-D, (Gabčíkovo – Trhová Hradská) along which max., min., and average depths of gravel layer below soil surface were estimated (see Tab.1 and Fig.10). Sites of detailed study: Site L1 Jozefov located on the channel Šuľany – Jurová. Site L2 (Amadeove Kračany) located on the channel Vojka – Kračany, and site L3 (Vrakúň) near the road Amadeho Kračany – Vrakúň.

The probes 1 and 2 (Fig. 8) were drilled to the depth 120 cm, the third one to the depth 70 cm (+ pipe 80 cm above surface). Probes coordinates are: P01 47°55.7051´; 017°29.1837´; P02 47°55.7168´; 017°29.1524´; P03 47°55.6980´; 017°29.1661´

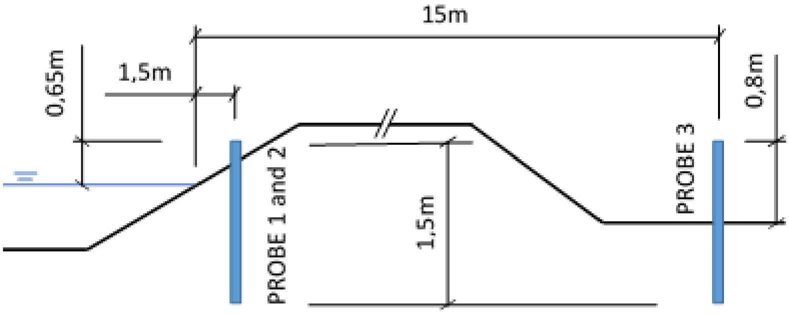

Fig. 8 Cross section of the B VII channel (Šuľany-Jurová) showing the location of hand drilled probes

Soil samples were measured in laboratory to obtain the data on:

- hydraulic conductivity of water-saturated soil (method of variable hydraulic gradient)
- soil bulk density and its vertical distribution
- soil water retention curves (measurements and calculation)

Representative sites that were chosen for further investigation are displayed in Fig. 7. All of them are located in vicinity of adjustable sluice gates, allowing control of the water table level in the channels to perform infiltration tests:

- ✓ Site L1 (Jozefov) is located at the channel Šuľany – Jurová (see Fig. 7), nearby the road between villages Horný Bar and Trstená na Ostrove,
- ✓ Site L2 (Amadeove Kračany) is located at the channel Vojka – Kračany, nearby the road between Amadeho Kračany and Vrakúň,
- ✓ Site L3 (Vrakúň) is located on the cross-section of the channels Vojka-Kračany and Gabčíkovo-Topoľníky.

It was necessary to combine field and laboratory investigations for determining hydraulic characteristics of the soil and subsoil layers.

Groundwater table in pilot area is strongly influenced by water infiltrated from the Danube. The western part of Žitný Ostrov is characterized by deep groundwater table (site Báč). Groundwater table level at sites Trstená and Vrakúň is relatively stable, it is oscillating between 2 and 3 metres below the surface (Tab.1). Gabčíkovo site is strongly affected by variation of the Danube River water table combined with water regime in outflow channel of Gabčíkovo Water Structure.

Tab.1. The depth of groundwater table below surface in pilot area of Žitný Ostrov (4 sites) z_{max}, z_{min}, and z_{avg} are max., min., and average depths of groundwater below soil surface in m.

SITE		Z_{min} (m)	Z_{max} (m)	Z_{avg} (m)
BÁČ	(NZ12)	4,49	5,50	4,87
TRSTENÁ	(NZ9)	1,55	2,75	1,88
VRAKÚŇ	(V3)	1,26	1,76	1,59
GABČÍKOVO	(G1)	0,85	3,29	1,92

The new hand-drilled probes in Jozefov site are located along B VII Šuľany-Jurová channel were drilled the depth up to 1,5 m below surface (Probes coordinates: P01 47°55.7051´; 017°29.1837´; P02 47°55.7168´; 017°29.1524´; P03 47°55.6980´; 017°29.1661´). The geologic profiles of the probes were: 0 - 0,4 m sandy-clayey loam (soil) and under the depth of 0,4 m sandy gravel, i.e. aquifer. The groundwater level was measured 5 times in 3 weeks intervals and data were used to verification of HYDRUS-2D model results. The groundwater level measurements in the third probe showed that originally wet area (depression) with groundwater table 0,2 m below the surface dried out and the groundwater level could not be detected by the probe anymore (Tab. 2).

Tab. 2. Groundwater table measurements in Jozefov site

Groundwater table (m below surface) **Jozefov site**		
Probe 1	**Probe 2**	**Probe 3**
1,05	1,07	0,20
0,90	1,11	0
0,93	1,10	0
0,84	1,11	0
0,87	1,08	0

During exploitation of Žitný Ostrov irrigation channels, on the bottom and sides of them, fine sediments created layers of fine material, which decreased seepage from channels to the neighbouring aquifers. According to measurements (Dulovičová, et al., 2018), the thickness of the bottom sediments in various channels ranged between 20 – 100 centimetres (depending on local conditions). Hydraulic conductivity of sediments in channels is about two orders lower, than saturated hydraulic conductivity of aquifers (sandy gravel). Characteristic saturated hydraulic conductivity of bottom sediments is K_s = 0.5 cm d^{-1}.

4.3. Water demand and supply, water source for MAR

4.3.1. Water demand

Annual operation and maintenance costs depend heavily on the amount of irrigation water demand and water supply by the MAR scheme. Tab. 3 outlines annual water supply from MAR scheme and projected volume of annual water demand for irrigation in 30 years, estimated by experts. The level of water supply is estimated under the condition of 3 new sluices/weirs added, in other words, more recharge dams are created along the channel in order to increase the infiltrated water amount.

Tab. 3. Projected water supply and demand

	Volume, m^3
Annual water supply by MAR scheme	
Dry year	11,967,985
Wet year	15,042,745
Annual irrigation water demand in 30 years	
Minimum[1]	8,699,090
Maximum[2]	15,004,000

Source: Experts' estimation based on the data for the reference area (northern part of Podunajska lowland)

The range of values of annual irrigation water demand is estimated taking into account long-term climate forecasts, anticipating that the pilot study area will be vulnerable to droughts. The assumption behind the minimum scenario is that irrigation water demand in 30 years will be 20% higher than the current level in the reference area. When it comes to the maximum expected irrigation water demand, its level is estimated based on a linear trend. The latest is obtained based on 18 years of historical data on irrigation water consumption by agricultural producers in the reference area. Fig. 9 shows the time series of projected irrigation water demand under the abovementioned scenarios and estimated via hydrological modelling level of potential MAR water supply in wet and dry years.

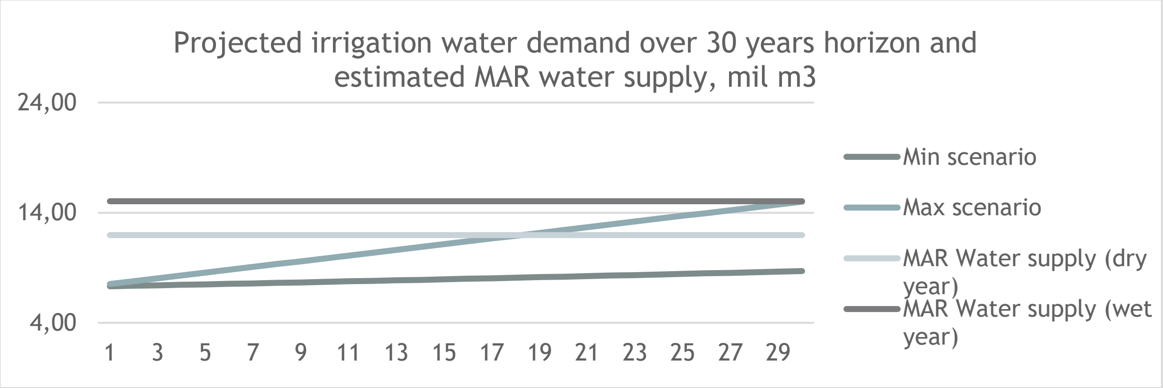

Fig. 9 Projected irrigation water demand and estimated water supply

Source: Experts' estimation based on the data for the reference area and hydrogeological modelling

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[1] Annual increase in total irrigation water consumption by 0.6% (water consumption in 30 years is 20% higher than current: 8.7 mil m^3)

[2] Annual increase in total irrigation water consumption by 0.2578 mil m^3 (linear trend, water consumption in 30 years is 15 mil m^3)

4.3.2. Water supply

4.3.2.1. Mathematical modelling - MODFLOW

For recharge and retention of surface water in aquifer and its subsequent using for irrigation during dry periods, the Recharge Dam MAR type was investigated using the numerical modelling technique.

The mathematical model MODFLOW enables to simulate the potential amount of infiltrating water. A numerical model was developed using the MODFLOW program in the Groundwater Modelling System (GMS) environment, which allows us to use a conceptual model approach.

MODFLOW is a computer program that numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite-difference method (Harbaugh et al., 2000). MODFLOW uses a modular structure. The three-dimensional movement of groundwater of constant density through porous earth material may be described by the partial-differential equation (1) (McDonald, Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_S\frac{\partial h}{\partial t} \qquad (1)$$

where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (Lt^{-1}); h is the potentiometric head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1}); S_S is the specific storage of the porous material (L^{-1}); and t is time (t).

Equation (l), together with specification of flow and/or head conditions at the boundaries of an aquifer system and specification of initial-head conditions, constitutes a mathematical representation of a ground-water flow system. A solution of Eq. (l), in an analytical sense, is an algebraic expression giving h(x,y,z,t) such that, when the derivatives of h with respect to space and time are substituted into Eq. (l), the equation and its initial and boundary conditions are satisfied. Except for very simple systems, analytical solutions of Eq. (1) are rarely possible, so various numerical methods must be employed to obtain approximate solutions. One of the approaches is the finite-difference method, wherein the continuous system described by Eq. (1) is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points. The finite-difference analogy of Eq. (1) may be derived by applying discretization conventions described in McDonald and Harbaugh (1988).

The modular structure consists of a main program and a series of highly independent subroutines called "modules." The modules are grouped into "packages." Each package deals with a specific feature of the hydrologic system, which s simulated, such as flow from rivers or flow into drains (McDonald, Harbaugh, 1988).

In the basic package, an IBOUND was used to represent the Dirichlet (the first-type) boundary condition with specified head – specifically a combination of IBOUND, which is used to identify specified head boundaries, and STR, which gives the head at those boundaries (the measured groundwater level in observation wells).

In addition to the basic package, which handles several administrative tasks for the model, the river package was also used. The river package simulates the effects of flow between surface-water features and groundwater systems. Input data for the package are a hydraulic conductance of the stream-aquifer interconnection (in GMS per unit length), a water level in the stream and an elevation of the bottom of the streambed.

4.3.2.1.1. Modelling protocol

A modelling protocol, which was used for creation of the numerical model, is described in Fig. 10. During the conceptual model stage, the system boundaries were identified, field data describing geomorphological (ALS: GCCA SR, 2021), geological (SGUDŠ, 2021), hydrogeological (SGUDŠ, 2021), hydrological (SHMI, 2021) and meteorological (SHMI, 2021) conditions were assembled, and the model area was visited. After that, the conceptual model was mapped to the designed grid, the boundary conditions were set and preliminary selection of values for aquifer parameters and hydrologic stresses was performed (model design). During the calibration stage, a set of values for aquifer parameters and stresses, that approximates field-measured heads and flows, was found. The calibration of hydraulic conductivity (using the automated parameter estimation code PEST) and conductance (done by trial-and-error adjustment of the parameter) was performed on a steady-state model of the 2010 flood situation. The verification of the model was done using the conditions during the “dry” hydrological year 2018.

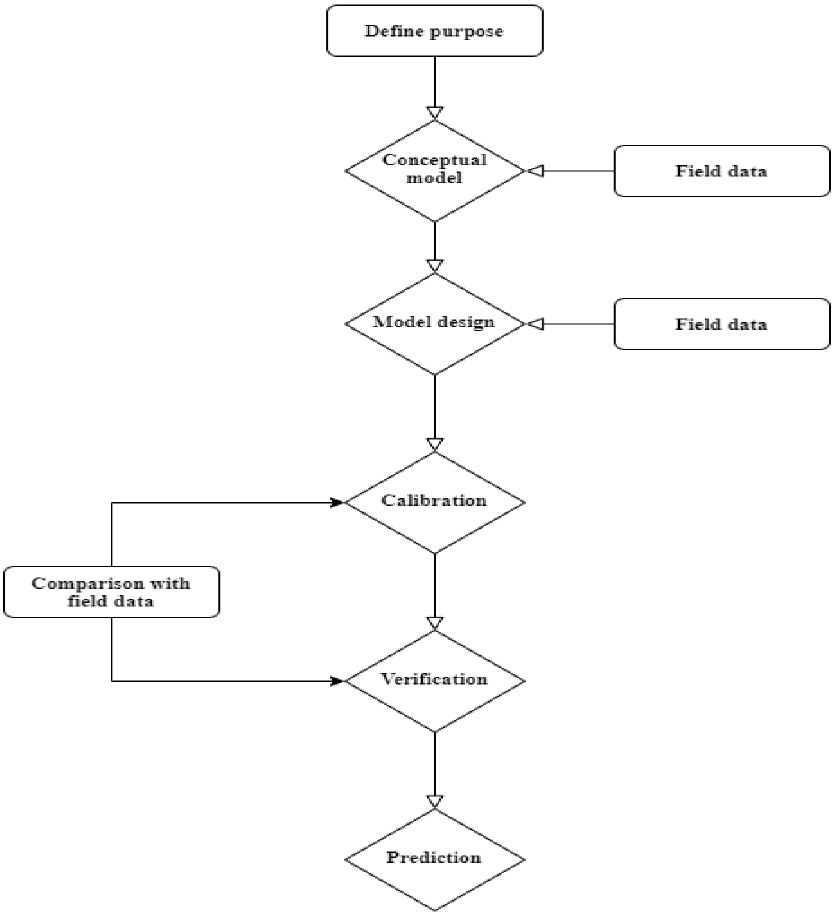


Fig. 10 Modelling protocol (adapted from Anderson, M. P., Woessner, W.W. 1992)

4.3.2.1.2. Input data

Tab. 4. Data availability and source of data

Data type	Description	Form	Source
Geomorphological	digital relief model (DRM) = top elevation of the aquifer	digital (raster)	Geodesy, Cartography and Cadastre Authority of the Slovak Republic (GCCA SR)
Geological and hydrogeological	bottom elevation of the aquifer, hydraulic conductivity	paper (final reports)	State Geological Institute of Dionýz Štúr (SGUDŠ)
Hydrological	water levels in channel S VII, daily precipitation, groundwater tables in boreholes	digital	Slovak Hydrometeorological Institute (SHMI) – cooperation
	Longitudinal profiles and cross sections of drainage channels	paper	Slovak Water Management Enterprise

The modelled area is bounded by the left-hand side seepage channel of the supply channel of Gabčíkovo water structure and 13 observation wells of the State Hydrological Network of groundwater quantity monitoring of the Slovak Hydrometeorological Institute.

Three hydrological years have been selected for the data analysis:

- **2008** as the **year which can be characterized as the precipitation normal** year for the regions of western Slovakia (100 to 109 % of the long-term normal);
- **2010** as the **year extremely above normal in terms of precipitation** (159 % of the long-term normal);
- and **2018 with extremely low precipitation** totals recorded in April, May, July and October.

A brief overview of minimum, maximum and median values of measured water levels on the S VII channel is presented in Tab. 5.

Tab. 5. Extreme and median values of water levels in two stage discharges on the S VII drainage channel [m a. s. l.]

Stage discharge/year	**2008**	**2010**	**2018**
9914_Gabčíkovo	**min: 112.35** **max: 113.96** median: 112.95	min: 112.41 max. 113.85 median: 112.90	min: 112.66 max: 113.49 median: 113.11
9924_Topoľníky	min: 109.24 max: 110.09 median: 109.40	min: 109.38 **max: 112.59** median: 109.66	**min: 109.16** max: 109.65 median: 109.40

OBSERVATION POINTS AND BOUNDARY CONDITIONS

For defining the boundary condition as well as for the calibration of the model, data from 32 groundwater level monitoring objects (Fig. 11) of the State Hydrological Network of groundwater quantity monitoring of the Slovak Hydrometeorological Institute (or observation wells) were evaluated. Data from 19 of these objects were used as point observation, where the elevation of the groundwater level (the head) was set using the calibration targets. The rest 13 observation wells were used for specifying the value of the boundary condition.

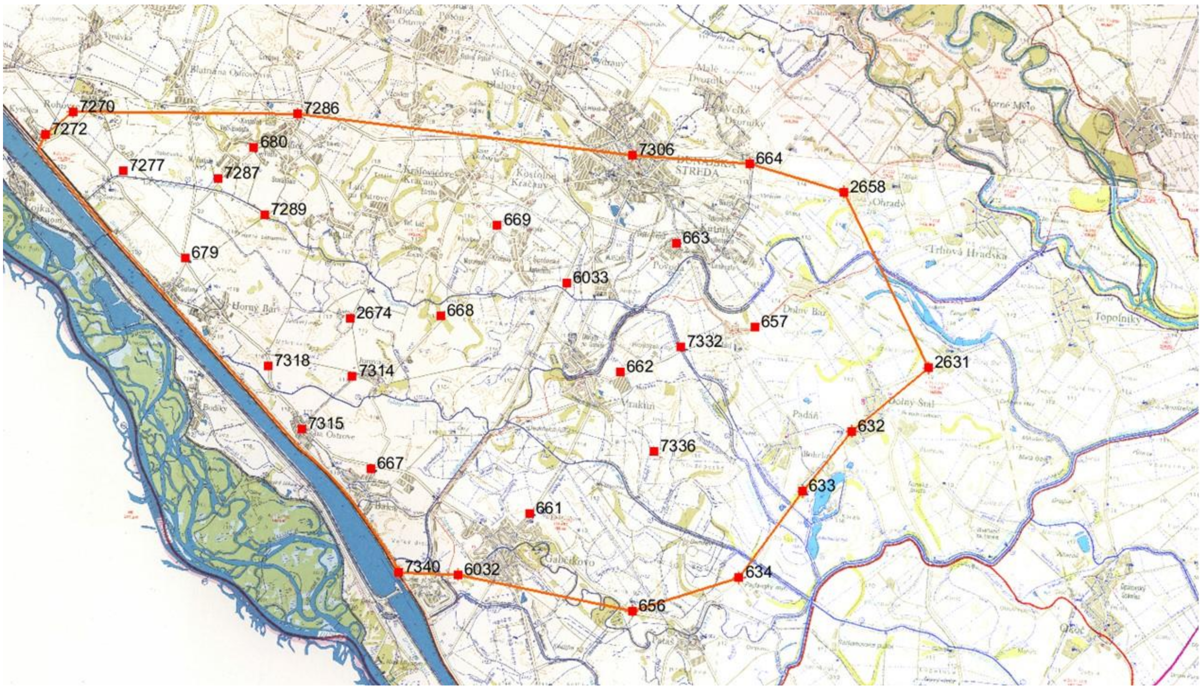


Fig. 11 Groundwater level monitoring objects of the State Hydrological Network of groundwater quantity monitoring of the Slovak Hydrometeorological Institute located in the modelled area

The Dirichlet (or first-type) boundary condition was specified on the entire edge of the model boundary. There are several ways for setting up the specified head boundary condition. In this simulation model, the combination of IBOUND (identifying specified head boundaries) and STRT (giving the head at those boundaries) in the Basic package was used. The value of the boundary condition was computed as the mean value of groundwater levels measured in every individual observation well during the modelled period (SHMI, 2021). For example, for the calibration of the model, the period from May 26, 2010 to September 9, 2010 was selected. The values of the boundary condition used during the calibration process are displayed in Fig. 12.

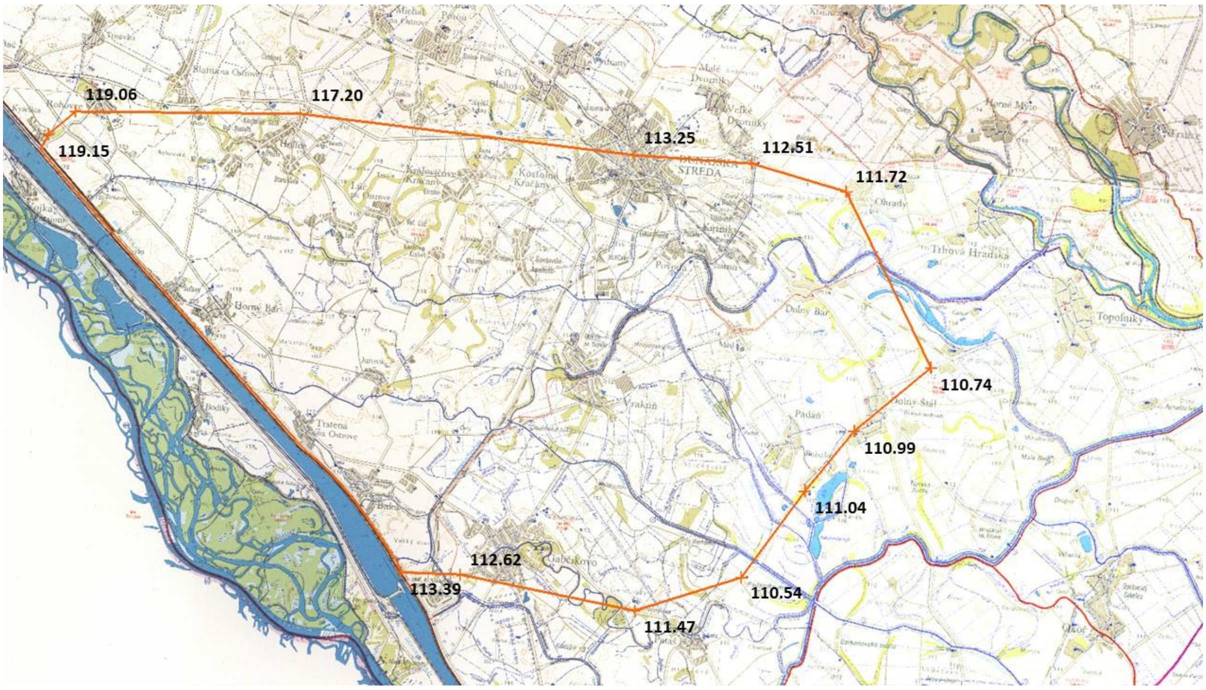


Fig. 12 The value of the boundary condition for the calibration period of May 26, 2010 to September 9, 2010 (SHMI, 2021)

The head-dependent flux boundary (which are examples of Robin, Cauchy or mixed boundary conditions) can be entered by a large number of head-dependent flux boundary packages. The drainage channels, which are represented by the Cauchy boundary condition, were modelled using the river package. Two elevations had to be specified – the elevation of the bottom of the river (channel) bed and the head in the river. Also, the conductance had to be specified. The value of the conductance was one of the calibration parameters.

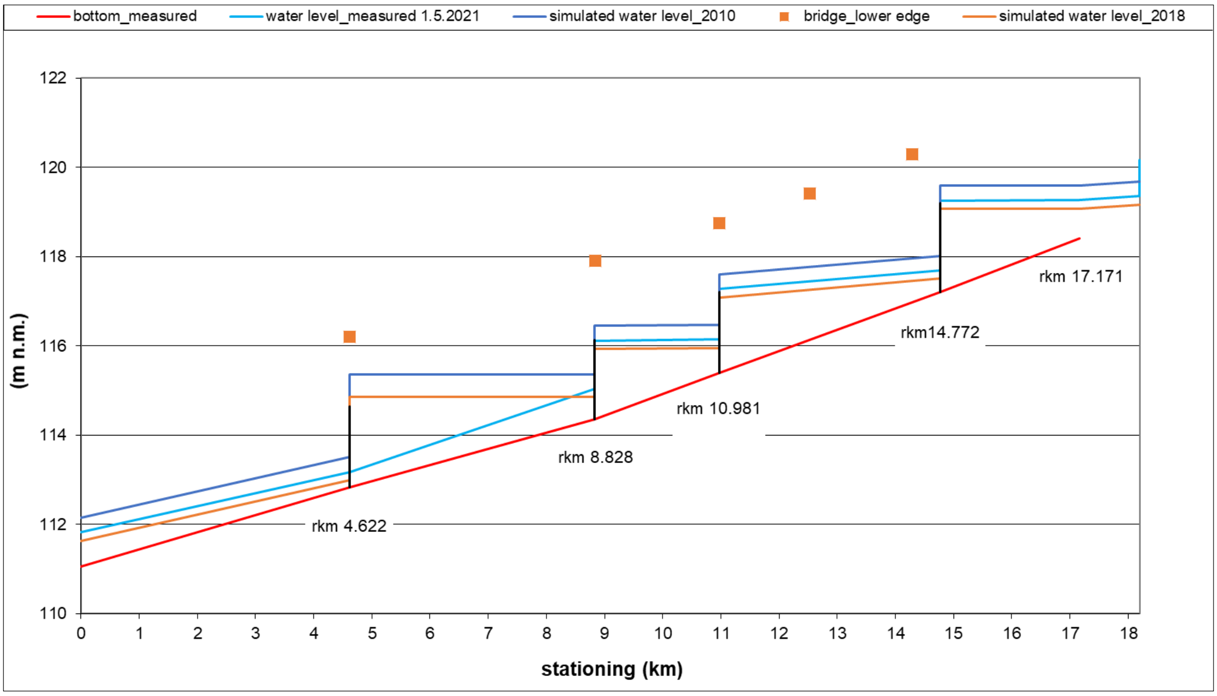


Fig. 13 Longitudinal profile of the A VII drainage channel – measured water level on May 1, 2021; simulated water levels in the selected periods from 2010 and 2018

The riverbed elevation was entered using the longitudinal profiles of drainage channels and the field-measured values (Fig. 14). The heads in the channels were set using the measured values in two stage discharges on the S VII drainage channels (SHMI, 2021) and information from the field measurements (Fig. 13) adapted to the situations during the 2010 flood and to the 2018 scenario. An example of the modelled water level in A VII drainage channel is in Fig. 13.

Fig. 14 River bottom elevation [m a. s. l.]

Fig. 15 Water levels in channels measured on May 1, 2021 [m a. s. l.]

Top elevation of the aquifer (Fig. 16) was interpolated using the DRM (*ALS: GCCA SR, 2021*).

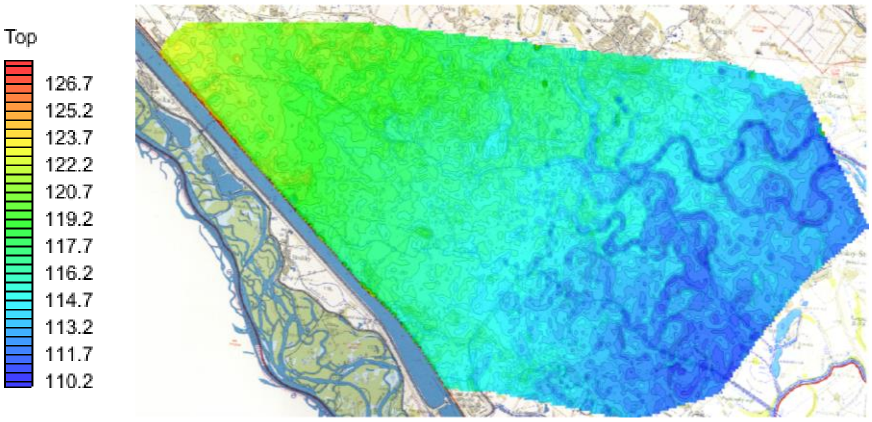


Fig. 16 Top elevation of the simulated aquifer in MODFLOW (ALS: GCCA SR, 2021)

Bottom elevation of the aquifer

The entire Žitný Ostrov, and thus also the investigated part, lies in the Gabčíkovo depression. Quaternary sediments form three complexes – lower, middle and upper. The lower complex is characterized by the cyclic alternation of layers of sandy-gravel-like sediments of smaller thickness with clay and loam layers of greater thickness. The thickness of the lower complex ranges from 10 to 350 m. The middle complex is formed by Danube gravels. It is separated from the lower complex by loam-clay layers. The thickness of this formation spatially varies, in the vicinity of Komárno it is about 8 – 12 m, in the middle of the depression about 160 m. The upper complex is formed by loam and sandy-loam sediments with a thickness from 0.5 to 3.0 m (Benková et al., 2013).

The variation of the thickness of the Quaternary sediments led us to studying the final reports and reviews of the Geofond digital archive of the State Geological Institute of Dionýz Štúr (SGUDŠ, 2021). The bottom elevation was adopted from these reports and reviews. Due to insufficient coverage of deep exploratory wells in the investigated area (Fig. 17), the value of the bottom elevation of the aquifer was considered as an average value of 60 m a. s. l.

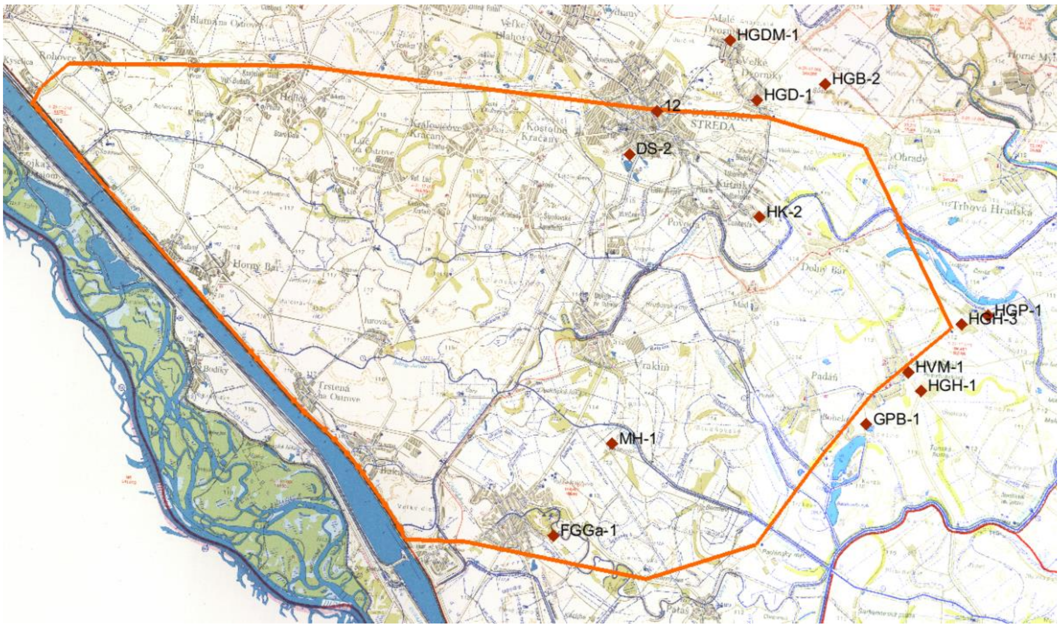


Fig. 17 Spatial distribution of deep exploratory wells with the information about the layer bottom elevation (SGUDŠ, 2021)

4.3.2.1.3. Model calibrating

The purpose of the calibration is to establish that the model can reproduce field-measured heads and flows with a certain degree of accuracy, which means that the model can successfully simulate observed behaviour of natural processes. Calibration is therefore the process of modifying parameters until the output from the model matches an observed set of data within an acceptable level of accuracy. The calibrated model is influenced by uncertainty owing to the inability to define the exact spatial (and temporal) distribution of aquifer parameter values in the problem domain and definition of boundary conditions and stresses.

The calibration of the model was performed on a steady-state model using the period from May 26, 2010 to September 9, 2010 (Fig. 18) during the 2010 flood situation on the rivers Danube, Váh and Little Danube.

Calibration of the model was done using:

- the automated parameter estimation code PEST for the calibration of the hydraulic conductivity
- and by trial-and-error adjustment of the conductance of the riverbed.

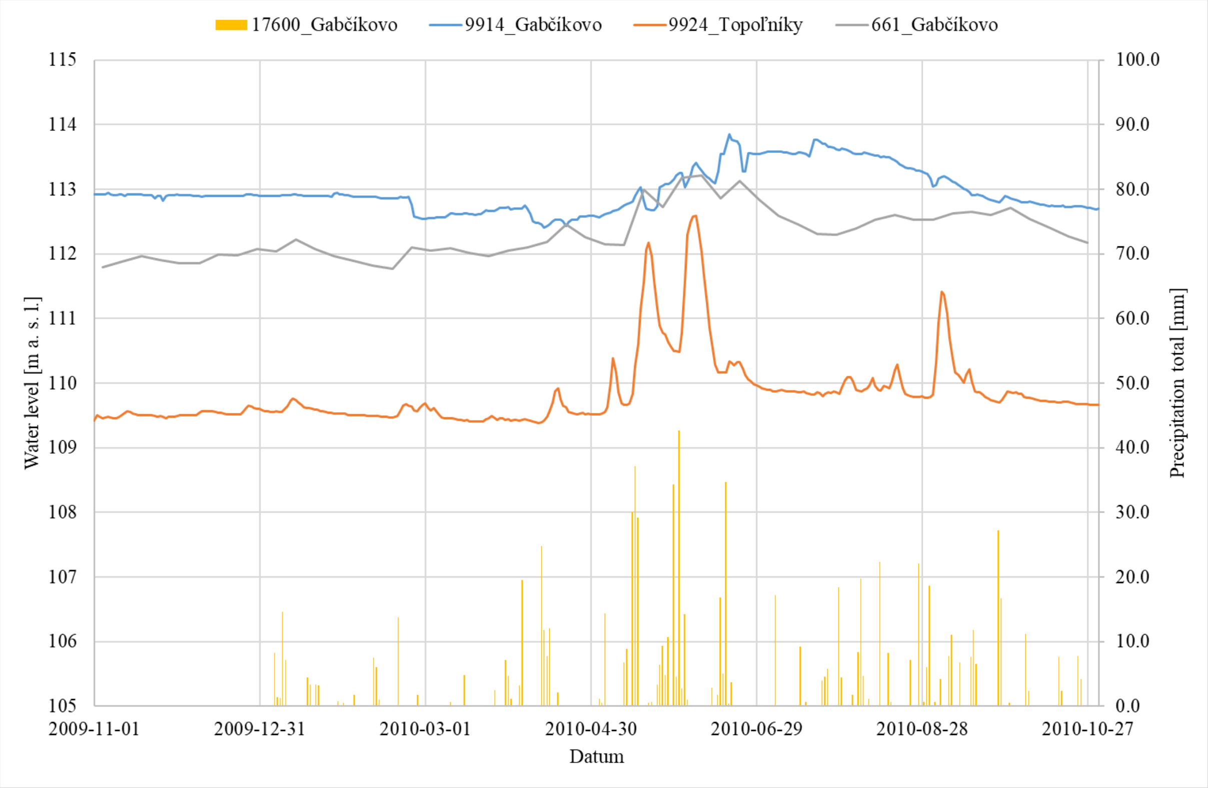


Fig. 18 The course of the water level at stage discharges on the S VII channel (9914 Gabčíkovo and 9924 Topoľníky) and the course of the groundwater level in well no. 661 in Gabčíkovo; daily total precipitation in the rain gauging station 17600 Gabčíkovo – hydrological year 2010 (SHMI, 2021)

HYDRAULIC CONDUCTIVITY

The value of the hydraulic conductivity was calibrated using the automated parameter estimation code PEST (Doherty, 2004) as a single value for the whole investigated area, assuming a homogeneous aquifer. The estimated range (from minimum to maximum value) was set from 90.72 to 683.64 md^{-1}. These values were obtained by studying the final reports from hydrogeological investigations in the area of interest as well as using the hydrogeological maps of the site (from the State Geological Institute Dionyz Stur. The first estimated value was 253.58 m. d^{-1}, which corresponds to the average value of the hydraulic conductance determined by the pumping tests located in the area of interest. The final value calibrated by PEST was 228.36 m. d^{-1}.

CONDUCTANCE OF THE RIVERBED

A conductance is defined as the hydraulic conductivity of the riverbed materials divided by the vertical thickness (length of travel based on vertical flow) of the riverbed materials, multiplied by the area (width times the length) of the river in the cell. The last term, area, is the hardest parameter to determine by hand since it varies from cell to cell. GMS can automatically calculate the lengths (i.e. sections of the channel), which were entered in the range of 1-10 m according to experience from previous models in Žitný ostrov area. Therefore, when a conductance is entered in particular sections of the channel, it should be in GMS entered in terms of conductance per unit length. When GMS applies the boundary condition from the arc to the grid cell, it automatically multiplies the entered value of conductance by the length of the arc that intersects the cell to create an accurate conductance value for the cell.

The values of the conductances were calibrated as follows:

- for the S VII drainage channel C = 2.0 m^2.d^{-1}/m;
- for the AVII and B VII drainage channels C = 3.0 m^2.d^{-1}/m.

RESULTS OF THE CALIBRATION

Calibration targets display a calibration error at each object. The centre of the target represents the observed value, a top of the target is equal to the observed value + an interval (0.10 m) and a bottom of the target is the difference of the observed value and the interval. If the colour of the calibration target is green, the bar lies entirely within the target. A yellow colour means the bar is outside the target, but the error is less than 200 %. For a red colour of the calibration target, the error is greater than 200 %.

All targets (except from two targets) have the green colour, which means that the difference between the observed and computed head is less than 0.10 m in every observation point. The difference between the observed and calculated head in the two yellow calibration targets is 0.17 (12.04 % of the difference between the maximum and minimum value in the observation well, or a variance) and -0.11 m (12.94 % of the variance) (see Fig.20). The model can be assumed calibrated in the accepted level of accuracy.

4.3.2.1.4. Model verification

The verification period of the model, which uses the set of calibrated parameter values and stresses to reproduce a second set of field data, was from the March 13, 2018 to May 2, 2018 (Fig. 19).

Fig. 20 captures the contours of the calculated groundwater head for the steady-state model of the verification period.

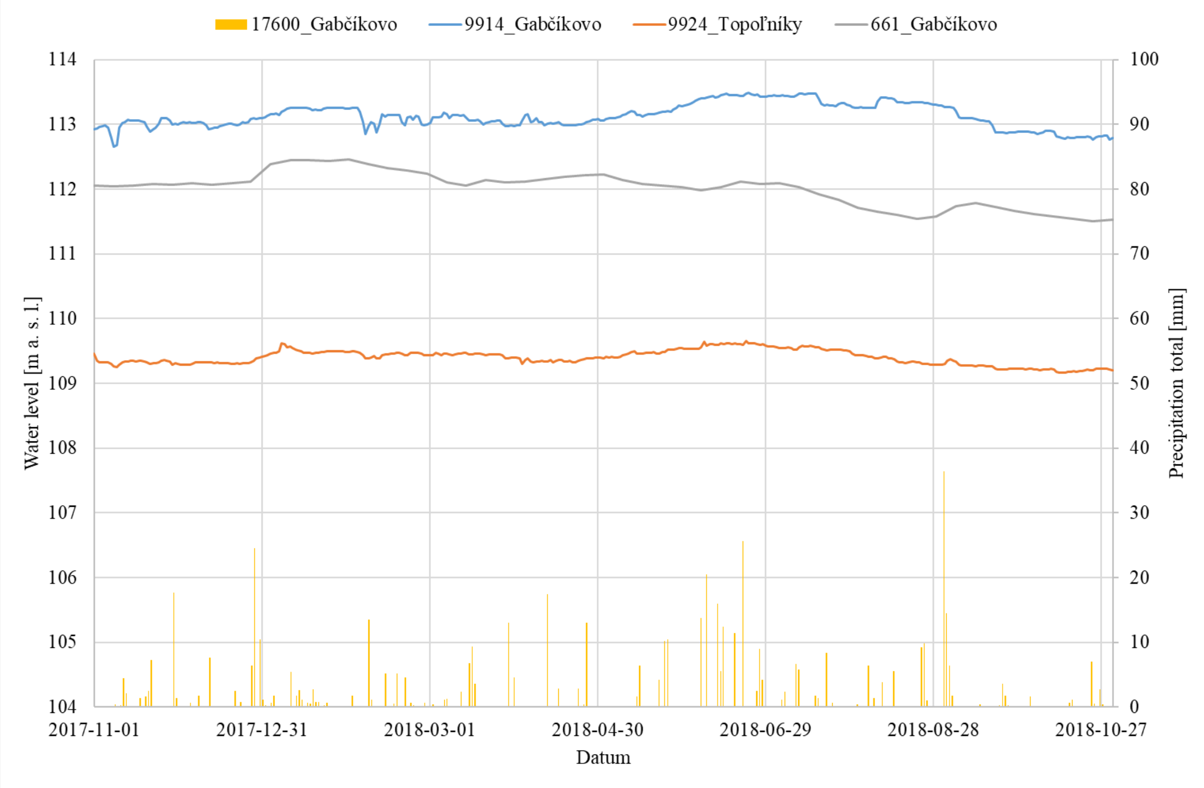


Fig. 19 The course of the water level at stage discharges on the S VII channel (9914 Gabčíkovo and 9924 Topoľníky) and the course of the groundwater level in well no. 661 in Gabčíkovo; daily total precipitation in the rain gauging station 17600 Gabčíkovo – hydrological year 2018 (SHMI, 2021)

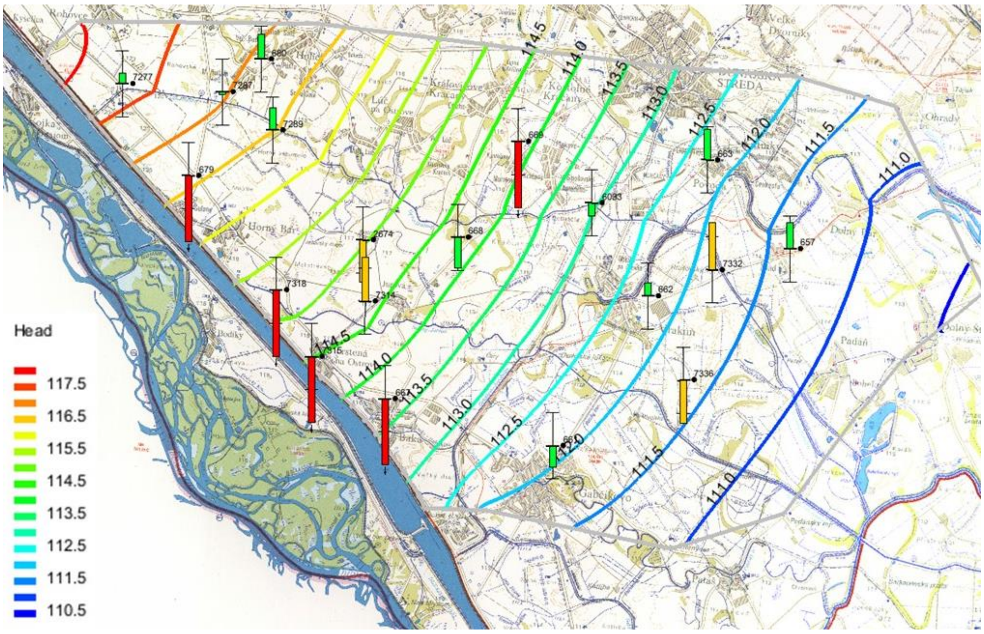


Fig. 20 The calculated groundwater head for the period from March 13, 2018 to May 2, 2018 [m a. s. l.] with error bars for the head measured vs calibrated points

Tab. 6. Differences of the observed and computed head (D) compared to the difference between the maximum and minimum measured level (variance, V) in every observation point

Name	*Variance (V)*	*Difference (D)*	*D/V*100*
657	0.32	-0.08	-24.6
661	0.96	0.07	6.82
662	0.55	-0.04	-7.33
663	0.25	-0.09	**-37.4**
667	0.70	0.38	**55.0**
668	0.45	0.09	20.7
669	0.33	0.28	**85.5**
679	0.58	0.22	**38.0**
680	0.32	-0.07	-23.2
2674	0.37	0.13	**34.2**
6033	0.35	0.04	11.4
7277	0.59	-0.03	-5.69
7287	0.41	0.01	1.63
7289	0.35	-0.07	-19.5
7314	0.41	-0.13	**-32.7**
7315	0.53	0.36	**68.3**
7318	0.47	0.34	**71.8**
7332	0.39	-0.14	**-36.8**
7336	0.76	0.13	17.3
	Σ =	1.38	

As can be seen from the Fig. 20, several targets have the green colour. The rest of the calibration targets have the yellow and red colour, which means, that the difference between the observed and computed head is more than 0.10 m. Nine of these objects (Tab. 6) have the proportion of the difference of the observed and computed head (D) to the variance, i. e. the difference between the maximum and minimum measured groundwater level (V), greater than 30 %. The reason is, on the one hand, that the influence of the left-hand side seepage channel is not taking into account because of the missing data – the water level on the seepage channel is not measured or observed. On the other hand, it could be caused by the estimation of the water level courses in channels A VII and B VII. There are not any records about the water levels on these channels, nor the records about the manipulation with gate slides of weirs on the channels. The course of water levels is therefore estimated based on the field measurements (see chapter 3.3). However, if we look at the sum of the differences, the value itself is close to zero.

4.3.2.1.5. Model results

A prediction represents a response of the system to future events. The model is run with calibrated values for parameters and stresses, except for those stresses that are expected to change in the future.

Two scenarios (prognosis) have been examined on the A VII channel for both modelled periods:

- Prognosis 1 – **water level corresponds to the maximum levels at each weir** (for the period from 2018, Fig. 23) **or to the maximum level during the flood situation** (in 2010, Fig. 21) **+ gate slides in the rkm 0.000 and 17.171 are closed;**
- Prognosis 2 – **water level corresponds to the maximum levels at each weir** (for the period from 2018, Fig. 24) **or to the maximum level during the flood situation** (in 2010, Fig. 22), **the gate slides on the rkm 0.0 and 17.171 are closed + 3 proposed weirs in the rkm 2.270, rkm 7.060 and rkm 12.530 are in operation (the height of each gate slide is 1.6 m).**
- Zero variant **- the natural surface water level regime.**

The calculated groundwater heads for the steady-state models capturing the prognosis 1 for the period of 2010 is in Fig. 25 and for the period from 2018 in Fig. 29. The prognosis 2 of the period from 2010 is in Fig. 27 and for the period of 2018 in Fig. 29.As can be seen from Fig. 26, Fig. 28, Fig. 30 and Fig. 32, the differences in groundwater levels vary from 0.0 to 0.25 m in the modelled period from 2010 (wet) and from 0.0 to 0.35 m in the modelled period from 2018 (dry). Increased groundwater level affects the volume of water infiltrated into the aquifer (Tab. 7) but does not cause the flooding of the adjacent area. Due to the slight increase in water level, the groundwater gets closer to the roots of cultivated crops.

Tab. 7. Predicted infiltrated water amount [$m^3.d^{-1}$]

Predicted infiltrated water amount [$m^3.d^{-1}$]	**2010 (wet)**			**2018 (dry)**		
	Infiltration to porous rocks (from channel)	Draining of porous rocks (to channel)	Total infiltrated amount	Infiltration to porous rocks (from channel)	Draining of porous rocks (to channel)	Total infiltrated amount
Zero variant	46648	-19767	26881	45318	-30959	14359
Prognosis 1	48053	-10143	37910	50784	-27186	23598
Prognosis 2	49946	-8733	**41213**	58029	-25240	**32789**

The amount of water infiltrated into aquifer after operation on existing weirs (Prognosis 1) increased in both investigated years more than 40 % (wet year 2010) and more than 60 % (dry year 2018). The present operation on water structures on the S VII channel system by Slovak Water Management Enterprise enables the realisation of managed aquifer recharge. **The infiltrated water amount into groundwater can be increased by construction of additional three weirs (Prognosis 2) up to more than 50 % (wet year 2010) and more than 75 % (dry year 2018) in comparison with the natural surface water level regime (Zero variant).**

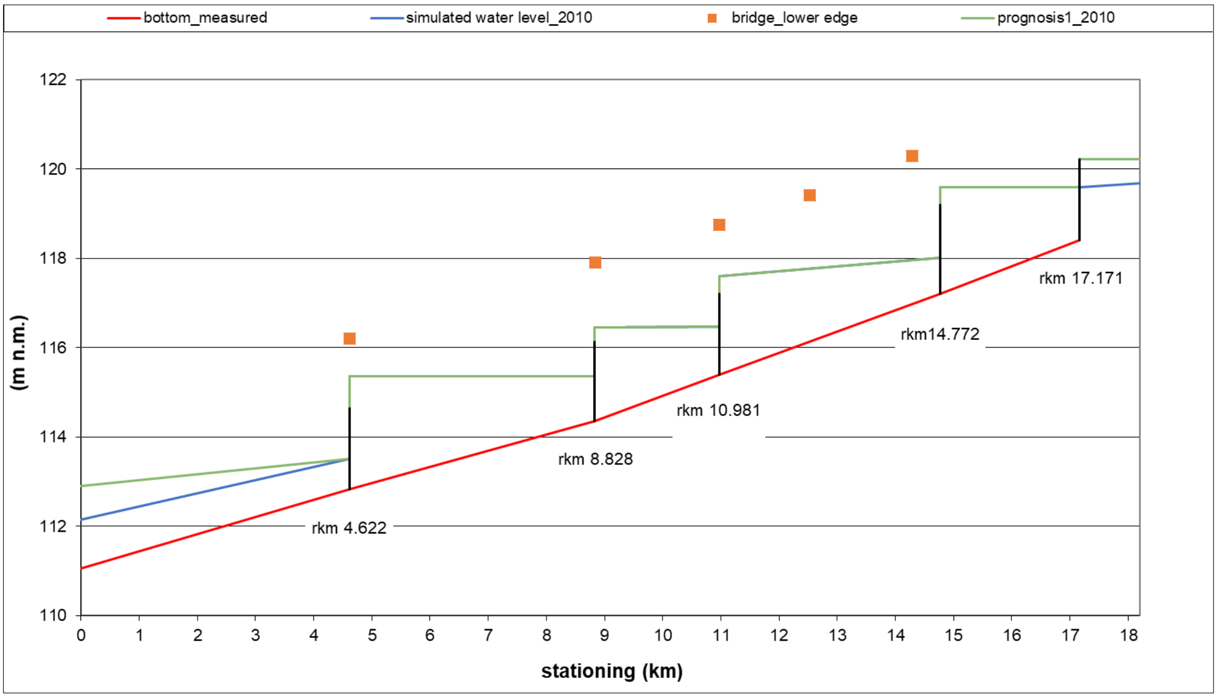


Fig. 21 Longitudinal profile of the A VII drainage channel – simulated water level and prognosis 1 (2010)

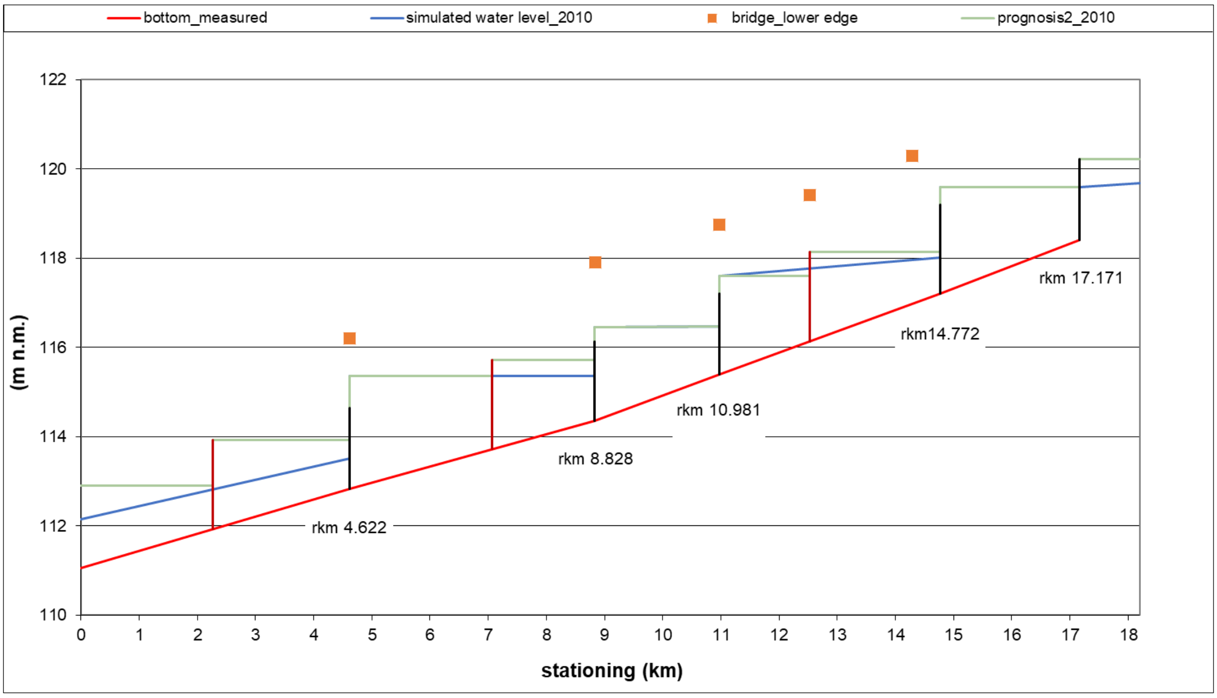


Fig. 22 Longitudinal profile of the A VII drainage channel – simulated water level and prognosis 2 (2010)

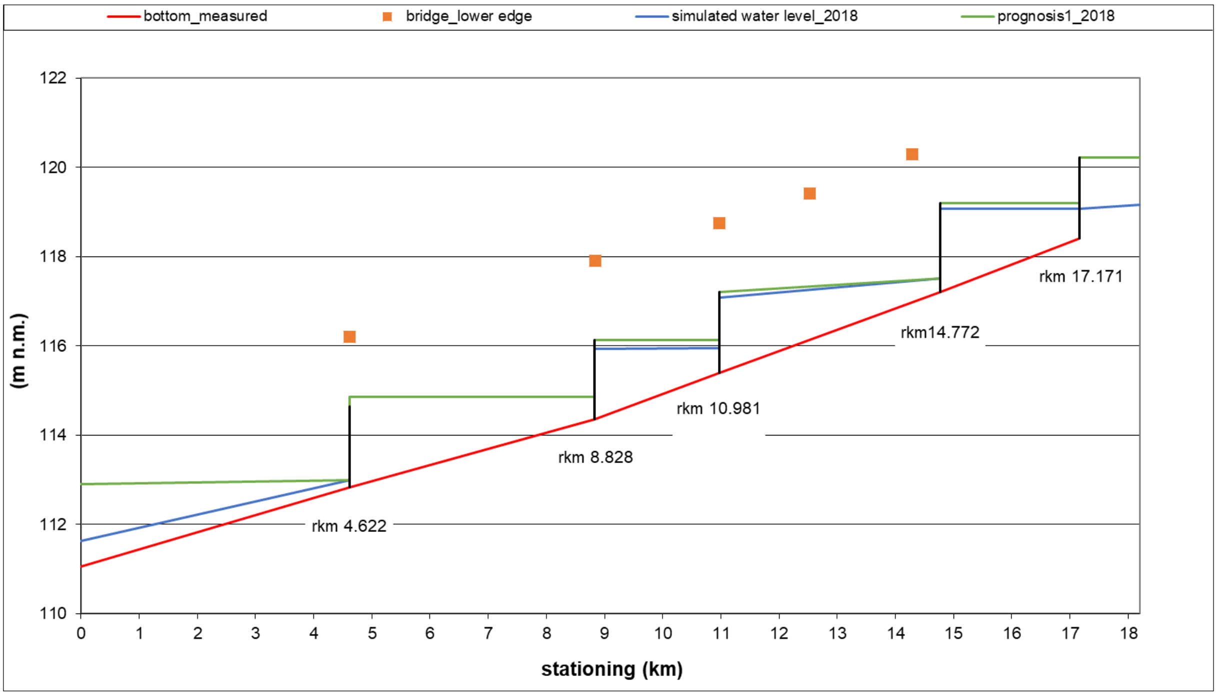


Fig. 23 Longitudinal profile of the A VII drainage channel – simulated water level and prognosis 1 (2018)

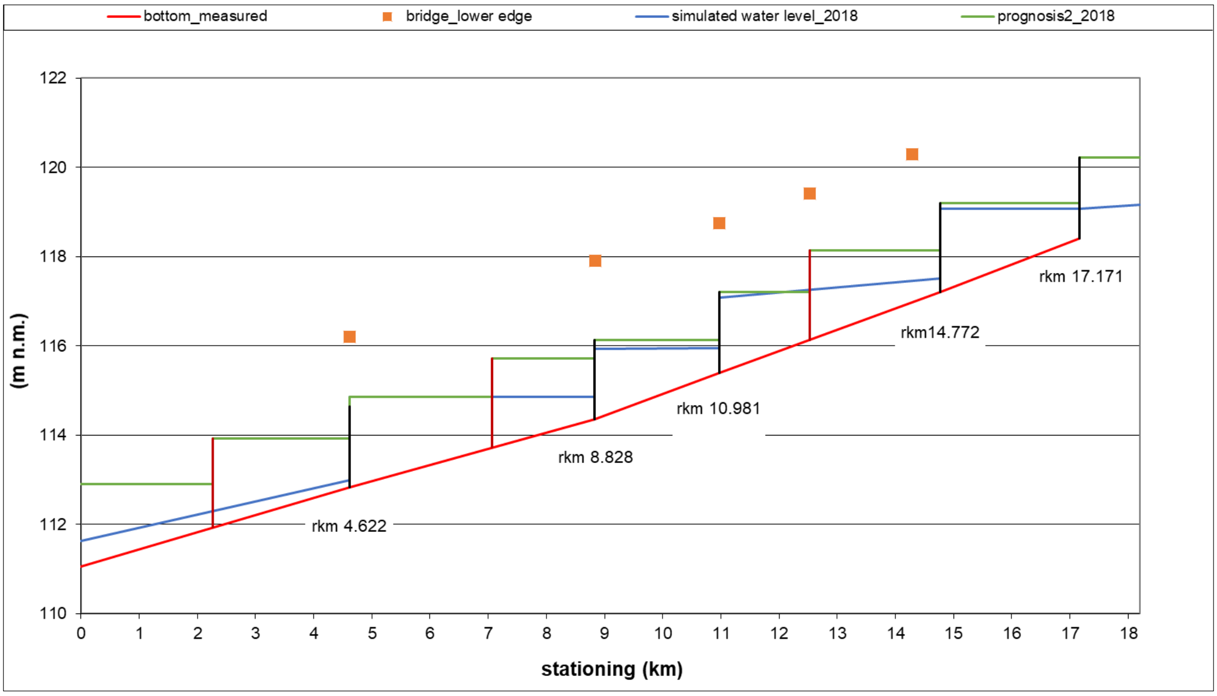


Fig. 24 Longitudinal profile of the A VII drainage channel – simulated water level and prognosis 2 (2018)

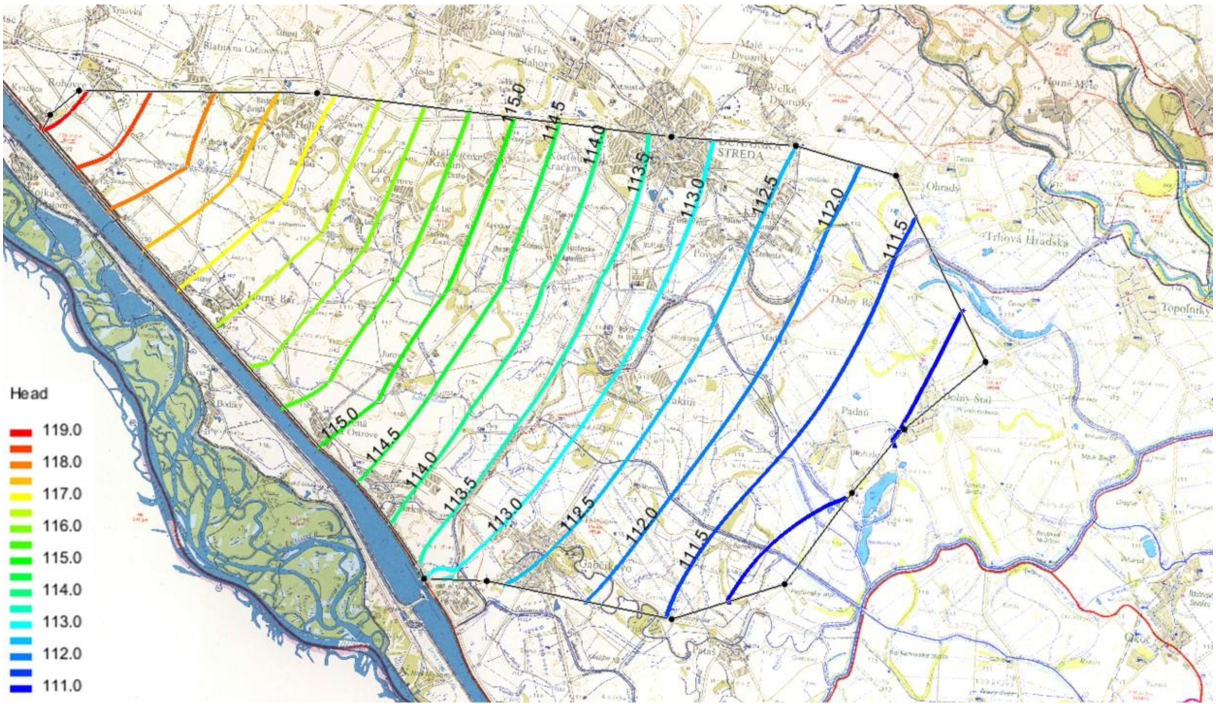


Fig. 25 Prognosis 1: calculated groundwater head for the period from May 26, 2010 to September 9, 2010 [m a. s. l.]

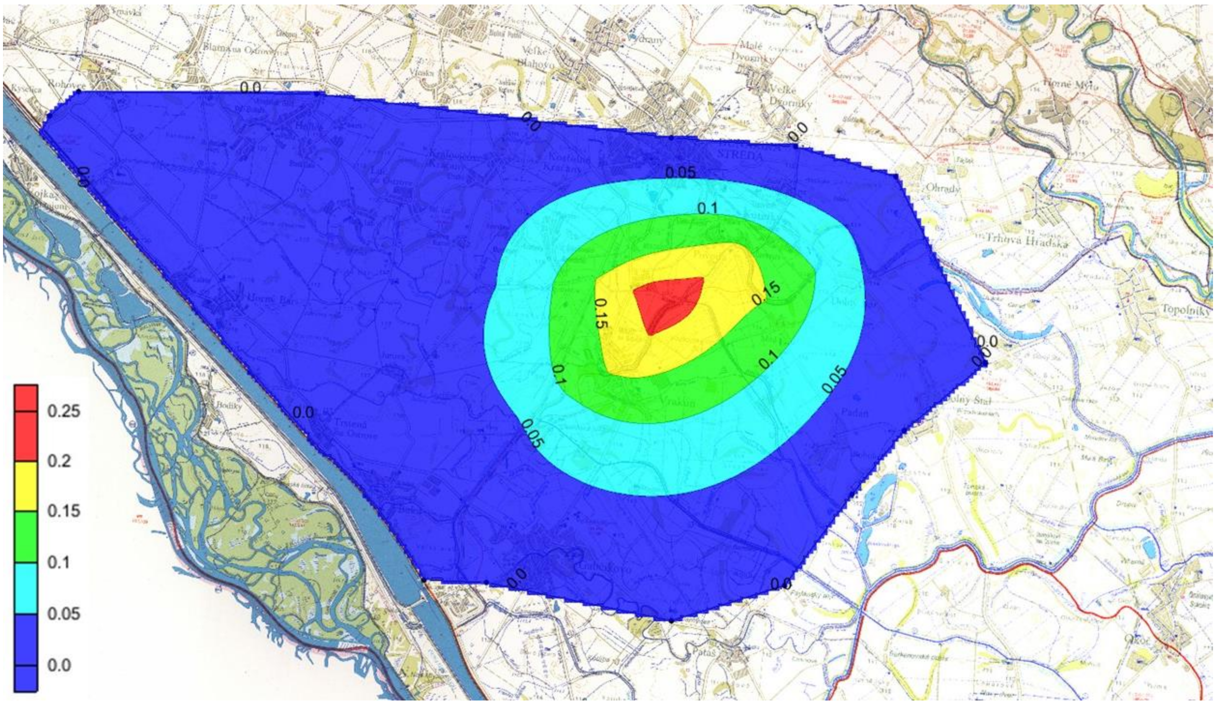


Fig. 26 Difference between the prognosis 1, 2010 and the „zero variant“

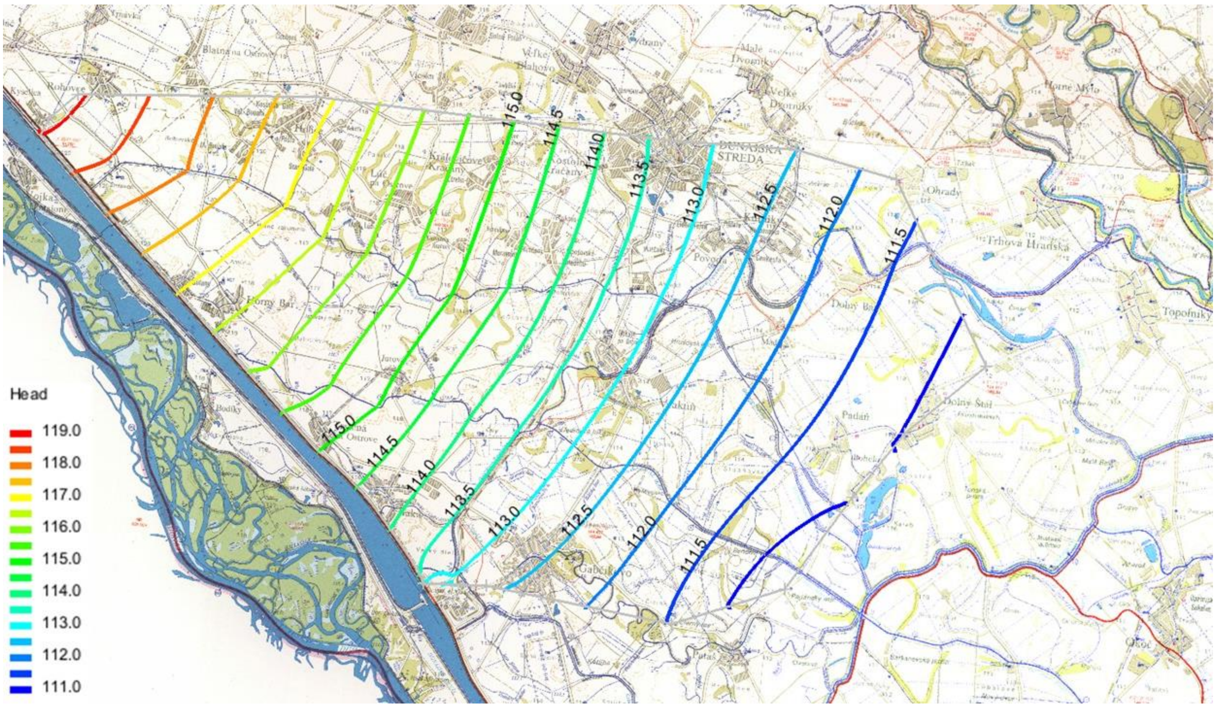


Fig. 27 Prognosis 2: calculated groundwater head for the period from May 26, 2010 to September 9, 2010 [m a. s. l.]

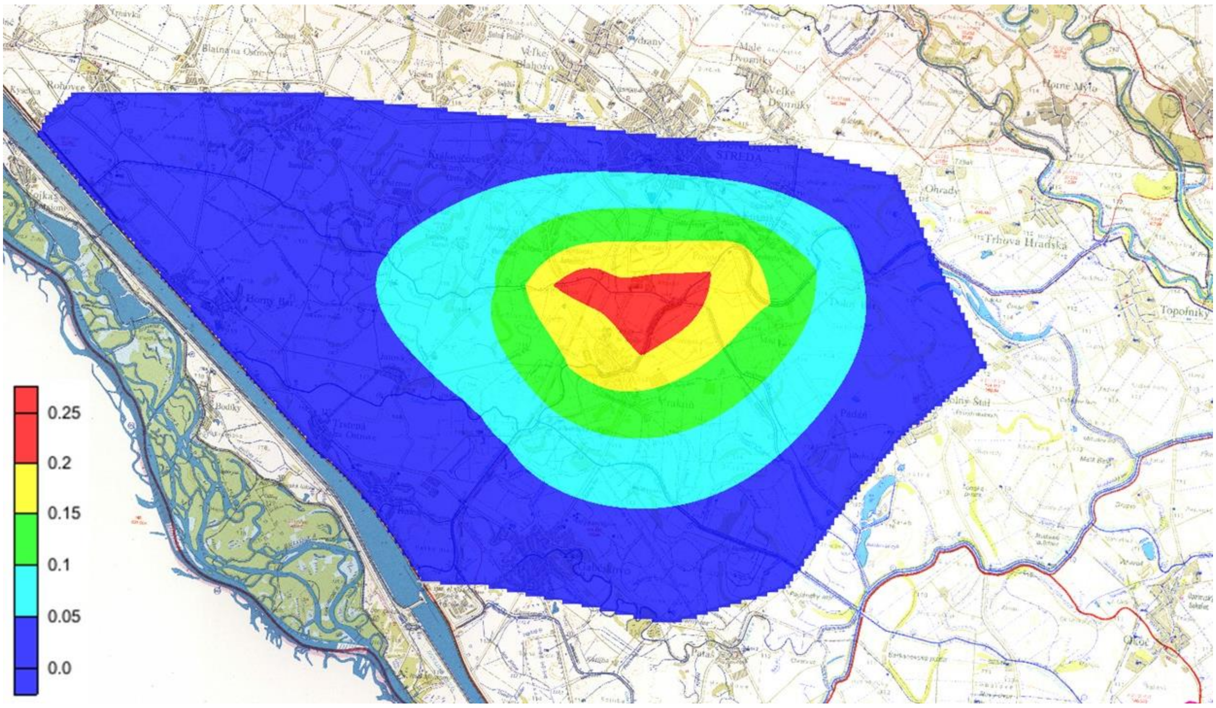


Fig. 28 Difference between the prognosis 2, 2010 and the „zero variant“

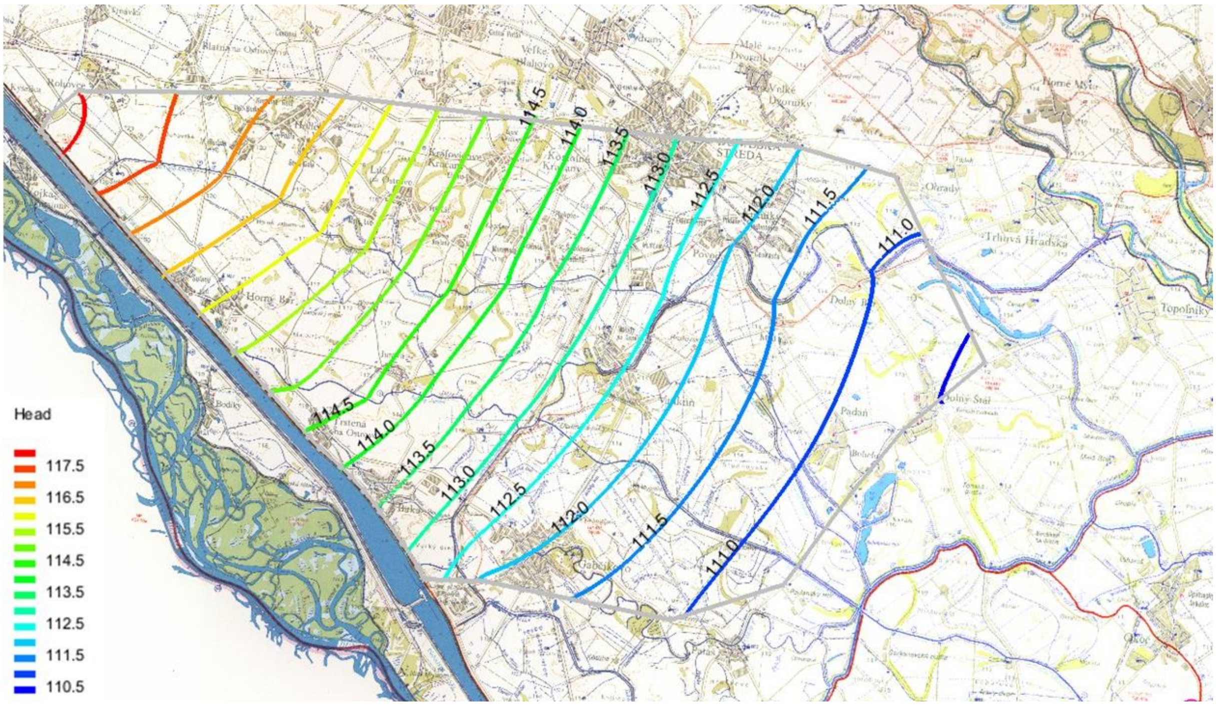


Fig. 29 Prognosis 1: calculated groundwater head for the period from March 13, 2018 to May 2, 2018 [m a. s. l.]

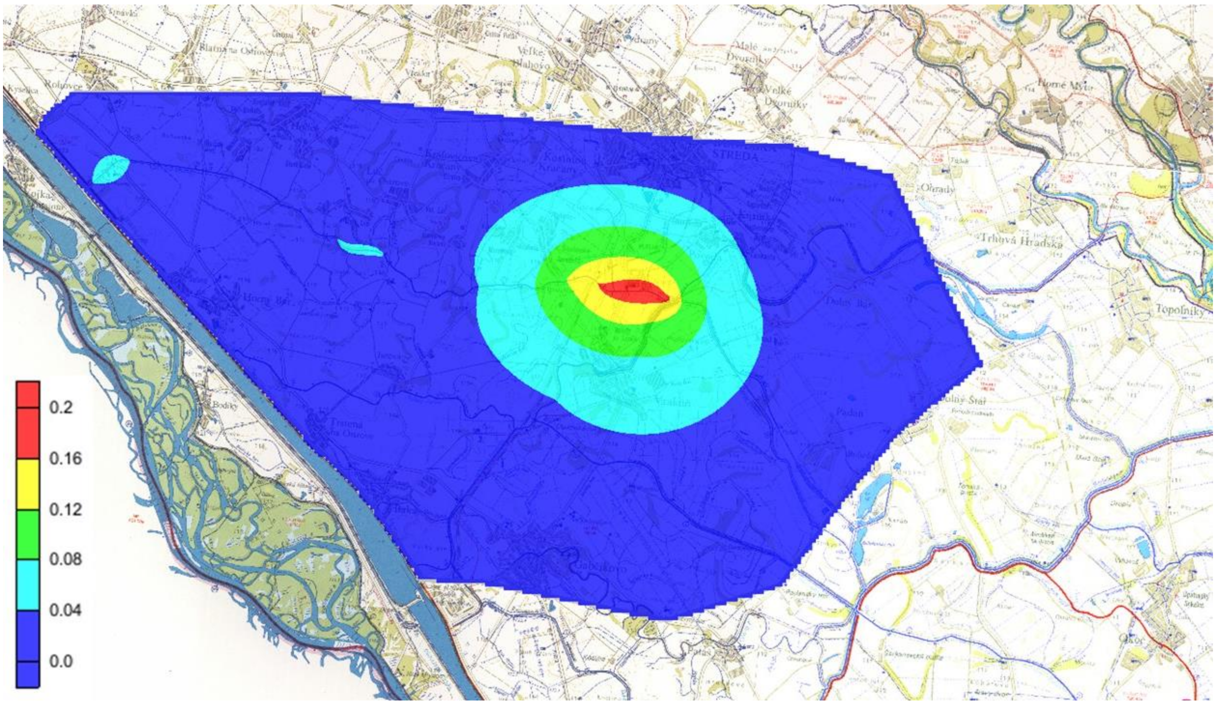


Fig. 30 Difference between the prognosis 1, 2018 and the „zero variant“

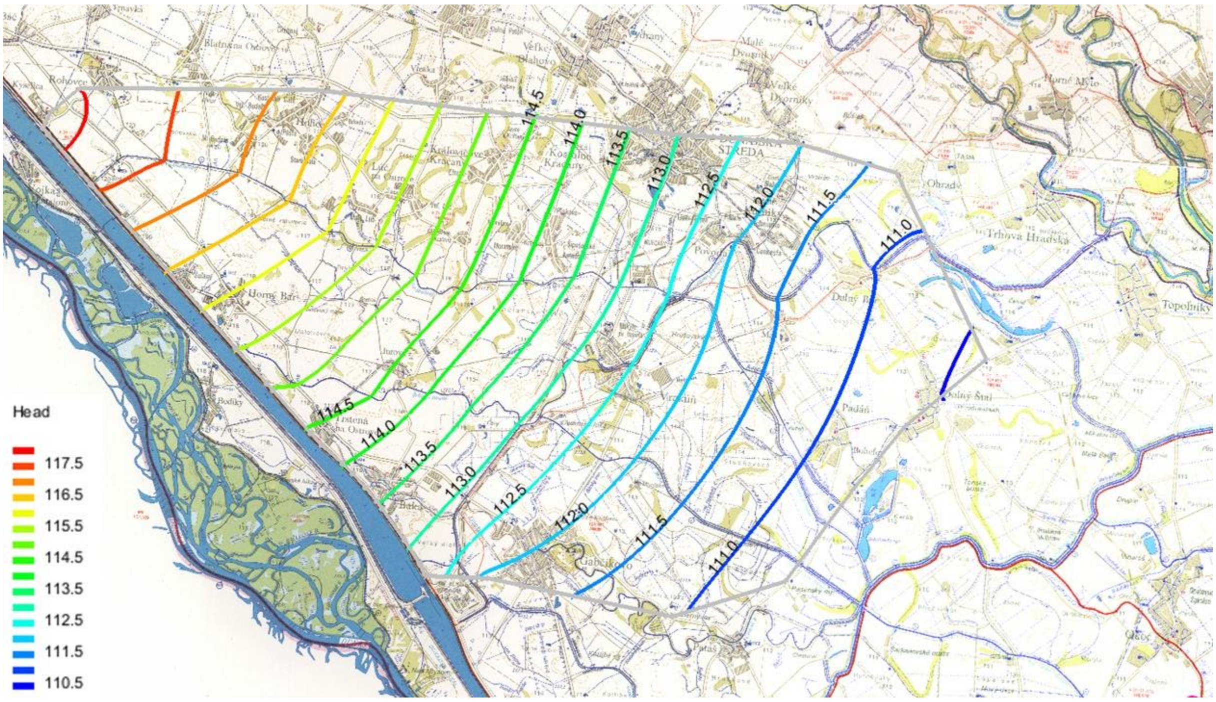


Fig. 31 Prognosis 2: calculated groundwater head for the period from March 13, 2018 to May 2, 2018 [m a. s. l.]

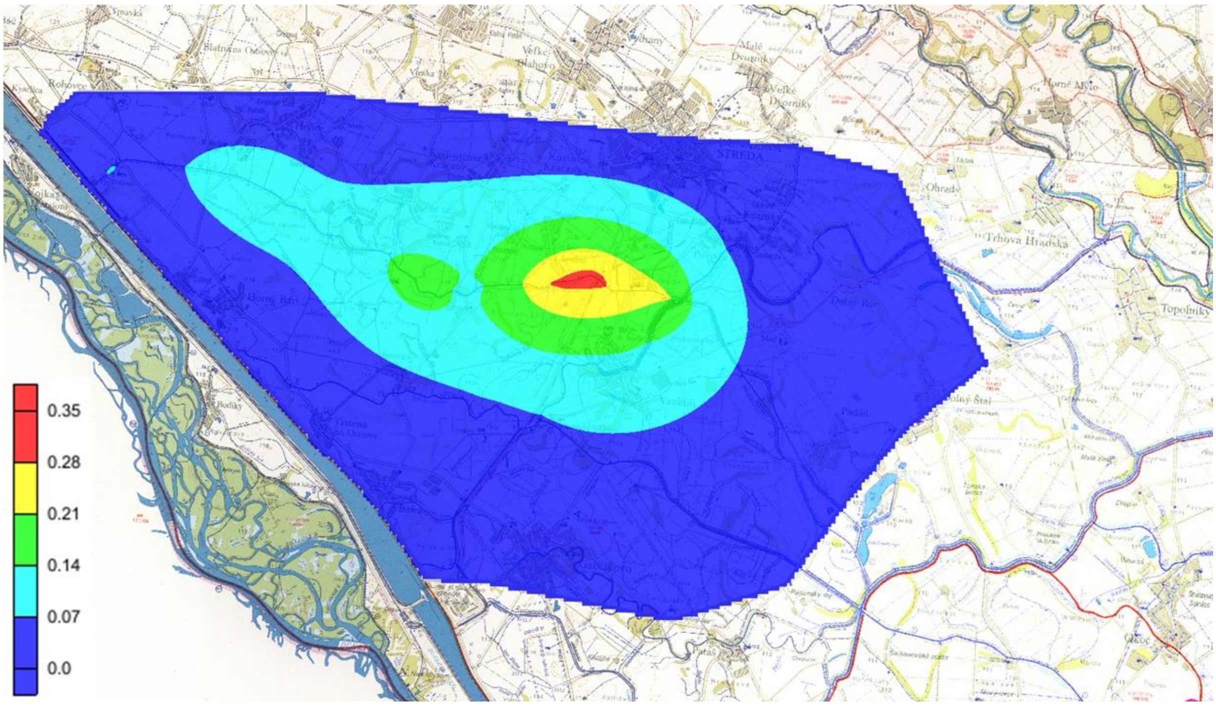


Fig. 32 Difference between the prognosis 2, 2018 and the „zero variant“

The idea of using former drainage channels for groundwater supply and for irrigation purposes was suggested already before putting GHPP into operation, but nobody considered pros and cons for the adjacent area. Moreover, when is about 5.000 km of drainage channels in the region of Žitný Ostrov. The selected S VII channel system is just one part of them (not more than 1.5 %) but maybe one of those where the surface water flow regulation can be a significant tool for water supply into aquifer. The advantage of the S VII channel system is the stable and controlled supply of water from the seepage channel which has very high water quality.

Modelling conclusion

Hydrological Network of groundwater quantity monitoring of the Slovak Hydrometeorological Institute. Three hydrological years have been selected for the data analysis, i.e. 2008 as the year which can be characterized as the precipitation normal year; 2010 as the wet year extremely (precipitation above normal); and 2018 with extremely low precipitation totals recorded in April, May, July and October. Then 2 scenarios (prognosis) have been examined on the A VII channel for above mentioned periods 2018 and 2010, i.e. Prognosis 1 – water level corresponded to the maximum levels at each weir when gate slides in the rkm 0.000 and 17.171 were closed; Prognosis 2 – water level corresponded to the maximum levels at each weir when the gate slides on the rkm 0.0 and 17.171 were closed and additional 3 newly proposed weirs in the rkm 2.270, rkm 7.060 and rkm 12.530 were in operation (the height of each gate slide is 1.6 m). Zero variant was the natural conditions – open gates surface water level regime.

The results of modelling showed the potential infiltration amount of surface water to groundwater – in Prognosis 1 it corresponds to 37910 [$m^3.d^{-1}$] in wet year and 23598 [$m^3.d^{-1}$] in dry year and in Prognosis 2 it corresponds to 41213 [$m^3.d^{-1}$] in wet year and 32789 [$m^3.d^{-1}$] in dry year. It is evident that the amount of water infiltrated into aquifer after operation on existing weirs (Prognosis 1) increased in both investigated years more than 40 % (wet year 2010) and more than 60 % (dry year 2018). The infiltrated water amount into groundwater can be increased by construction of additional three weirs (Prognosis 2) up to more than 50 % (wet year 2010) and more than 75 % (dry year 2018) in comparison with the natural surface water level regime (Zero variant). The present operation on water structures on the S VII channel system by Slovak Water Management Enterprise enables the realisation of managed aquifer recharge.

4.3.2.2. Numerical modelling – HYDRUS-2D

The model HYDRUS is a mathematical, deterministic model simulating the transport of water, heat and multiple solutes in variably saturated porous media (soil) (Šimunek, et al., 2013). Model HYDRUS can be applied as one dimensional (HYDRUS-1D), as well as two and three dimensional (HYDRUS-2D/3D).

Governing equation of the simulation model HYDRUS-2D is so called Richard's equation in two dimensions (Radcliffe, Šimůnek, 2010, Novák, Hlaváčiková, 2019).

$$c(h_w)\frac{\partial h_w}{\partial \mathrm{t}} = \frac{\partial}{\partial \mathrm{z}}\left[k(h_w)\frac{\partial h_w}{\partial z}\right] + \frac{\partial}{\partial x}\left[k(h_w)\frac{\partial h_w}{\partial x}\right] + \frac{\partial k(h_w)}{\partial z} \pm S(z,t)$$

$$c(h_w) = \frac{\partial \theta}{\partial h_w}$$

$c(h_w)$ is so called specific soil water capacity; it is the change of soil water content of a unit volume of soil due to unit change of soil water matric potential (here expressed in pressure heads h_w, cm), x, z are horizontal and vertical coordinates, cm, $k(h_w)$ is hydraulic conductivity of porous media (soil), cm/s. $S(z,t)$ is the rate of water (solution) extraction from soil by roots, expressed as volume of water extracted from unit volume of soil during unit of time (s^{-1}). It is usually function of depth below soil surface and time, because the depth and density of the root systems are changing during vegetation period of plants.

By this model can be estimated infiltration, evapotranspiration, plant root water uptake, surface runoff and groundwater recharge by infiltration of water from precipitation as well as by infiltration from the surface watercourses (channels, rivers).

Managed groundwater recharge (MAR) from channels depends on properties of an environment. Therefore following issues - channels dimensions, properties of porous rocks, water level in channels and the initial depth of groundwater have to be quantified as input to model.

In principle, this problem is formulated as 3D transport of water from channels to aquifer. Result of 3D approach will be 3D simulation of water movement in groundwater aquifers of Žitny Ostrov selected area. Generally, the flow of water from channels to surrounding porous aquifers is performed perpendicularly to the channel axis, therefore it is sufficiently to solve this problem (infiltration from channels to gravel aquifers) as 2D infiltration of water from channels into aquifer. 2D approach is simpler and can lead to more exact and reliable results (Radcliffe and Šimunek, 2010). Principle in mathematical modelling is to make model as simple as possible, but do not neglect basic features of the process that allows involving into calculation channel bottom sediments and soil variability in vertical dimension.

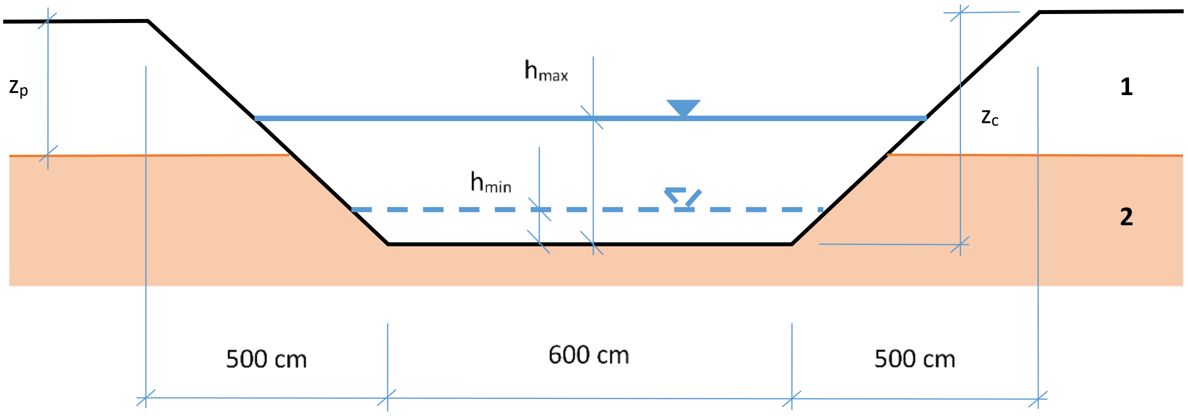
Another possible simplification of the groundwater recharge modelling is to neglect infiltration of water from precipitation, which can simplify the calculating procedure and better evaluate the role of channel infiltration (groundwater recharge) to groundwater aquifers. This simplification is supported by the water balance analysis of the Žitný Ostrov area.

4.3.2.2.1. Channels characteristics

Groundwater recharge by infiltration from channels depends on properties of channels, hydraulic characteristics of porous rocks and on water table level in channels. Modelling of MAR considers variation of these aspects.

Channels geometry and depth of aquifers

The channels´ geometry is approximately the same, as it is shown in Fig. 33. The depth of the channels (z_c) differ in the range 150 – 250 cm below the soil surface level. Those differences depend on the uneven terrain surface, which is a little bit undulating. Because the channels bottom slope have to be constant, the depth of channels reflect variability of terrain surface. Important is, that variability of the conductive layer (aquifer) depth (z_p) is practically always above the channels bottom, therefore infiltration of water from channels can be high, so have a hydraulic conductivity with the aquifers. This is not always true, because of bottom sediments, but proper maintenance of channels can preserve a good infiltration capacity of channels.



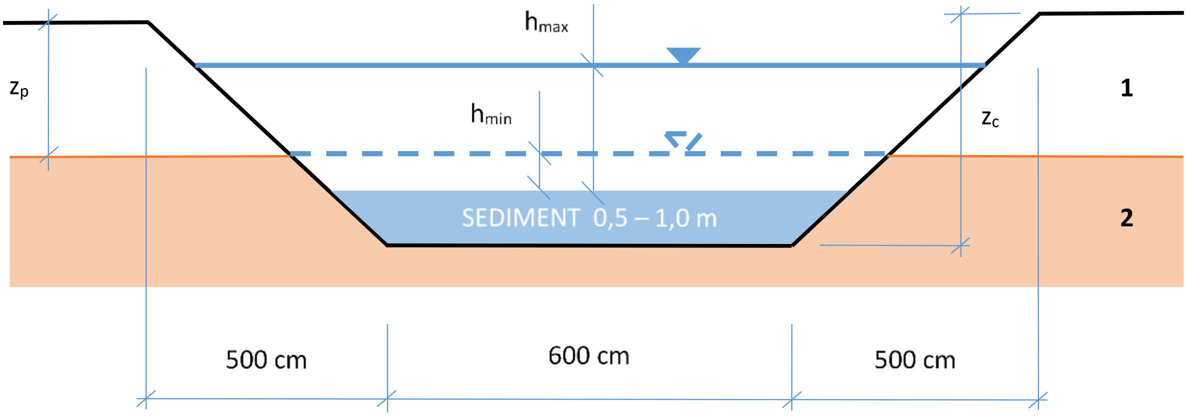


Fig. 33 Channels (AVII, BVII and SVII) cross- section without and with layer of bottom sediments. Depth of channel is (z_c), the thickness of the upper less permeable soil layer is changing, and is identical with the depth of the more permeable (gravel) layer (z_p). The depth of bottom sediments layer is (z_s). Water table depth in channels (h) is fluctuating in the in the range h_{min} = 40 cm, and h_{max} = 200 cm.

Water table level in channels

Water table level in channels can significantly influence water infiltration rate. Therefore, in modelling procedure, there were used different water table levels as it is shown in Tab. 1. The water table levels in channels (AVII, BVII and SVII) are regulated by sluice gates. According to results of measurements by Šoltész, et al., (2021), under condition of open sluices, the „minimum“ water table depth in channels is h_{min} = 40 cm, maximum water table depth in channels is h_{max} = 200 cm. Because of the channels slope, the depth of the water layer is changing in „stepwise“ manner, i.e. it is oscillating between h_{min} and h_{max}, accordingly to the position of sluices. Without sluices influence, the depth of water layer in channels is around 40 cm.

Bottom and bank sediments

During channels operation (irrigation channels) significant layers of fine particles sediments were found in the bottom of channels. The thickness of bottom sediments varies according to slope of channel bottom and water flow velocity. Water flow velocity is determined not only by slope of the channel (and water table) but significantly by vegetation growth in the channel sediments, especially during the vegetation period. But this phenomenon is not important when calculating infiltration of water into groundwater, it depends on water table level/ pressure head in the channel. Thus, bottom sediments thickness were measured along channels. Their thickness varies between 0.5 – 1.0 m and its saturated hydraulic conductivity is in the range K_{bs} =2.7 – 385 cm/d with average measured value K_{bs} = 2.8 cm/d (Dulovičová, et al., 2018). Saturated hydraulic conductivities seem to be relatively high, in comparison to the porous medium sublayer (aquifer) which is composed of fine gravel clogged by fine particles from infiltrated water (suspension) to the groundwater. This porous material composed by gravel and fine particles is less conductive than sediments itself and therefore, the infiltration capacity of the channels is not significantly influenced by sediments. The longitudinal profiles of the sediments conductivities in the channels are summarised in Dulovičová et al. (2018). Sediments in the channels contain organic matter and minerals, which is good substrate for plant growth. Therefore channels are overgrown by dense vegetation which decrease water flow velocity and transportation capacity of the channels. To increase it, it is necessary to keep channels clean of plants.

Bank sediments were found near bottom part of banks only; it is assumed their minor effect on water infiltration. Sedimentary rocks forming bank of channels are usually two orders less conductive than permeable gravel area (Tab 8.). They will be involved into model according to measured hydrophysical properties of soils and thickness of their layers.

Tab. 8. Results of saturated hydraulic conductivity K of soil samples in laboratory at two sites (L1 Jozefov, L2 Amadeove Kračany).

Site L1 - Jozefov				Site L2 - Amadeové Kračany			
Depth	**Sample**	**K**	**K_{avg}**	**Depth**	**Sample**	**K**	**K_{avg}**
(cm)	number	(cm/d)	(cm/d)	(cm)	number	(cm/d)	(cm/d)
10 -15	2	188	220	20 - 25	23	1.62	1.49
	22	252			24	1.36	
30 - 35	4	181	426	70 - 75	3	6.76	7.67
	5	671			5	8.58	

4.3.2.2.2. Input data to the model HYDRUS-2D

As input data to the model hydrophysical characteristics of soil (saturated/unsaturated hydraulic conductivities, soil water retention curves, properties of plant canopy (leaf area index-LAI, roots mass distribution) and characteristics of an atmosphere at standard height above the field (air temperature, air humidity, wind velocity) are needed. Then, groundwater table level change during aquifer recharge by infiltration from channel can be calculated (by the model HYDRUS-2D), the measurements are in Tab.9.

Tab. 9. The depth of gravel layer below soil surface across the pilot area of Žitný Ostrov, along two cross sections C-C, (Horný Bar – Veľké Blahovo) and D-D, (Gabčíkovo – Trhová Hradská); as they are shown on the map. z_g, z_g,(max), z_g,(min), and z_g(avg) are maximum depths of gravel layer, minimum depths of gravel layer and average depth of gravel layer below soil surface, (cm).

	CROSS - SECTION	
z_c (cm)	C - C	D - D
z_g (max)	350	350
z_g (min)	70	85
z_g (avg)	244	247

Soil water retention curves as input data are involved through analytical function proposed by van Genuchten (1980):

$$S_e\left(h_w\right) = \frac{\theta-\theta_r}{\theta_s-\theta_r} = \left[\frac{1}{1+(\propto|h_w|)^n}\right]^m \qquad (3)$$

Terms involved in Eq. (3) are input data into model Hydrus, and are shown in the Tab 5. Parameters α, n, m are so called van Genuchten parameters, θ_s is volumetric soil water content of soil saturated with water, θ_r is so called residual soil water content, i.e. water content, when its hydraulic conductivity is so low, that it can be neglected, it is close to zero. $S_e(h_w)$ is degree of soil saturation, dimensionless. For fully saturated soil $S_e(h_w) = 1$.

Hydraulic conductivity of saturated rocks in 3 sites measured by auger hole method are input data for HYDRUS-2D model (Tab. 10)

Tab. 10. Results of auger hole method measurement of saturated hydraulic conductivity *K* of three sites (L1, L2 and L3).

SITE	**z** (cm)	**K** (cm/d)	**K_{avg}** (cm/d)
L1 - Jozefov	80 - 95	336	223
	80 - 95	210	
L2 - Amadeové Kračany	80 - 90	44.5	44.5
L3 - Vrakúň	0 - 32	226.2	181.1
		136	

According to Šimůneket al. (2016), (2018) an updated version of the model allows to involve additional parameters of soil layer.

Hydrophysical characteristics of porous media (soil, aquifer, sediments)

Soil hydraulic parameters (θ_r, θ_s, a, n, K_s, l) of porous layers (Tab.11). Soil hydraulic characteristics used as an input data were measured in the field and laboratory.

Tab. 11. Basic hydrophysical characteristic porous layers (typical vertical profile in channel): θ_r, θ_s, are residual and water saturated volumetric soil water contents, K_s is hydraulic conductivity of saturated porous rocks; alpha, n, m are so called van Genuchtens parameters, where m= 1-1/n (see Tab. 12)

	Q_r	Q_s	Alpha 1/cm	n	K_s cm/min	K_s cm/day
Aquifer	0.057	0.41	0.124	2.28	0.2432	350.20
Sediment	0.100	0.38	0.027	1.23	0.0020	2.88
Soil	0.095	0.41	0.019	1.31	0.0043	6.24

Tab. 12. Soil water retention curves and their characteristics of the four sites in the pilot area of the project, z is the depth below soil surface, cm; θ_s is volumetric soil water content of soil saturated with water, θ_r is so called „residual“ soil water content, alpha, n, m are so called van Genuchtens parameters, where m= 1-1/n.

z (cm)	θ_s	θ_r	K (cm/d)	m	n
ML - 29, Horný Bar					
10 - 20	0.53	0.040	29.0	0.055	1.20
35 - 40	0.48	0.040	16.0	0.056	1.16
60 - 70	0.49	0.033	42.0	0.084	1.17
80 - 90	0.53	0.027	9.0	0.037	1.26
100 - 110	0.52	0.039	7.0	0.027	1.24
ML - 32, Baka					
0 - 30	0.55	0.051	26.0	0.160	1.21
30 - 70	0.51	0.051	47.0	0.060	1.25
ML - 33, Vrakúň					
10 - 20	0.58	0.050	170.0	0.046	1.19
35 - 40	0.45	0.050	150.0	0.031	1.16
50 - 55	0.48	0.051	26.0	0.060	1.15
62 - 67	0.46	0.035	44.0	0.046	1.20
100 - 105	0.53	0.020	29.0	0.027	1.31
ML - 34, Gabčíkovo					
0 - 30	0.57	0.042	83.0	0.061	1.20
30 - 70	0.45	0.039	23.0	0.079	1.19
70 - 75	0.44	0.038	61.0	0.136	1.17
90 - 95	0.48	0.017	7.0	0.042	1.32

Initial and boundary conditions

In the pilot area sites (L1-Jurová, L-2 Amadeove Kračany and L-3 Vrakúň), the groundwater level is oscillating just around the bottom of the channels (Tab. 1, page 24) that corresponds to function of channels (irrigation / drainage). Their function depends on the water level in channels, regulated by movable sluices.

Time variable boundary conditions as meteorological conditions (T_{max}, T_{min}, (max. and min daily air temperature), humidity, wind velocity, precipitation, leaf area index, solar radiation. Meteorological inputs were measured at Hurbanovo meteorological station which is representative for the whole Žitný Ostrov area.

Channels Geometry - FE Mensch is automatically generated by the programme, according the size and shape of modelled area.

4.3.2.2.3. Scenarios of HYDRUS-2D modelling

The aim of the modelling is evaluation of the infiltration rate of water from channels to the aquifers considering the influence of soil/sediment/rock properties. Especially, it will be concentrated on the role of less permeable topsoil and aquifer characteristics, bottom sediments properties and water table depths in channels.

Infiltration of water from channels - scenarios:

1. **channel is located in the upper layer of quaternary sediments**

This is the ideal case: channel is in the upper layer of quaternary sediments (gravel with silt), with different water table level in channel. Modelling episode assumes immediately increase of water table in the channel, by closing sluice gates. This is hypothetical situation, because even in a case of immediate closing of sluice gates, the water table in channels will be „step wise“, with maximum water table 2 m above the channel bottom and the lowest water table will be about 0,5 m above the channel bottom. Nevertheless, the situation with immediate increasing of water table to height 2 m leads to the maximum possible infiltration rate from channel to aquifer.

The simulated relationships between infiltration rate (v_i) as a function of time (t) by HYDRUS-2D are given in Fig. 34, 35, 36.

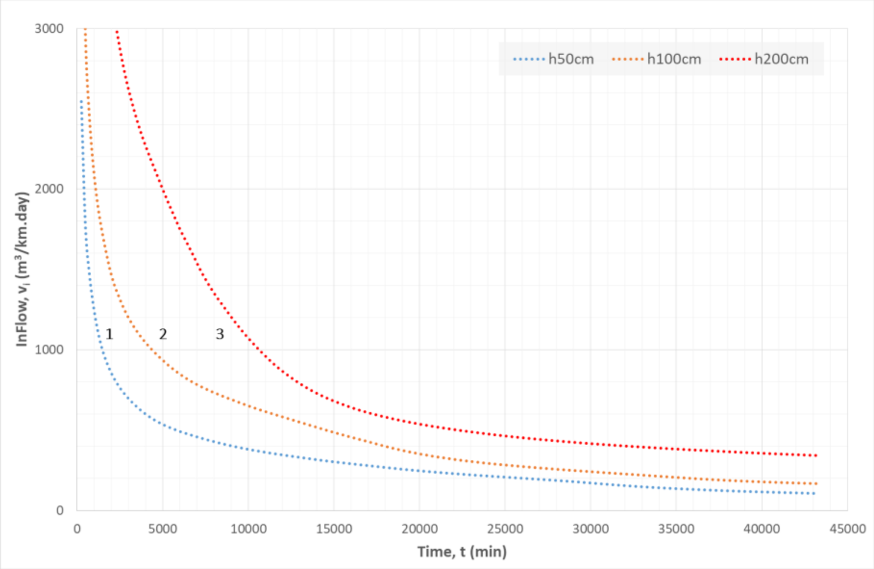


Fig. 34 Infiltration rate (v_i) as a function of time (t) after immediate increasing water table heights in channel to 50 cm (curve 1), 100 cm (curve 2) and 200 cm (curve 3) respectively, above the bottom of the channel, modelled by the simulation model HYDRUS-2D. Rates of infiltration are expressed in (m^3 km^{-1} day^{-1}).

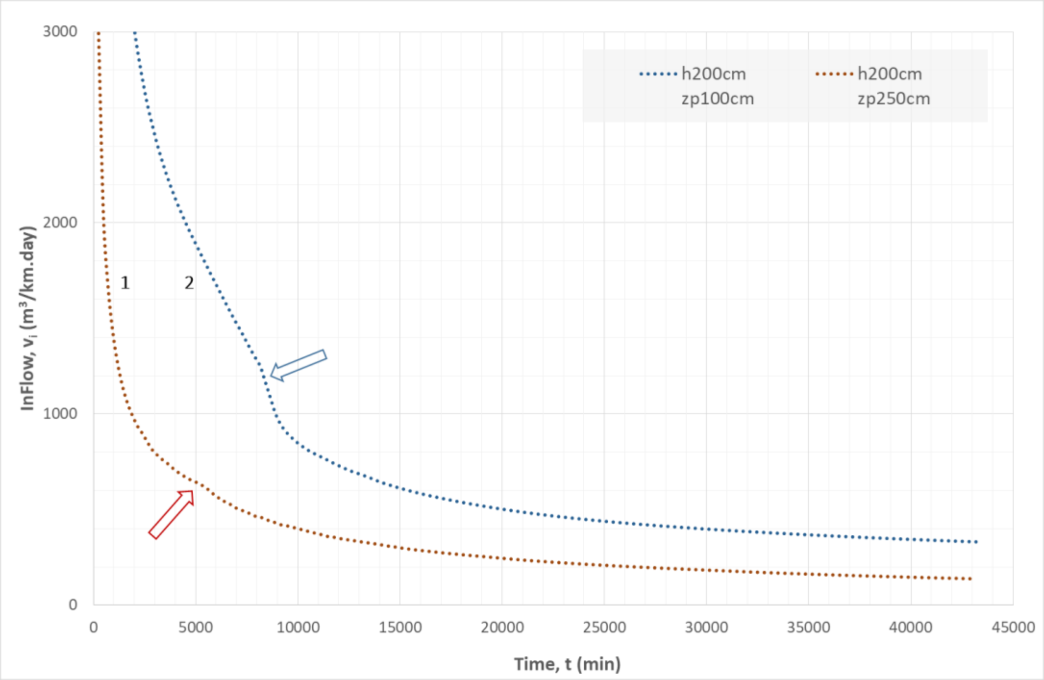


Fig. 35 Infiltration rate (v_i) as a function of time (t) after immediate increasing water table in channel to 200 cm above the bottom of the channel modelled by simulation model HYDRUS-2D. Curve (1) represents 200 cm thick layer of soil, curve (2) represents 100 cm thick soil layer; the last one is of the same depth as the channel bottom.

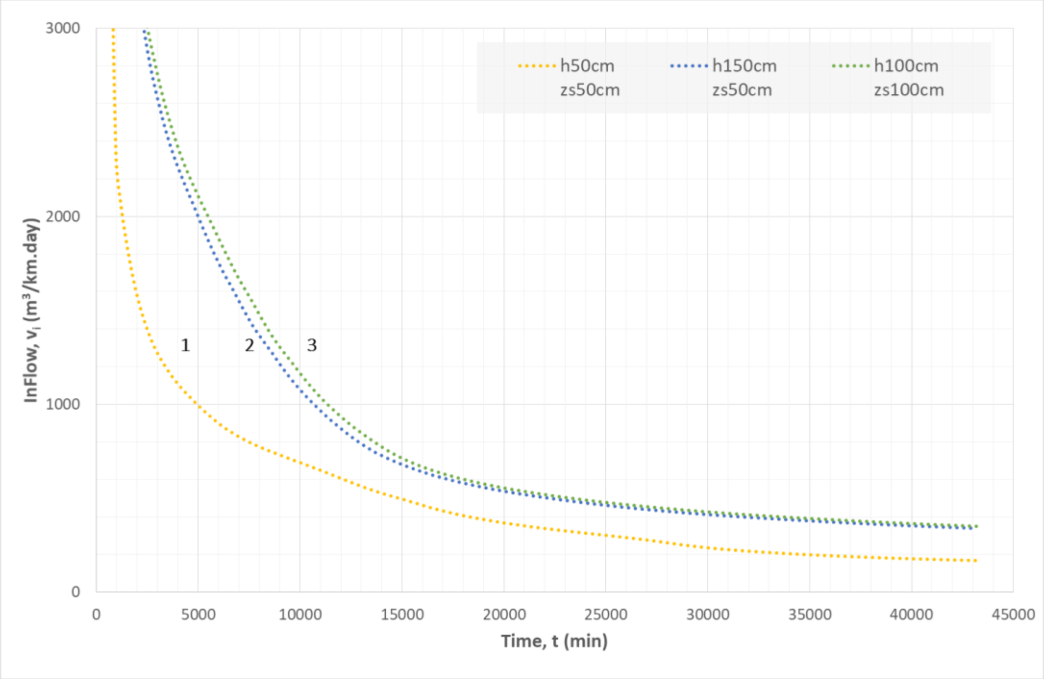


Fig. 36 Modelled relationships between infiltration rate (v_i) as a function of time (t) after immediate increasing water table in channel with sediments modelled by simulation model HYDRUS-2D. Water layer height is 100 cm and 200 cm above the bottom of the channel with 50 cm thick layer of sediments (curves 1 and 2). Curve (3) represents channel with sediment layer thickness 100 cm and with water table 200 cm above the bottom of the channel.

The shapes of the infiltration curves are typical for water infiltration into the soil (Novák, Hlaváčiková, 2019). High gradient of pressure at the beginning of the process allows high infiltration rates, but this rate decreases rapidly. In fact, close to real situation is infiltration curve corresponding to different „stepwise" water table level in channel between 50 and 200 cm, due to location of the sluices and their position. During quasi-steady state (QST), the infiltration rate is between 100 – 350 $m^3\ km^{-1}\ day^{-1}$. The length of the channel system in pilot area is 100.86 km, which means, the total inflow into aquifers is in between 10,000 – 35,000 $m^3\ day^{-1}$, which corresponds to the data estimated by simulation model MODFLOW (Šoltész et al., 2021). But, this situation simulating infiltration from the channel located in upper aquifer is close to the ideal one. In reality channels are located in the less permeable soil layer of different thickness; therefore the infiltration rates should be smaller, in comparison to the case when channels are ideally located in gravel layer.

2. Channel in porous media: soil layer above the aquifer

Interesting infiltration curves can be seen in Fig 35, illustrating the influence of upper soil layer thickness on infiltration rate. Because soil saturated hydraulic conductivity is significantly lower than the gravel layer, the rate of infiltration is significantly lower than it is in an ideal case illustrated in Fig 34. On both curves can be observed very small temporary decrease of infiltration rate at time t_1 for infiltration curve corresponding to z_p = 250 cm (Fig.35, curve 1, shown by arrow), and more significant decrease of v_i for infiltration curve corresponding to lower thickness of upper soil layer z_p = 100 cm (Fig.35, curve 2, shown by arrow).

This phenomenon is less significant in a case, when soil layer depth (and thickness) is 250 cm (and its bottom is at the same depth as the bottom of the channel). However, this phenomenon is more visible in the soil layer of smaller thickness. But, after relatively short time the infiltration rate becomes stable in both cases. The analysis indicates that this phenomenon (deformation of the infiltration curves) will start, when increasing groundwater table (GWT) during infiltration will reach bottom level of the soil layers. This time interval from the infiltration start can be denoted as critical time. Therefore, thicker (and deeper) the soil layer is, the sooner infiltration rate deformation can be observed. So, this critical t_1 for z_p = 250 cm appears sooner, than critical t_2 for thinner soil layer z_p = 100 cm (Fig. 35).

3. Channel in homogeneous gravel layer with bottom sediments

The aim of modelling was to evaluate quantitatively the role of bottom sediments on infiltration rate of water from channel. Infiltration curves of water from such channels are in Fig. 36. The infiltration rate of water is indirectly proportional to the sediment thickness as it was expected (see curves 2 and 3 in Fig. 36.). Bottom sediments in channels are thick 0.5 - 1.0 m (lower value is more frequent). The surprise was relatively low significance of the sediments thickness on infiltration rate. The reason is in relatively high hydraulic conductivity of saturated sediments (Ks) in comparison to the soil, or upper layer of aquifer, which pores are clogged by small particles transported during infiltration of water through bottom sediments. Hydraulic conductivity data of sediments were verified by different methods, because they seemed to be an error at the beginning. However, they were proved by measurements to be realistic. As it is obvious from Tab.11, saturated hydraulic conductivities of soil and upper layer of aquifers are lower than bottom sediments because the bottom sediments have low density, and their particles are in the state of "floating" in water. This phenomenon is resulting in relatively high hydraulic conductivities of saturated sediments and therefore their relatively small influence on infiltration from channels. Data used in this simulation were measured in the field and in laboratory. They were also verified by number of empirical equations (Dulovičová et al., 2018).

The infiltration rates (v_i) at 10 days from the start of infiltration as well as quasi-steady infiltration rates illustrate the role of time in infiltration rate dynamics.

The most important factor influencing inflow rate is the water table level in the channel. Water table when sluices are open is around 0.5 m; the maximum water table is 2.0 m at closed sluices. The first case is realistic and corresponds to the rate of infiltration 100 $m^3\ km^{-1}\ day^{-1}$. But the maximum estimated value is hypothetical, because not all the channels are equipped by such number of movable sluices, to keep water table at level 2 m. To increase infiltration capacity, further sluices should be built – see MODFLOW modelling. Although the water table level raises and infiltration rate will be lower than maximum estimated.

As it can be seen (Figs.33-35), infiltration rates (after immediate increase of water table in channel by regulating sluices) are decreasing with time and finally are reaching quasi-steady state (QST). The quasi-steady state represents sustainably accessible rate of infiltration to the pilot area (Žitný Ostrov) aquifers, here shown as v_i (QST). For comparison, there are shown even v_i (10d), which means the infiltration rate after 10 days from the beginning of infiltration (Tabs 13-15).

Tab. 13. Infiltration rates (v_i) for different height of water table in channel (h). Infiltration rates were calculated after 10 days from the beginning of infiltration (10 days) and quasi-steady infiltration rate (v_i QST).

h cm	v_i $m^3/(km.day)$	
	10 days	QST
50	310	110
100	500	170
200	710	340

Tab. 14. Infiltration rates (v_i) for height of the water table in channel h = 200 cm and different thickness of upper soil layer (z_p).

Tab. 15. Infiltration rates (v_i) for heights of the water table in channel (h = 100 and 200 cm) and thickness of the bottom sediments (z_s =50 cm).

Infiltration rates (v_i) were calculated after 10 days from the beginning of infiltration (10 days) and when quasi-steady infiltration rate (v_i QST) was reached.

h cm	z_p cm	v_i $m^3/(km.day)$	
		10 days	QST
200	100	630	330
200	250	310	140

h cm	z_s cm	v_i $m^3/(km.day)$	
		10 days	QST
100	50	510	170
200	50	710	350
200	100	750	340

To illustrate infiltration rates (v_i) as they depend on significant variables, which are shown in tables, graphical presentation of tables is shown in Figs. (36-38). Relationships are assumed to be linear.

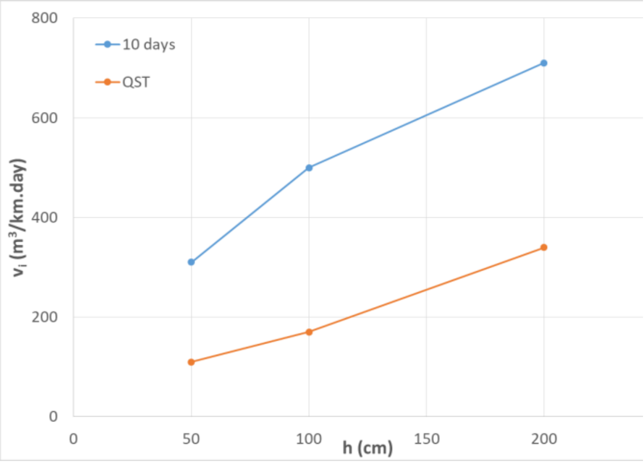


Fig. 37 Infiltration rates (v_i) for three heights of water table in channel 50, 100 and 200 cm. Infiltration rates after 10 days from the beginning of infiltration (10 days) and quasi-steady infiltration rate (v_i QST).

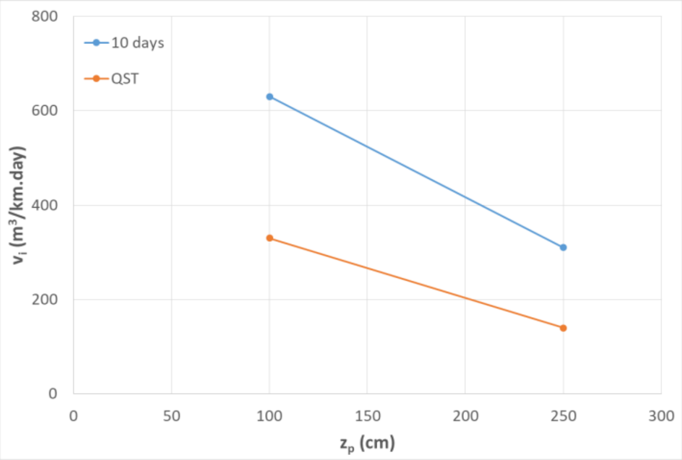


Fig. 38 Infiltration rates (v_i) for height of the water table in channel *h* = 200 cm and different thickness of upper soil layer (z_p). Infiltration rates after 10 days from the beginning of infiltration (10 days) and quasi-steady infiltration rate (v_i QST).

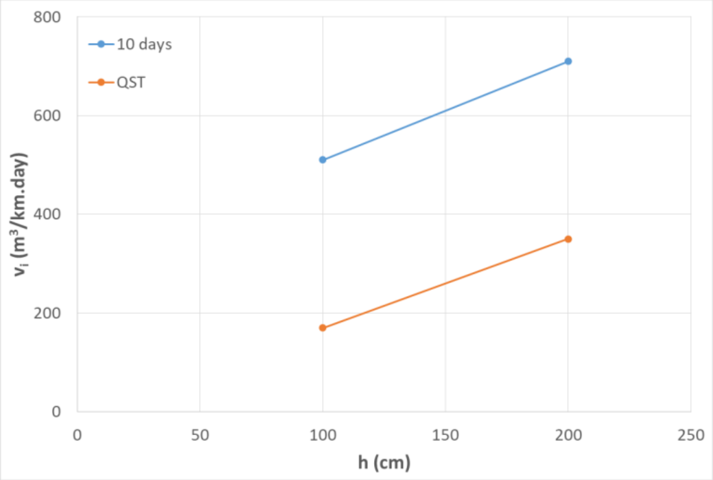


Fig. 39 Infiltration rates (v_i) for heights of the water table in channel (*h* = 100 and 200 cm) and thickness of the bottom sediments (z_s =50 cm). Infiltration rates (v_i) were calculated after 10 days from the beginning of infiltration (10 days) and when quasi-steady infiltration rate (v_i QST) was reached.

Quasi steady rate of water infiltration from channels located in pilot area in Žitný Ostrov (Danube lowland) was estimated in the range 100 – 350 m^3 km^{-1} day^{-1}. Assuming the length of the channel system in pilot area (100.86 km), it means that the total quasi steady state inflow into aquifers is in between 10,000 – 35,000 m^3 day^{-1}, which is the water layer in the range 0.042 - 0.16 mm per day when it is recalculating to the pilot area of 226 km^2. This is about one tenth of the average daily evapotranspiration. During initial state of infiltration this rate can be up to 25 times higher, than quasi-steady rates, but it is covering narrow strip of soil around channels only. The particular rate of infiltration depends on channel dimensions, hydraulic properties of porous media, channel bottom sediments properties and height of water table in channel.

Properly managed water retention in channels (MAR) and consequent infiltration of water from channels to the aquifers, can significantly improve soil-water regime, especially during dry season. So, the rate of water infiltration can be expected higher due to higher hydraulic gradient. As it can be seen from Tab. 1, the depth of the groundwater table is currently oscillating in depths 0.85 – 3.30 m below the soil surface. MAR as a method of groundwater replenishing in Žitný Ostrov can be particularly useful in situation, when water level of Danube river (and discharge as well) will be extremely low, which can be a real situation in near future due to climate change.

5. Risk management

The risk assessment report introduces the recharge dam MAR system located in Žitný Ostrov pilot area in Slovakia where the MAR system was utilized for agricultural purposes. In this regard there were recognized possible risks for the MAR system coming from environmental and human health, technical, socio-economic, governance and legislative risks as well as risks related to the sensitivity of MAR to climate-induced extreme situations.

Risks were assessed by combination of two methods; i.e risks were identified according to the methodology developed by MARSOL project (Rodrigues-Escalantes et al. 2018). Quantitative risk assessment was done in with risk factor matrix by Swierc et al, 2005 (also mentioned as a method in the Australian guidelines) (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009) where the likelihood and the severity of a risk is interpreted by risk factor matrix. According to MARSOL methodology, there were evaluated quantitative technical and non-technical risks (social, economic, governance & legislation) during design, construction and operational phases.

5.1. Risk identification and treatment

In Slovakia, the recharge dam MAR system dedicated to the agricultural purposes was located on the S VII drainage system (i.e. 3 channels – Vojka-Kračany; Šuľany-Jurová and Gabčíkovo-Topoľníky) which is very flexible in flows and farmer–friendly (good cooperation between the Slovak Water-Management Enterprise and farmers). Because the drainage system is already operating, at the end we will just recommend possible (or necessary) improvement of the system.

Related to identified risks, i.e. risks related to environment and human health, technique, socio-economic issues, governance, legislation, and risks related to the sensitivity of MAR to climate-induced extreme situations; we identified risks distinguished in two phases –

1. **design and construction phase;**
2. **operational phase.**

The identified risks within these two phases were summarised in the form of tables, where non-technical and technical constraints are specified for each phase (Tables 16 – 19).

As non-technical risks during design and construction phase, the lack of private/public funding was identified as very high risk. Possible treatment is to disseminate and publicize the MAR schemes benefits to be able to involve as many investors as possible. Within this group, two other risks were evaluated as high: low price of water and high installation cost. Low price of water risk was evaluated in operational phase as well. These risks can be overcome by additional support for the use of MAR facilities (state support, private financial sources) in order to promote its financial viability.

Evaluation of technical risks revealed several high probabilities of occurrence during design and construction phase: construction technical difficulties, risk of low water storage, hydrogeological setting. These risks can be treated by preparation of specific technical project, and proper and detailed geological and hydrogeological investigation. During operational phase, high risks are represented by swelling clays, nutrients, droughts and rainfall events periodicity, changes in water demand and supply. To treat this group of risks there considered following issues accordingly: (i) detailed study on geological/rock mechanic conditions of the channels banks; (ii) agricultural pollution can be avoided by applying of Good Agricultural Practice and waste water pollution by centralised sewage system and WWTP; (iii) efficient manipulation with water in channels; (iv) proper regulation of water flow in channels and monitoring of water quantity/quality.

To ensure effective functioning of the MAR system and to be informed about all risks mentioned above in time, the thorough monitoring system of risks should be put into operation.

Tab. 16. Potential risks during design and construction of a MAR facility – non technical constraints

POTENTIAL RISKS DURING DESIGN AND CONSTRUCTION OF A MAR FACILITY						
NON-TECHNICAL CONSTRAINTS	**Constraint description**	**Likeli-hood**	**Severity of consequences**	**Risk score**	**Risk rating**	**Suggested risk treatment**
Legislation risks						
European territorial constraints	Changes in European legislation	3	1	3	low	Transpose the EU legislation related to MAR into national legislation in order to ensure the proper operation of MAR systems. Cooperation of decision makers, water legislative experts, health legislative experts and other stakeholders.
National territorial constraints	Changes in national legislation	2	1	2	low	
Regional/Local territorial constraints	Changes in regional legislation	2	1	2	low	
Health legislation	Amendments to regulations related to water intended for human consumption	2	1	2	low	
Others	Other changes in legislation affecting MAR facilities in design phase	3	1	3	low	
Governance risks						
Lack of coordination	Mismanagement of MAR facility by its operators	2	2	4	low	Well-trained MAR management, MAR operators, logistic experts responsible for the supervision of the MAR operation
Commitment of stakeholders	Joint interest and commitment for a joint MAR project	2	3	6	moderate	Dissemination of MAR benefits, knowledge sharing and promotion of MAR systems. Popularise and spread MAR benefits (financial, environmental, etc.) to support operation of MAR systems among investors and users
Insufficient technical knowledge	Lack of technical knowledge on the side of staff responsible for the design of the MAR facility	2	2	4	low	Well trained operators and technical staff responsible for the design and construction of the MAR systems. Might be considered the involvement of external professionals.
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	1	3	3	moderate	Control of water usage, water safety plans for water works (to supply the system), proper regional control of the groundwater use
Low price of water	The low price of accessible water from other sources makes the proposed MAR facility potentially unviable.	3	3	9	high	Additional support for the use of MAR facilities (preferably supported by state financial mechanism) in order to promote its financial viability.

POTENTIAL RISKS DURING DESIGN AND CONSTRUCTION OF A MAR FACILITY

NON-TECHNICAL CONSTRAINTS	Constraint description	Likelihood	Severity of consequences	Risk score	Risk rating	Suggested risk treatment
Economic risks						
High installation cost	High cost of construction related to material prices, workmanship and services.	5	3	15	high	Targeted support from the state budget, EU financial mechanisms or other sources. Consider proper and optimal MAR system design; evaluate its capacity, size, feasibility and effectiveness to be reached by more users/investors.
High maintenance cost/ maintenance requirements	Increase in maintenance requirements of MAR facility resulting in increased costs	2	2	4	low	To incorporate the budget for maintenance costs of the MAR system in designing of MAR financing.
Lack of private /public funding	Underestimation of the project costs, lack of funds at a certain stage of the planned implementation	4	4	16	very high	Disseminate and publicise the MAR schemes benefits to be able to involve as many investors (private, public and state) as possible.
Social risks						
Health risk perception by society	Health concern due to MAR technology implementation	2	1	2	low	Sharing information on water quality of infiltrated /pumped water (e.g. design of proper monitoring system, data shared with public).
High cost perception by society	Concern about the increase in water prices due to MAR design.	2	2	4	low	Provide information on MAR benefits, especially considering climate change impacts and conflicts of users for irrigation of agricultural crops; emphasise the water accessibility in dry seasons
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	6	moderate	Water distribution system should be designed to supply the users properly, without any preferences due to distance from water source. The water distribution plan must be approved by all users.
Perception of effectiveness by society	Public understanding and awareness of the benefits of MAR solutions.	3	2	6	moderate	Knowledge share and promotion of MAR systems emphasising the environmental benefits (sufficient water availability in dry seasons for agriculture and ecosystems, water retention as adaptation measure to climate change, etc.), but also notice economic benefits (sustainable cultivation of water demanding agricultural crops).

Tab. 17. Potential risks during operational phase of MAR – non technical constraints

POTENTIAL RISKS DURING OPERATIONAL PHASE OF MAR						
NON-TECHNICAL CONSTRAINTS	Constraint description	Likeli-hood	Severity of consequences	Risk score	Risk rating	Suggested risk treatment
Legislation risks						
European territorial constraints	Changes in European legislation	3	1	3	low	Transpose the EU legislation related to MAR into national legislation in order to ensure the proper operation of MAR systems. Cooperation of decision makers, water legislative experts, health legislative experts and other stakeholders.
National territorial constraints	Changes in national legislation	3	1	3	low	
Regional/Local territorial constraints	Changes in regional legislation	2	1	2	low	
Health legislation	Amendments to regulations related to water intended for human consumption	N/A	N/A	No risk	no risk	
Others	Other changes in legislation affecting MAR facilities in operation	3	1	3	low	
Governance risks						
Lack of coordination	Mismanagement of MAR facility by owners of waterworks	2	2	4	low	Well-trained MAR management, MAR operators, logistic experts responsible for the supervision of the MAR operation
Insufficient technical knowledge	Lack of technical knowledge on the side of staff responsible for the operation of the MAR facility	2	2	4	low	Well trained operators and technical staff responsible for the design and construction of the MAR systems. Might consider involvement of external professionals.
Economic risks						
Macroeconomic constraints	Global factors that can affect entire economies, e.g. the variation in interest rates, inflation rates, and unemployment rates	2	2	4	low	Hard to avoid global factors, partially it is possible by taking into account as most details as possible in preparing cost-benefit analysis
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	9	high	Additional support for the use of MAR facilities (preferably supported by state financial mechanism) in order to promote its financial viability.

POTENTIAL RISKS DURING OPERATIONAL PHASE OF MAR						
NON-TECHNICAL CONSTRAINTS	Constraint description	Likeli-hood	Severity of consequences	Risk score	Risk rating	Suggested risk treatment
Economic risks						
High maintenance cost/ maintenance requirements	Increase in maintenance requirements of MAR facility (outdated equipment) resulting in increased costs	2	3	6	moderate	To incorporate the budget for maintenance costs of the MAR system in designing of MAR financing. The operational costs should cover the re-constructions of technical tools caused by operation (e.g. lifetime of materials, mechanical damages, dredging, etc.)
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 with-drawal facilities (wells, other MAR, etc.) from the pathway of the groundwater flow for agricultural purposes	1	3	3	moderate	Control of water usage, water safety plans for water works (to supply the system), proper regional control of the groundwater use
Social risks (unacceptance)						
Health risk perception by society	Health concern due to MAR technology implementation	2	1	2	low	Sharing information on water quality of infiltrated/pumped water (e.g. design of proper monitoring system, data shared with public)
High cost perception by society	Concern about the increase in water prices due to MAR	2	3	6	moderate	Provide information on MAR benefits, especially considering climate change impacts and conflicts of users for irrigation of agricultural crops; emphasise the water accessibility in dry seasons
Behavioural requirements	Fear that MAR will affect people's daily lives (e.g. longer road to work, due to existence of new infiltration channels, prohibitions & restrictions near MAR site)	2	3	6	moderate	Information sharing and promotion of recharge dam MAR system within local community in the way that MAR system is established at the already existing network of irrigation channels, so during operation it will not affect daily life of people
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; relation between the water supply administrator of the channel system (SWME) and farmers cultivating the agricultural land.	3	2	6	moderate	Water distribution system should be designed to supply the users properly, without any preferences due to distance from water source. The water distribution plan must be approved by all users. Currently administrator and farmers cooperate. The administrator is storing the water to maximum possible extent for increasing the infiltration rate into aquifers, but there are still possibilities to improve the system.
Perception of effectiveness by society	Public understanding and awareness of the benefits of MAR solutions.	2	2	4	low	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

Tab. 18. Potential risks during design and construction of a MAR facility – technical constraints

POTENTIAL RISKS DURING DESIGN AND CONSTRUCTION OF A MAR FACILITY						
TECHNICAL CONSTRAINTS	**Constraint description**	**Likeli-hood**	**Severity of consequences**	**Risk score**	**Risk rating**	**Suggested risk treatment**
Not enough water recharged due to low input water quality						
Sanitary / biological restrictions (e.g. due the pathogens)	Recharge 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	2	2	low	Monitor MAR system´s water quality regularly in order to detect biological pollution of the water in time
Turbidity /particles	Turbidity of the water entering the MAR system leads to a reduction in the efficiency of the MAR system due to excessive suspended solids. Material that causes water to be turbid include clay, silt, very tiny inorganic and organic matter, algae, dissolved coloured organic compounds, plankton and other microscopic organisms	2	3	6	moderate	Since the water source of recharge dam MAR type is in seepage channel, except of the extreme climate events, we do not expect the distribution of fine particles. Regulated turbidity is used to cleaning up the channels from fine sediments. The regular monitoring system will be designed in the way to monitor the fine particles.
Metals	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 water quality standards for irrigation	1	1	1	low	Monitor MAR system´s water quality regularly in order to detect metals, salts, nutrients and organic chemicals in time. Especially nutrients are expected to be present due to agricultural use of neighbouring land.
Salinity and sodicity		2	2	4	low	
Nutrients (nitrogen, phosphorous)		2	2	4	low	
Organic chemicals (pollutants, EOCs)		2	2	4	low	
Technological constraints						
Construction difficulties	Special requirement of construction due to unusual size or big depth of the building structures.	3	3	9	high	Prepare detailed technical project of the sluices construction, difficulties are expected in getting all the permits for construction (according to Building Act 50/1976 Coll.)
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	6	moderate	Extreme climate events (floods and droughts) can negatively influence the flow in irrigation channels. To tackle with droughts - to propose efficient manipulation with water in channels to store it during wet seasons. In case of floods - threat of sluices damage and sediments/trees in channels. The situation will be solved after the event.

POTENTIAL RISKS DURING DESIGN AND CONSTRUCTION OF A MAR FACILITY

TECHNICAL CONSTRAINTS	Constraint description	Likeli-hood	Severity of consequences	Risk score	Risk rating	Suggested risk treatment
Water scarcity risks						
Changes in water demand and supply	Increased demand and overuses deplete the system or production with higher capacity cannot fulfil requirements	3	2	6	moderate	Difficult to predict behaviour of agricultural producers, which depends on market conditions, state subsidence, etc. The channels system has limited capacity, but according to scenarios, it can supply increased demand.
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	6	moderate	The usage of the water is regulated by Water Act (364/2004 Coll.) put into practice via state authorities. The legislative requirements of state water administration must be met to get permit of water usage.
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 (water-transporting ditches) which reduces the effectiveness of the MAR or leads to the need for renovation work at the MAR facility.	2	3	6	moderate	Clogging can be caused by fine sediments, so the regulated turbidity should be applied to clean up the channels from fine sediments. To tackle this problem is to design the efficient monitoring system to detect clogging 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	3	9	high	Proper and detailed geological and hydrogeological investigation (desktop study and field measurements) to define precisely the hydraulic characteristics, storage capacity of the aquifers, supported by hydraulic tests and modelling.
High thickness and not shallow aquifer	Aquifers with significant depth to the water table (high thickness of the unsaturated zone) may not be suitable for some MAR methods	1	1	1	low	Proper and detailed geological and hydrogeological investigation (desktop study and field measurements) to define precisely the hydraulic characteristics, storage capacity of the aquifers, supported by hydraulic tests and modelling.
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	9	high	

POTENTIAL RISKS DURING DESIGN AND CONSTRUCTION OF A MAR FACILITY						
TECHNICAL CONSTRAINTS	**Constraint description**	**Likelihood**	**Severity of consequences**	**Risk score**	**Risk rating**	**Suggested risk treatment**
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	6	moderate	Stimulate farmers in the application of the MAR system with reduced water prices or other benefits.
Lack of technical solution for capturing the water		N/A	N/A	No risk	No risk	The water regulation sluices already exist
Lack of water pre-treatment infrastructures		N/A	N/A	No risk	No risk	The origin of the water is seepage channel, i.e. groundwater in fact
Lack of wells		2	2	4	low	Propose hydrogeological investigation in order to locate the wells on the most suitable places, perform pumping tests to find the possibility of well yields and calculate available supply to cover the corresponding demand.

Tab. 19. Potential risks during operational phase of MAR – technical constraints

POTENTIAL RISKS DURING OPERATIONAL PHASE OF MAR						
TECHNICAL CONSTRAINTS	**Constraint description**	**Likelihood**	**Severity of consequences**	**Risk score**	**Risk rating**	**Suggested risk treatment**
Structural damages due to environmental events or human activity (civil work failures)						
Flooding	Destruction of infrastructure, interruption of the well field operation, pollution of the aquifer, sudden changes in recharged water quality, damage of the inlet structure, damage of existing sluices in channels.	1	1	1	low	The risk caused by flooding should be treated by proper regulation of water flow in channels by their administrator.
Groundwater flooding	Flooding of basements, below-ground cables	1	2	2	low	Building small draining ditches, which could also act as water-distributing channels (in dry season), the excessive amount of water during floods can be drained by channels.

POTENTIAL RISKS DURING OPERATIONAL PHASE OF MAR

TECHNICAL CONSTRAINTS	Constraint description	Likeli-hood	Severity of consequences	Risk score	Risk rating	Suggested risk treatment
Terrorism activities or vandalism	Destruction of the well casing, deliberate contamination of the infiltration ditch or well, destruction of the monitoring network, etc.	1	2	2	low	Ensure that untrained person cannot manipulate the sluices
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	9	high	Detailed study on geological/rock mechanic conditions of the channels banks
Instrument breakage	Breakdown of any instrument (water-collecting pipe, valves, etc.) in the MAR system may cause the MAR to stop operating	2	2	4	low	Remote control of the sluices, and water flow to register failure as soon as possible.
Others	Any other risks associated with civil work-related breakdowns, but usually quickly fixable and does not endanger the MAR operation	4	1	4	low	Inform nearby population on MAR system, conclude insurance to MAR system, keep financial reserves for covering unforeseen costs
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	2	2	low	Monitor MAR system´s water quality regularly in order to detect biological pollution of the water in time
Turbidity/particles	Turbidity of the water entering the MAR system leads to a reduction in the efficiency of the MAR system due to excessive suspended solids. Material that causes water to be turbid include clay, silt, very tiny inorganic and organic matter, algae, dissolved coloured organic compounds, plankton and other microscopic organisms.	2	1	2	low	Since the water source of recharge dam MAR type is in seepage channel, except of the extreme climate events, we do not expect the distribution of fine particles. Regulated turbidity is used to cleaning up the channels from fine sediments. The regular monitoring system will be designed in the way to monitor the fine particles.
Water pollution from navigation	Due to navigation on the Danube River there is possible accident of a boat. The pollution of shipment (e.g. fuel, chemicals, etc.) can be spread in the Hrušov reservoir and consequently in channel, source of MAR water.	1	1	1	low	The accident can be avoided by well-managed operation on the waterway. In case the accident happens, the quick response in waterway by responsible bodies is required to avoid ecological catastrophe.

POTENTIAL RISKS DURING OPERATIONAL PHASE OF MAR						
TECHNICAL CONSTRAINTS	**Constraint description**	**Likeli-hood**	**Severity of consequences**	**Risk score**	**Risk rating**	**Suggested risk treatment**
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 intensive agricultural production, industry and households (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.)	2	2	4	low	Monitor MAR system´s water quality regularly in order to detect metals, salts, nutrients and organic chemicals in time. Especially nutrients are expected to be present due to agricultural use of neighbouring land. The agricultural pollution can be avoided by applying of Good Agricultural Practice. The waste water pollution should be reduced by centralised sewage system and WWTP, but there can occur point sources of pollution from individuals.
Salinity and sodicity		2	2	4	low	
Nutrients (nitrogen, phosphorous)		3	3	9	high	
Organic chemicals (pollutants, EOCs)		2	3	6	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	9	high	Extreme climate events (floods and droughts) can negatively influence the flow in irrigation channels. To tackle with droughts – to propose efficient manipulation with water in channels to store it during wet seasons. In case of floods - threat of sluices damage and sediments/trees in channels. The situation will be solved after the event.
Changes in water demand and supply	Increased demand and overuses deplete the system or production with higher capacity cannot fulfil requirements.	3	3	9	high	Difficult to predict behaviour of agricultural producers, which depends on market conditions, state subsidence, etc. The channels system has limited capacity, but according to scenarios, it can supply increased demand.
Clogging risks						
Deposition (transport sedimentation in water-distributing ditches)	The deposition of organic and inorganic solids at the bottom of water-distributing ditches with non-cemented bottom leads to a "clogging mat" (outer blockage)	2	2	4	low	Sedimentation in channels should be regularly removed by increased flow of water or dredging of sediments. The clogging of banks and bottom of the Hrušov reservoir by fine sediments (water source) is removed by regular dredging. The seasonal fluctuations of water level in channels cause the sedimentation, but on the other hand cleaning of the channels in sudden change of velocity.
Erosion (transport sedimentation in water-distributing ditches)	Submergence of a soil may give rise to the disintegration of aggregate structures, which may lead to erosion. As a result of this process soils from the slope can settle on a permeable sand/gravel bottom, thus reducing infiltration	1	2	2	low	Floods and extreme rainfalls usually cause erosion of channels that should be avoided by consolidated banks of channels.

POTENTIAL RISKS DURING OPERATIONAL PHASE OF MAR

TECHNICAL CONSTRAINTS	Constraint description	Likeli-hood	Severity of consequences	Risk score	Risk rating	Suggested risk treatment
Bioclogging	Microorganism growth can create microbial biomass which restricts the volume of water that can infiltrate in the pore space.	1	1	1	low	To ensure constant flow in channels to avoid increasing of water temperature and development of microorganisms that should cause bioclogging. To ensure constant flow in channels to avoid increasing of water temperature and consequently evaporation.
Evaporation (excess) (chemical clogging)	Excessive evaporation increases the mineralisation of water, precipitates minerals and reduces the availability of water for MAR.	1	2	2	low	
Water mixtures (chemical clogging)	Recharge of water not in equilibrium with the groundwater or aquifer sediments can cause chemical reactions. These lead to the production of insoluble precipitates that alter the aquifer permeability.	3	1	3	low	To monitor water inlets to channels and chemical composition of the water in order to take measures in time.
Risks connected to unacceptable quality of water at sensitive location						
Organic matter (as the result of inefficient natural attenuation)	Risks associated with insufficient potential of the MAR system to natural attenuation of organic matter	2	1	2	low	Regular monitoring and sampling the water to presence of organic matter, excess nutrients, N-compounds, emerging substances and metals in order to take remediation measures in time. Regular monitoring and sampling the water to presence of organic matter, excess nutrients, N-compounds, emerging substances and metals in order to take remediation measures in time.
Emerging organic compounds (as the result of inefficient natural attenuation)	Risks associated with insufficient potential of the MAR system to natural attenuation of emerging organic compounds	2	2	4	low	
Nutrients (as the result of inefficient natural attenuation)	Risks associated with insufficient potential of the MAR system to natural attenuation of nutrients	2	2	4	low	
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	2	2	4	low	
Emerging organic compounds (as a product of metabolite generation)	Risks associated with insufficient potential of the MAR system to reducing products of metabolite of emerging organic compounds	2	2	4	low	
Other nutrient cycles (e.g. H_2S)	Risks associated with insufficient potential of the MAR system to reducing products of other than nitrogen cycle compounds e.g. phosphorus, H_2S etc.)	2	2	4	low	
Metals mobilization	Risk of metal mobilisation in water at a MAR facility	1	2	2	low	

5.2. Risk related to the sensitivity of MAR to climate-induced extreme situations

Climate change is expected to have a significant impact on the hydrologic cycle, creating changes in freshwater resources. The Intergovernmental Panel on Climate Change (IPCC) predicts that, as a result, floods and prolonged droughts will take place at increasingly frequent periods (IPCC, 2012). The Mediterranean has been described as one of the main climate change "hot-spots", with recent simulations showing a collective picture of substantial drying and warming (Tsanis et al., 2011).The reality is that the problem of drying and warming occurs more frequently in the Central and Eastern Europe, as well. Developed sensitivity analysis for extreme situation cases (Vranovská et al., 2020) has identified trigger parameters causing natural hazards in wet and dry periods. In dry periods due to extremely low amount of precipitation and extremely high evapotranspiration the MAR system in investigated S VII drainage channel system can respond to mentioned extreme situation. It should work to full extent, i.e. maximum water supply through inlet structures and closed sluice structures increasing the water level to increase the aquifer recharge and minimize the consequences of drought.

In opposite climate – induced extreme situation (water surplus) in the lowland the flash flood is very rare and improbable. Mostly, the excessive inland water (ponding after snowmelt in the spring time) or groundwater flood (after long – lasting precipitation period) can appear. According to data from boreholes of the SHMI observation system (Červeňanská, Baroková, 2021) and due to high permeable aquifer the MAR system is not really vulnerable and changes of groundwater table for investigated precipitation rich years (2010, 2013) are in limited figures.

Recognized risks for the MAR system are connected with climate change (Tab. 20). It is apparent that there will be still more water needed in the vegetation period for the agricultural plants because of greater differences between precipitation on one side and evapotranspiration on the other, especially in vegetation period (Fig.40).

In vegetation period, the effectively operated MAR system by rational regulation of water flow enables the water retention between closed sluices in channels. So, the water storage and infiltration time increases what enable efficient replenishment of aquifer (proved by numerical modelling). In this case the groundwater supplies for irrigation will be available.

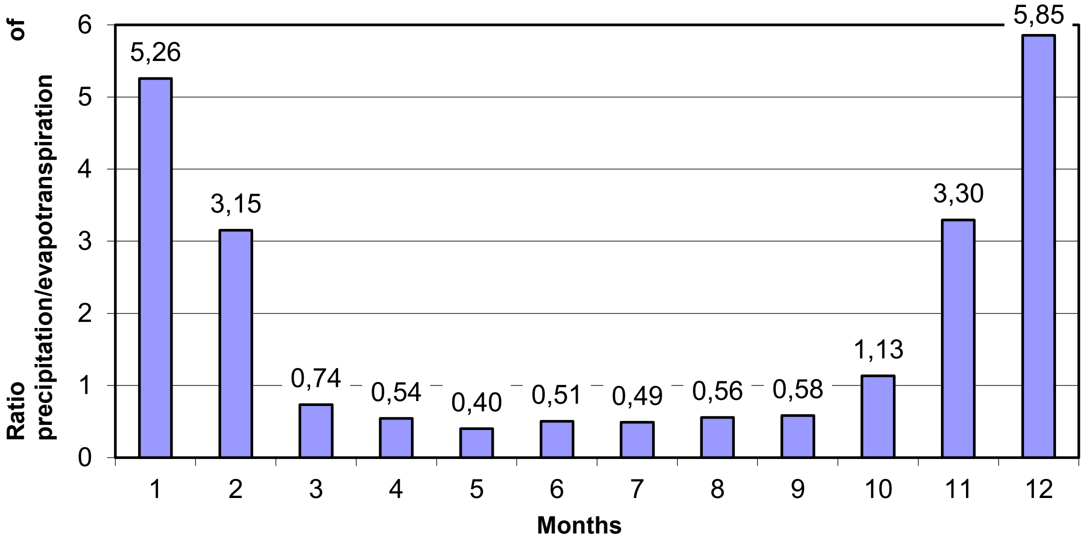


Fig. 40 Ratio of average monthly precipitation and evapotranspiration totals for period 1955-2004 (Gabčíkovo)

Tab. 20. Recognized risks for the MAR system connected with climate change extreme events for dry and wet periods

			Dry period	Risk assessment
Trigger / Stimulus		Climate extremes	Extremely low amounts of precipitation Extremely high temperature/ evapotranspiration Extremely low temperature	Droughts can negatively influence the flow in irrigation channels. To tackle droughts – an efficient management of water in channels to store it during wet seasons.
Hazardous events	Natural hazards	Hazard groups	Hydrological drought	
		Hazard types	Low water level for an extremely long time period Drought (lack of physical precipitation) GW table depression	
		Anthropogenic impacts	Land use (urban, industrial, agricultural) Water overexploitation for various uses (e.g. changes in GW dynamics) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water)	The agricultural users can influence the water demand related to the cultivated crops. In the case of regular droughts occurrence, the farmers should cultivate the crops which meet the water availability (not to overcome the supplies with water demand, i.e. to cultivate lower water demanding crops). The risk of point or diffuse pollution is relatively high since the area is intensively used for agricultural crops cultivation, i.e. using herbicides, pesticides, fertilisers, etc. Moreover, there are industrial sites (Eastern Sugar Slovensko Joint Stock Company, ZVS, a.s. O.Z. Dunajská Streda, Thermalpark D.S.) and 9 small environmental loads in the area*.
		Surface & hydrogeological environment	Land cover (e.g. agricultural crops) Surface water source (e.g. surface water level dynamics) Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) Vertical groundwater flow between different aquifers	Agricultural land use threats the surface water quality by pesticides and fertilisers application. The water flow dynamics in channels (i.e. surface water source for infiltration) is regulated by Slovak Water Management Enterprise (SVME). The system operates during the wet season (spring) SWME closes sluices in channels, i.e. accumulate the water for infiltration to be available in dry season. Since the hydraulic conductivity of the aquifers is very good, the storage capacity can retain the water. The risks related to surface water quality in the dry seasons (low water levels with increased temperature and eutrophication) can be present. Other risk may occur in dry periods when the groundwater table is decreasing, so the infiltrating water cannot remarkably influence the groundwater table.

			Wet period	Risk assessment
Trigger / Stimulus	Climate extremes		Short period of extremely high amounts of precipitation Extremely long period of precipitation Extremely high frequency of precipitation events Long period of extremely high amounts of precipitation	Floods negatively influence the flow in irrigation channels. To tackle floods the risks are-sluices damage and occurrence of sediments/trees in channels. The situation will be solved after the event (e.g. reconstruction of sluices, dredging, etc.).
Hazardous events	Natural hazards	Hazard groups	Flood	
		Hazard types	Extreme runoff; Flood (high precipitation)	
	Anthropogenic impacts		Land use Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water)	Risk of point pollution as described in the “Dry period” section, but also flood event can cause rapid spread of pollution in the larger area. Consequently, in extreme situations possibly the groundwater in aquifer can be contaminated (in extremely high pollution of surface water source) that is not highly probable.
	Surface & hydrogeological environment		Land cover (e.g. grass, trees/forest, asphalt, agricultural crops) Aquifer characteristics (e.g. porosity, transmissivity, properties related to pollutant transport & fate)	Agricultural land use can threat the surface water quality by pesticides and fertilisers, so pollution can be spread by floods in the big areas. The sluices in channels regulated the flow are operated Slovak Water Management Enterprise (SVME). Floods can cause damage of the sluices, sedimentation, filling channels by trees and rubbish and in critical case disruption of the banks. The long-term storage of flood water can cause impossibility to cultivate the crops, increasing temperature and eutrophication. Since the area is flat, torrential floods are not expected. The flood risks are handled by opening the sluices to allow the water to flow away and consequent cleaning/dredging the channels.

5.3. Risk monitoring

There are no special national regulations in place concerning operational monitoring of MAR systems. Anyway, existing rules of surface water and groundwater monitoring can be effectively applied for monitoring of MAR system operation.

Responsible for risk assessment of the MAR site will be the company/institution managing the MAR facility (for instance in Slovak pilot site it is Slovak Water Management Enterprise).

Surface water and groundwater monitoring is done under EC Directives, particularly the Water Framework Directive (2000/60/EC), Groundwater Directive (2006/118/EC) and Nitrates Directive (91/676/EEC). Surface water monitoring is performed in accordance with Act No 364/2004 Coll (Water Act); Act No 201/2009 Coll. (on state hydrological service and state meteorological service); Act No 7/2010 Coll., (on flood protection) and Government Regulation No 269/2010 Coll (on requirements to achieve good status of waters), Government Regulation No 167/2015 Coll (on environmental quality standards in the field of water policy), Government Regulation No 201/2011 Coll. (on technical specifications concerning chemical analyses and monitoring of water), Government Regulation No 354/2006 Coll. (on drinking water standards) in accordance with Decree No 418/2010 Coll. of the Ministry of Agriculture, Environment and Regional Development of the Slovak Republic (on occurrence, monitoring and assessment of quantity and quality of surface water and groundwater).

Groundwater monitoring relates to item 4 of Collection of Slovak Republic, Act No 364/2004 Coll (Water Act), Act No 201/2009 Coll. (on state hydrological service and state meteorological service), Act No 569/2007 Coll. (Geological Act), Act No 7/2010 Coll. (on flood protection), Government Regulation No 416/2011 Coll (on the assessment of chemical status of groundwater body) and Decree No 418/2010 Coll. of the Ministry of Agriculture, Environment and Regional Development of the Slovak Republic.

Surface water and groundwater monitoring data are stored in the Slovak Hydrometeorological Institute. Surface water monitoring is partially performed by the Slovak Water Management Enterprise and Water Research Institute, other monitoring activities are covered by Slovak Hydrometeorological Institute. Within the River Basin Plan of Slovakia, framework programmes of water monitoring covering 5 years are prepared. The framework programme of water monitoring in Slovakia for the period 2016 – 2021 can be found at: http://www.vuvh.sk/RSV2/download/02_Dokumenty/26_Ramcovy_program_monitorovania_vod/RPM_2016_2021.pdf

The S VII channel system is operated by Slovak Water Management Enterprise, state enterprise (SWME), for more than 28 years. In the past after putting Gabcikovo hydropower plant into operation, there was observed the impact of the water level regime in S VII channel system on groundwater level during the drainage and recharge periods. The observation showed the interval of groundwater level changes and the extent of this effect.

Risk monitoring milestones will be specified in detail based on specific MAR case. In general, the periodically will be monitored identified non-technical risks during design and construction phase (i.e. the lack of private/public funding; low price of water and high installation cost); and during operational phase (i.e. low price of water); as well as technical risks during design and construction phase (i.e. construction technical difficulties, risk of low water storage, hydrogeological setting) and operational phase (i.e. swelling clays, nutrients, droughts and rainfall events periodicity, changes in water demand and supply). According to experience in operating the sluices during the year there are still possibilities to improve the recharge the water from channel system into aquifer. As already mentioned nowadays it is dependent on beginning of the freezing period, but sometimes the administrator of the channel system (SWME) opens the sluices too early. Improved operation plan would help to replenish the groundwater sources in enhanced rate as well as drilling the observation boreholes for monitoring of groundwater level regime in adjacent area. That would be the best way for risk identification and for following operational interference. The surface water and groundwater quality should be monitored.

6. Economic feasibility (Cost Benefit Analysis)

6.1. Materials and methods

6.1.1. Cost analysis

Capital costs for the Slovak pilot site consist of two parts: investigation costs (collecting archive data, fieldwork, laboratory tests, modelling) and cost of improvement of the existing system (channel cleaning and building new sluices). Investigation costs are planned for the first year of the project, while costs of the system's improvement will be realized in the second year.

Estimates of annual operation, maintenance and management costs along with the capital costs are presented in Tab. 21.

Tab. 21. Costs associated with MAR scheme

Cost group	Units of measurement	Value
Initial investment-Capital costs		
Investigation costs	EUR	28,000
Cost of improvement of the existing system[3]	EUR	1,970,000
Annual operation and maintenance costs		
Cost of extraction and distribution	EUR/m3	0.2
Labor cost	EUR	50,000
Electricity cost	EUR/m3	0.07
Regulatory testing costs		
per year	EUR	1,920
once per 4 years		4,320

Source: Experts' estimation based on data from Slovak state Water Management Enterprise and archive data

6.1.2. Benefit analysis

Direct benefits for agricultural producers in the project lifespan period are obtained by multiplying the value of agricultural production in Euro per m3 by the annual consumption of water from the MAR scheme used for irrigation. Based on the data for major crops grown in the reference area, we calculated the value of crop revenue per volume of applied irrigation water as a weighted average for all crops with the irrigated area used as weights (Tab. 22).

Tab. 22. Crop revenue per volume of applied irrigation water

Crop	Crop per drop, Euro/m3	Irrigated area, ha
Potatoes	4.18	1,406
Fodder maize	0.95	772
Onion	5.92	742
Wheat	1.49	352
Sugar-beet	1.47	312
Carrot	5.09	259
Poppy seed	4.25	149
Parsley	8.44	66
Peas	1.13	63

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[3] Channel cleaning to improve infiltration (cleaning of 2 km) and building 3 new sluices

Rapeseed	2.47	59
Cabbage	4.52	50
Soya beans	0.96	39
Root celery	10.16	36
Pepper	12.21	30
Beet	17.23	18
Weighted average	**3.68**	

Source: Own calculation based on National Agricultural and Food Centre data

For years when the projected maximum irrigation water demand is higher than the potential MAR water supply in the dry year, we use supply volumes in the calculation of direct benefits. Tab. 23 contains the calculation results for the first five years (beginning from the 3rd year when the MAR scheme is expected to start operation).

Tab. 23. Calculation of direct benefits

Year	Projected irrigation water demand, mil m^3		The weighted mean of crop revenue, Euro/m^3 of irrigation water	Benefits value, mil Euro	
	Min scenario	Max scenario		Min scenario	Max scenario
3	7.40	8.04	3.68	27.24	29.60
4	7.45	8.30	3.68	27.40	30.55
5	7.49	8.56	3.68	27.57	31.50
6	7.54	8.82	3.68	27.73	32.45
7	7.58	9.07	3.68	27.90	33.39

Source: Own calculations based on National Agricultural and Food Centre data and experts' estimations

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):

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

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

In other words, 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.

Literature suggests that 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. Willing to Pay Survey (WTP)

To estimate both use and non-use (socio-environmental) benefits, a survey was conducted to explore the maximum amount of money that local farmers and agricultural producers 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.

6.2.1. Details on survey design and implementation

The design of the survey is partially based on the paper by Damigos at el. (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 consists of questions on how typical are recurring droughts and periods with inland excess water for the area, amounts of applied irrigation water, awareness of problems related to groundwater quality and quantity, self-assessed impact on groundwater.

Also, this section contains a part aimed to reveal the profile of crop production, including sowing area, total harvest, crop revenue, the volume of irrigation water applied and its cost. All these data are provided as totals for all produced crops.

Questions gradually become specialized 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 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. If the farmer or representative of the agricultural company selects not to contribute to the proposed plan, he or she is asked to choose the reason for such a decision. 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.

When it comes to the ways of conducting the survey, in Slovakia questionnaires were distributed in paper and online form (implemented via LimeSurvey) for self-filling by agricultural producers.

6.2.2. Survey results

In the Slovak 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 for the Slovak pilot study is 10 (2 responses given by individual farmers, 8 responses given by representatives of agricultural companies), which is around 30% of the total population of the agricultural producers in the pilot area. Thus, we might treat obtained results as fairly representative.

From the responses of farmers, we get the following main information: both types of farmers do not normally irrigate crops, they mentioned that the last growing season all crops were rain fed. They stated that recurring droughts are typical for the area to a moderate extent, and they are concerned with the negative consequences of climate change also to a moderate extent. The first farmer expressed non-zero

WTP, distributing the amount of his financial support equally among use and non-use benefits of the scheme. At the same time, the second farmer stated that he would not like to make a financial contribution to the MAR scheme because he can't afford it.

The majority of surveyed agricultural companies (75%) didn't irrigate crops in the last growing season (more than 60% of them hasn't used groundwater for irrigation purposes. Concerning WTP for the MAR system, half of the agricultural companies wouldn't like to make a financial contribution, while the other half expressed willingness to pay with the following distribution of maximum amount they are willing to pay: 46% to the use of groundwater by the company for irrigation purposes, 40% to the preservation of groundwater quantity and quality for future generations and the remaining 14% to support of groundwater by groundwater-dependent ecosystems.

6.3. Feasibility of MAR scheme

To conclude whether the MAR scheme is economically feasible, we compared direct costs and benefits associated with it. 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 (Fig. 41). Obtained positive differences between direct costs and benefits suggest that the MAR scheme is economically feasible, having a positive expected NPV over 30 years of project lifespan.

WTP survey results provided useful insights on agricultural production in the pilot area, farmers' knowledge regarding groundwater issues, and their perceptions. However, since the pilot area is quite small and we obtained only 10 full survey responses, it prevents us from using regression techniques to estimate mean WTP, controlling for farmers' characteristics. Thus, we do not calculate the expected total economic value of the MAR scheme and make conclusions based on direct costs and benefits comparison. At the same time survey results are helpful for defining policy recommendations.

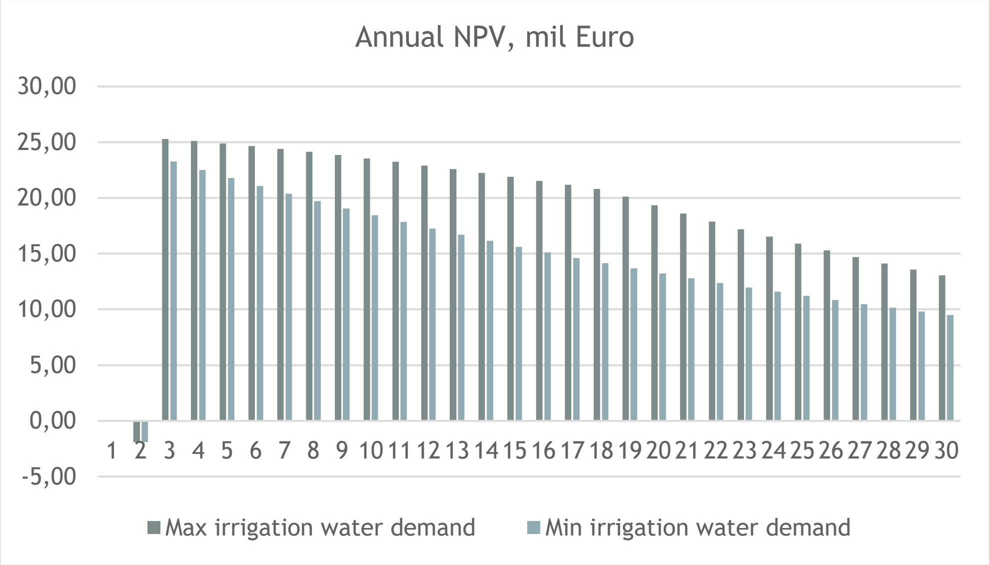

Fig. 41 Annual net present value of irrigation water MAR scheme

To incorporate uncertainty in our CBA, we developed three scenarios based on the following criteria:

- level of forecasted demand for irrigation water
- crop per drop value: average level of crop revenue per volume of applied irrigation water

Assumptions that define each scenario are presented in Tab. 24.

Tab. 24. Developed scenarios

SCENARIOS			Assumptions	
			Costs	Benefits
	Demand for irrigation water	*The average level of crop revenue per m3 of irrigation water*		
First	Maximum	Weighted average based on reference area data 3.68 Euro/m3	The maximum value of capital and maintenance costs	The maximum value of direct benefits
Second	Average	Q1 value based on reference area data 1.48 Euro/m3	The average value of capital and maintenance costs	The average value of direct benefits
Third	Minimum	Minimum value based on reference area data 0.95 Euro/m3	The minimum value of capital and maintenance costs	The minimum value of direct benefits

Our aim is to check how sensitive NPV can be to the changes in parameters mentioned in Table 5. Under all scenarios, NPV always remains positive (Tab.25), suggesting that it is profitable to put the MAR scheme's extension in place in any of the assumed conditions under the three different scenarios presented above.

Tab. 25. NPV under different scenarios

Scenarios	NPV over 30 years, mil Euro	Change compared to the second scenario
First	566.60	2.9 times
Second	145.23	
Third	83.45	-42.5%

6.4. 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 of 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 a number of 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 are 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 pre-treatment 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 Slovak MAR scheme, Tab. 26 presents a matrix of possible socio-economic risks associated with the MAR scheme in the pilot study and the probability of occurrence for each risk as it was assessed by local experts. Expert assessment defines lack of funding as the only economic risk with a high probability of realization and major risk consequences. Among social risks, the changing standards for the end-user could also carry a high risk probability together with major consequences.

According to expert assessment risks that have a medium probability of realization with moderate consequences are unplanned additional costs, water demand lower that potential level and overestimated WTP that leads to lower actual benefits than anticipated. Assessed by local experts level of risk probability is highly correlated with the expected magnitude of risk consequences due to risk realization.

Tab. 26. Matrix of socio-economic risks

Socio-economic risk	Risk probability			Risk consequences		
	Low	Medium	High	Minor	Moderate	Major
Lack of funding/financial support			+			+
Unplanned additional costs (installation, maintenance etc.)		+			+	
Changing standards for end-user			+			+
Insufficient communication and negative risk perception of the public	+			+		
Missing acceptance and trust of the public	+			+		
Not fully realized water demand (e.g. for irrigation water under different climate change scenarios)		+			+	
Lower benefits than anticipated due to overestimated WTP		+			+	

Potential policy implications:

In order to have a complex assessment of the MAR scheme, it is essential to evaluate its economic feasibility along with its hydrological, geological, and institutional considerations. Cost-Benefit Analysis (CBA) allows us to assess the profitability of the MAR scheme by comparing costs of its construction and maintenance with the scheme’s economic value, which is the sum of use benefits and non-use values. To reveal the value of non-use benefits, stated preference techniques, and in particular survey-based contingent valuation methods, are widely used in MAR studies. In our study, we developed a Willingness-to-Pay (WTP) survey, which provided useful insights for policy-makers regarding the agricultural production in the pilot area, but also farmers’ knowledge regarding groundwater issues, their concerns and perceptions.

We can conclude the presence of economic feasibility of the MAR scheme in the pilot site of Slovakia, based on direct costs and benefits comparison. To incorporate uncertainty in our analysis, scenarios with plausible variations of core parameters, such as expected irrigation water demand and levels of revenue per drop, were developed. Under all of them, the MAR scheme in the pilot site is expected to be economically feasible over the project’s horizon. However, since our analysis relies substantially on the data for the reference area, obtained CBA results should be treated as more indicative and with a portion of cautiousness.

Finally, from a policy-relevant perspective, this study provides an overview of possible socio-economic risks associated with the MAR scheme, including the level of risk probability and its consequences based on experts’ assessment. Specific attention needs to be paid by policy-makers on risks with a high probability of realization and major risk consequences when designing the MAR scheme. Based on the assessment of local experts for the pilot site such risks are the lack of funding and the changing standards for the end-users.

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