Interreg
CENTRAL EUROPE
European Union
European Regional Development Fund
DEEPWATER-CE

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

O.T3.2

Version 1

01 2022

Activity Leader	PP4, University of Silesia in Katowice
Editor	Sławomir Sitek
Date last release	January, 2022

Contributors	Institution
Sławomir Sitek	University of Silesia in Katowice
Krzysztof Janik	University of Silesia in Katowice
Sabina Jakóbczyk-Karpierz	University of Silesia in Katowice
Jacek Różkowski	University of Silesia in Katowice
Marek Sołtysiak	University of Silesia in Katowice
Kinga Ślósarczyk	University of Silesia in Katowice
Dominika Dąbrowska	University of Silesia in Katowice
Andrzej Witkowski	University of Silesia in Katowice
Rafał Ulańczyk	University of Silesia in Katowice
Hanna Rubin	University of Silesia in Katowice
Piotr Siwek	University of Silesia in Katowice
Marta Kondracka	University of Silesia in Katowice
Tomasz Krzykawski	University of Silesia in Katowice
Justyna Smolarek-Łach	University of Silesia in Katowice
Jacek Wróbel	University of Silesia in Katowice
Ewa Kaczkowska	University of Silesia in Katowice
Katarzyna Stachniak	University of Silesia in Katowice
Grzegorz Wojtal	Tarnów Waterworks
Jakub Mukawa	Tarnów Waterworks
Olha Halytsia	Technical University of Munich
Anne Imig	Technical University of Munich
Arno Rein	Technical University of Munich
Johannes Sauer	Technical University of Munich
Maria Vrachioli	Technical University of Munich

Table of contents

List of Figures

List of Tables

Foreword

This output presents results of activities carried out at Polish pilot site and was prepared within the DEEPWATER-CE project. The main objective of this output is to indicate the (positive) environmental, social and economic effects of Managed Aquifer Recharge (MAR), with particular emphasis on two methods, i.e. induced bank filtration and infiltration ditches, which were of particular interest in the Polish pilot area.

The activities described in the outputs are in line with the main objective of the DEEPWATER-CE project which is to develop a comprehensive transnational approach for the adoption of MAR solutions in Central European countries to mitigate climate change affecting water resources and to avoid user conflicts regarding access to water.

This reports reflects the authors' view and the funding authorities are not liable for any use that may be made of the information contained therein. All chapters below were written by the University of Silesia in Katowice, except chapter no. 6, which was written by the Technical University of Munich. Part of the data for the work carried out was provided by the associated partner Tarnow Waterworks.

This project is funded by the European Regional Development Fund (ERDF) via the Interreg Central Europe programme. The project's own participation was co-financed by the Ministry of Science and Education, programme entitled "PMW" 2019-2022, contract no. 5016/INTERREG CE/2019/2.

1. Summary

The aim of this output was to present the results and conclusions of the work carried out in the Polish pilot area for the DEEPWATER-CE project.

The pilot area, selected based on the methodology developed within the project, is located in the Tarnów region, southern Poland. Tarnów is a city with a population of about 100 000 people and is characterised by a highly developed industry (mainly chemical). Approximately one hundred years of development of this kind of industry motivated the city expansion but at the same time had a negative impact on the environment, including groundwater. The results described below show, however, that by using Managed Aquifer Recharge (MAR) it is possible to significantly improve the quality of groundwater and to increase its resources.

Of the six MAR methods of interest in the DEEPWATER-CE project, two methods were analysed in detail at the Polish pilot site. The first of them is Induced Bank Filtration (IBF) and the second Infiltration Ditches.

The first method, IBF, is the process by which surface water infiltrates (through the bank of river or lake) into aquifers, when the hydraulic head in the surface water is higher than in the adjacent groundwater (Gillefalk et al., 2018). The term "induced" is used when infiltration does not take place naturally (which is also possible) but through a planned human action, in this case by groundwater abstraction from wells next to the surface water. River water infiltrating into the aquifer can be self-purified (quality improvement) by physical processes such as soil filtration reducing suspended solids, biological processes such as removing organic matter by microorganisms, or geochemical processes such as ion exchange.

The second method - infiltration ditches - can be implemented in the pilot area due to the favourable permeability of the aquifer and its shallow subsurface location. The aquifer, composed of sands, gravels and pebbles, facilitates rapid infiltration through the ditches bottoms which can represent a substantial part of groundwater recharge.

At the Świerczków well field (pilot site), where the effectiveness of the MAR methods was tested, the water inflow into the aquifer was estimated based on modelling studies. Results indicated that the ditches alone account for 60% of the total pumped water at the well field. As in the case of the IBF, the water infiltrating from the ditches into the aquifer may undergo the same physical, biological and/or chemical processes.

The MAR regulatory framework in Poland is not subject to specifically tailored laws or regulations at local, regional or national level. The main legislative act in Poland concerning groundwater and surface water is the Water Law Act, where MAR according to its terms, should be treated as an intentional additional groundwater recharge, which is subject to the regulation related to the so-called “special water use”. Therefore, any MAR facility in Poland has to comply with the provisions of the Water Law Act and several other regulations derived from this act, mentioned in the Chapter 3.

In addition to the legal possibilities which may encourage the development of new MAR sites, it is important to meet the technical and environmental conditions which may have a decisive influence on the investment success. Studies and analyses carried out in the pilot area have shown that the water demand increase year by year by a small (but constant) percentage. The total water abstraction by Tarnów Waterworks in recent years is about 10 million m^3 per year. A highly important problem is to ensure the continuity of water supply in the situation of very large periodic fluctuations of abstraction (from 20 000 to over 40 000 m^3/d) due to

climate change. Particularly critical are the hot summer periods.

As a result of problematic climate change and the expected more frequent occurrence of extreme weather events (droughts and floods), ensuring a rational and continuous supply of good quality drinking water to the citizens will be a rising challenge. In this context, the MAR solutions proposed by the DEEPWATER-CE project will help to increase groundwater resources that will provide a reserve for water supply during periods of drought.

MAR systems, although they can significantly increase groundwater resources locally, can only be located in regions with suitable hydrogeological and geological conditions. Both the subsurface parameters that determine the aquifers ability to store the water and those that will subsequently allow it to be recovered are of importance here. To achieve these aims, a series of geological, hydrogeological and geophysical surveys were carried out in the pilot area. These provided information on the aquifer characteristics, and helped to evaluate the ability of the aeration zone to recharge the aquifer naturally. Also, a monitoring system to evaluate the effectiveness of the MAR system and to create an early warning system against pollution from the industrial zone was designed and installed at the pilot site.

All the designed studies, which are briefly described in Chapter 4 and in more detail in the report D.T3.4.2, are examples that can be replicable and useful for assessing the feasibility of implementing MAR solutions and evaluating its effectiveness in other areas of Central Europe, where the infiltration ditches or/and bank filtration are present or planned.

Another important issue, apart from ensuring adequate groundwater quantity and storage capacity, is groundwater quality. In our case it is endangered by the industrial zone located to the east of the Świerczków well field. Hazards include, directly adjacent to the well field, a combined heat and power plant (CHP) with an unprotected coal storage, as well as ash deposits in small pits to the south of the well field. However, based on the results of the pilot feasibility study conducted in the Świerczków well field, where two MAR techniques are already implemented (infiltration ditches and IBF), it has been proven that the existing MAR facility significantly improves the quality of groundwater abstracted by the wells. Our studies have shown that groundwater flowing into the well field is of low quality and is not suited for human consumption. Our research has also proved that the infiltrated water from the ditches dilutes concentrations of most compounds to an acceptable level and thus significantly improves groundwater quality.

Another crucial part of the conducted feasibility study was a risk analysis that showed which risks can occur during the operation of the investigated MAR facility but also during the construction of its potential expansion. The analysis covered 74 various risks, divided into 12 groups, covering technical and non-technical risks. They were related to e.g. to clogging, low water quality or floods, but also to economics, social acceptance of MAR or legal constraints.

The results of two methods used for the analysis (Qualitative Risk Analysis Matrix and Probabilistic Risk Assessment method - Fault Trees Analysis) showed that the most important risks for the analysed area are those related to: 1) groundwater and surface water quality deterioration, 2) clogging of the wells and infiltration ditches, 3) extreme fluctuations of river Dunajec water levels and 4) extreme groundwater table fluctuations.

Based on the risk assessment and experiences gained during the field work, we propose that the MAR at the well field Świerczków, or other similar sites in Central Europe, should adequately be monitored, including:

- Measurement of groundwater levels in wells and piezometers and surface water levels at the MAR site and its surroundings in order to determine the local directions of groundwater flow and delineate the zone of MAR impacts on native groundwater.

- Installing data loggers for continuous measurement of temperature and water table fluctuations in wells, piezometers and surface water will allow understanding the MAR reaction and its effectiveness during extreme climate conditions such as drought or flood.
- Ion concentration in groundwater and surface water should be analysed 2-4 times per year.
- Physical-chemical parameters (temperature, pH, Eh, el. conductivity, O2 concentration) of surface water and groundwater should be measured in situ; inorganic N ions (ammonia, nitrite and nitrate) should be measured in situ using portable equipment or in the laboratory immediately after sampling.
- Screening monitoring of groundwater and surface water should be performed in order to recognize the pollution of water; it should cover a wide range of potential/known pollutants (e.g. heavy metals, organic pollutants, pharmaceuticals and personal care products, pesticides, surfactants); if any of the analysed pollutant is found in the water samples, then regular monitoring should be established to assess the threat to abstracted groundwater.

Regular monitoring in the contaminated areas like Świerczków well field should include sampling of:

1) groundwater at the inflow to the well field area,

2) water from the river that is a source for recharge, as well as water from infiltration ditches,

3) groundwater at the production wells.

In order to obtain a full picture of the possibilities and potentials resulting from the use of MAR in the pilot area, a Cost-Benefit Analysis (CBA) was also done. Results of this study regarding the MAR scheme's extension show that it is expected to increase the water withdrawal at the well field with simultaneous monitoring and improvement of groundwater quality. Results of a survey with the local population of Tarnów suggest that the non-use benefits of the MAR scheme are particularly important for the residents. Calculated net present values indicate that the extension and operation of the existing MAR scheme is economically feasible under all considered scenarios.

Based on our comprehensive research and further analysis, the pilot area can be considered a suitable region for the application and development of Managed Aquifer Recharge (MAR). The use of MAR methods in the area of research, apart from the very important and beneficial improvement of groundwater quality, also positively influences the increase in groundwater resources with simultaneous non-negative impact on other elements of the natural environment. This was demonstrated during the preliminary analysis of Environmental Impact Assessment (EIA). The positive social and economic aspects and the acceptance by the local community has also been demonstrated during the CBA analysis.

The output O.T3.2 “Pilot Feasibility Study of MAR schemes with integrated environmental approach in porous geological conditions in Poland”, prepared in the following chapters, shows the individual stages of conducting a comprehensive MAR feasibility study for solutions of Induced Bank Filtration and Infiltration Ditches, which can be replicated by project stakeholders and other entities interested in the implementation and development of MAR technology.

2. Introduction

The idea of the DEEPWATER-CE project is based on the key role that Managed Aquifer Recharge (MAR) can play in managing water resources in Central European countries to prevent and resolve potential user conflicts on access to water. Solutions based on MAR have an unique potential to mitigate negative effects of climate change on water resources, which will effectively contribute to stable and secure water supply in the long run.

Expending this approach, the DEEPWATER-CE consortium has developed a decision support toolbox for designating potentially suitable Managed Aquifer Recharge (MAR) locations in Central Europe (**D.T2.4.3 DEEPWATER-CE, 2020a)**. The methodology chosen for the investigation of a potentially suitable MAR location site selection was based on climatological, geological and hydrogeological criteria (mapping on the general and specific level). All of these criteria show spatial variability and therefore the results have been presented in form of maps. These have been published and made available digitally for project stakeholders on the Global Groundwater Information System web portal managed by the International Groundwater Resources Assessment Centre (IGRAC). The maps are also available to project stakeholders from the project website (https://www.interreg-central.eu/Content.Node/DEEPWATER-CE.html).

In the case of Poland, one of the prospective areas where MAR has a high application potential is the Tarnów region. For this pilot site, two MAR methods were selected for which a pilot feasibility study was done. These are induced river and lake bank filtration (IBF) and infiltration ditches. The remaining 4 of the 6 MAR methods considered in detail in the DEEPWATER-CE project were of interest and investigated in pilot areas located in Hungary (underground dam), Slovakia (surface dam) and Croatia (aquifer storage and recovery, infiltration pond).

The choice of these two methods (IBF and ditches) for further studies at Polish pilot site was determined by the existence of a site in the study area where these two types of MAR already operate together, successfully, for supplying drinking water to the population of Tarnów city. Therefore, according to the authors, it was worth to analyse this area in more detail in order to demonstrate the qualitative and quantitative advantages of this type of MAR methods for groundwater and to identify replicable elements, which would help to carry out a feasibility study for the application of this type of MAR in other areas of Central Europe. An additional feature of the pilot site in Poland is its specific location in the immediate vicinity of a large industrial zone, which provides additional opportunities to assess the impact of the potential application of MAR on improving groundwater quantity and quality.

The work carried out at the Tarnów pilot site on conducting a feasibility study for MAR represents the fourth final step of the methodology developed in DEEPWATER-CE project (DEEPWATER-CE, 2020a). This stage was elaborated in detail in the report D.T3.2.5 - Common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies (DEEPWATER-CE,2020b). The results obtained based on the above methodology are the subject of this output O.T3.2 -pilot feasibility study of MAR schemes with integrated environmental approach in porous geological conditions in Poland.

The work carried out for the feasibility study included aspects related to the characterisation of the pilot site based on a desk study and field investigations, legal regulations, water demand and supply, risk analysis and cost-benefit analysis. Some of these issues were elaborated in more detail in separate reports that will be available on the DEEPWATER-CE project website:

D.T3.4.1 - report on the desk analysis of the pilot feasibility study for MAR deployment in porous aquifers located near industrial sites on contamination of aquifers (DEEPWATER-CE, 2021a).

D.T3.4.2 - report on the field work of the pilot feasibility study for MAR deployment in Tarnów area (DEEPWATER-CE, 2021b).

D.T3.4.3 – compiled check list for the application of risk management protocol during the field works for MAR in Tarnów shallow aquifers (DEEPWATER-CE, 2021c).

Therefore, in this document O.T3.2 we would like to mainly focus on indicating those elements of the feasibility study that can or should be used for the MAR schemes of IBF and/or infiltration ditches. Based on lessons learn at the Polish pilot site, similar areas in Central Europe can be analysed.

3. Regulatory framework

According to the Water Law Act, any intentional artificial groundwater recharge is understood as a special use of water. In Poland, the owner of the site where MAR is incorporated have to operate in accordance with the following legal acts: 1) Water Law Act (Journal of Laws 2021, item 624); 2) Geological and Mining Law Act (Journal of Laws 2021, item 1420); 3) Ordinance of the Minister of the Environment on hydrogeological documentation and geological and engineering documentation (Journal of Laws 2016, item 2033); 4) Act on sharing information on the environment and its protection, public participation in environmental protection and on environmental impact assessments (Journal of Laws 2021, item 247); 5) Ordinance of the Prime Minister on projects that may have a significant impact on the environment (Journal of Laws 2019, item 1839).

Any type of managed aquifer recharge has to be in accordance with the legal regulations described above. It is required to obtain a water law permit for special use of water which must be preceded by the preparation of an aquatic legal survey, which is made on the basis of hydrogeological documentation. The scope of an aquatic legal survey is defined by the Water Law Act, and the scope of hydrogeological documentation is defined by Regulation of the Minister of the Environment. Hydrogeological documentation is approved by the Starosta (head of the county) if the water abstraction is less than 50 m^3/h or by the voivodship marshal if the water abstraction is greater than 50 m^3/h. A permit for water abstraction is issued by the State Water Holding Polish Waters. The decision on environmental conditions is issued by the head of the commune/mayor or a mayor of the city.

In the case of the planning of devices enabling groundwater abstraction or artificial groundwater recharge systems with a water capacity of not less than 1100 m^3/h, it is necessary to conduct an environmental impact assessment and obtain a decision on environmental conditions. The planning of devices enabling groundwater exploitation or artificial groundwater supply systems, with a water withdrawal not less than 10 m^3/h, is one of the projects that may have a significant impact on the environment. In this case, an environmental impact assessment may be required by the authority administration.

A comprehensive comparison of the legal systems and regulations of the Central European countries involved in the project (Hungary, Germany, Poland, Slovakia and Croatia) in relation to MAR is part of Work Package T4 – Development of policy recommendations and national action plans and are described in the report D.T4.1.2 – comparative transnational report of CE legislation and policies on MAR.

4. Characterization of the pilot site

4.1. Selection and description of the pilot site

Site selection

Research on the selection of the pilot site started with the production of climate exposure maps, at the scale of the whole country (area 312 685km^2), in order to show areas where MAR will be more needed in the future due to negative climate change. Then, by mapping the potential suitability of the areas based on hydrogeological and geological parameters, a preliminary classification of suitability was made for the Dunajec river basin (4854 km^2). At that point, from the three pre-selected feasible areas for the application of MAR, one area located in the Tarnów region was selected for more detailed investigation. In this area further assessment of suitability was conducted, taking into account new (more specific) hydrogeological and geological parameters and applying differently set threshold values in the O.T2.1 decision support toolbox. In this region, sites with high potential suitability for two studied MAR methods (IBF and infiltration ditches) were identified. The MAR feasibility study was performed for this area (27 km^2) with special focus on well field Świerczków where existing and operational MAR is located in close vicinity of an industrial zone. The whole process of mapping and selection of the area for detailed investigation of the feasibility study is presented in report **D.T3.1.2** (DEEPWATER-CE, 2021d) and based on the methodology developed in the decision support toolbox (DEEPWATER-CE, 2020a). All created maps are available online at Global Groundwater Information System of IGRAC: https://ggis.un-igrac.org/maps/2171/embed.

Description of the pilot site

This subchapter describes the pilot area in the Tarnów region for introducing the reader into the specifics of this site by characterising the different elements of the environment and land use, with particular emphasis on the well field Świerczków (existing MAR: IBF and infiltration ditches) and the adjacent area to the north (area of potential MAR system expansion) for which the main field research was carried out.

The study area is located within the river valleys of the Dunajec and the Biała Tarnowska (Fig. 4.1, Fig. 4.4), which cover the flood and alluvial terraces of both rivers. The average width of the Dunajec valley in this region is about 1000 m. The Biała Tarnowska valley has an average width of about 300 m. In the area of the Świerczków well field (part of the area of detailed studies at the Polish pilot site), elevations of the river terraces are approx. 190 - 200 m a.s.l. The land surface is nearly flat there, rising a bit in the southern part of the well field. Larger elevation differences are mostly of anthropogenic origin and include flood banks, gravel pits, drainage trenches or landfills. In the southern part of the area in study, in the region of Zbylitowska Góra, there is an upland rising up to 230 - 260 m a.s.l.

The main land use type of the study area are anthropogenic areas (47%). These are areas related to the so-called "urban fabric" and the industry of Tarnów, the most important of which is the big chemical plant in property of Grupa Azoty S.A. It is situated in the immediate vicinity of the pilot site. The Świerczków well field is also surrounded by two reclaimed ash landfills and a toxic waste reservoir (Wojtal et al., 2009; Treichel et al., 2015). Several roads (for instance, the busiest no. 94) and railway lines (no. 115 and 91) pass through the southern and central part of the study area.

Agriculture is the second largest land use type (39%), including non-irrigated arable land (15,7%), pastures (8,7%), land principally occupied by agriculture, with significant areas of natural vegetation (8,6%) and complex cultivation patterns (6%). The remaining 14% is the natural vegetation (e.g. forests) and water areas. The land use types were derived from the CORINE Land Cover database (Corine Land Cover, 2018). Their detailed breakdown is presented in the Table 4.1 and on the Fig. 4.2.

The operating MAR system of the Świerczków well field and the potential MAR system expansion are located within areas intended for water supply systems according to local spatial development plan (LSDP) of Tarnów city. This area is covered by grassland.

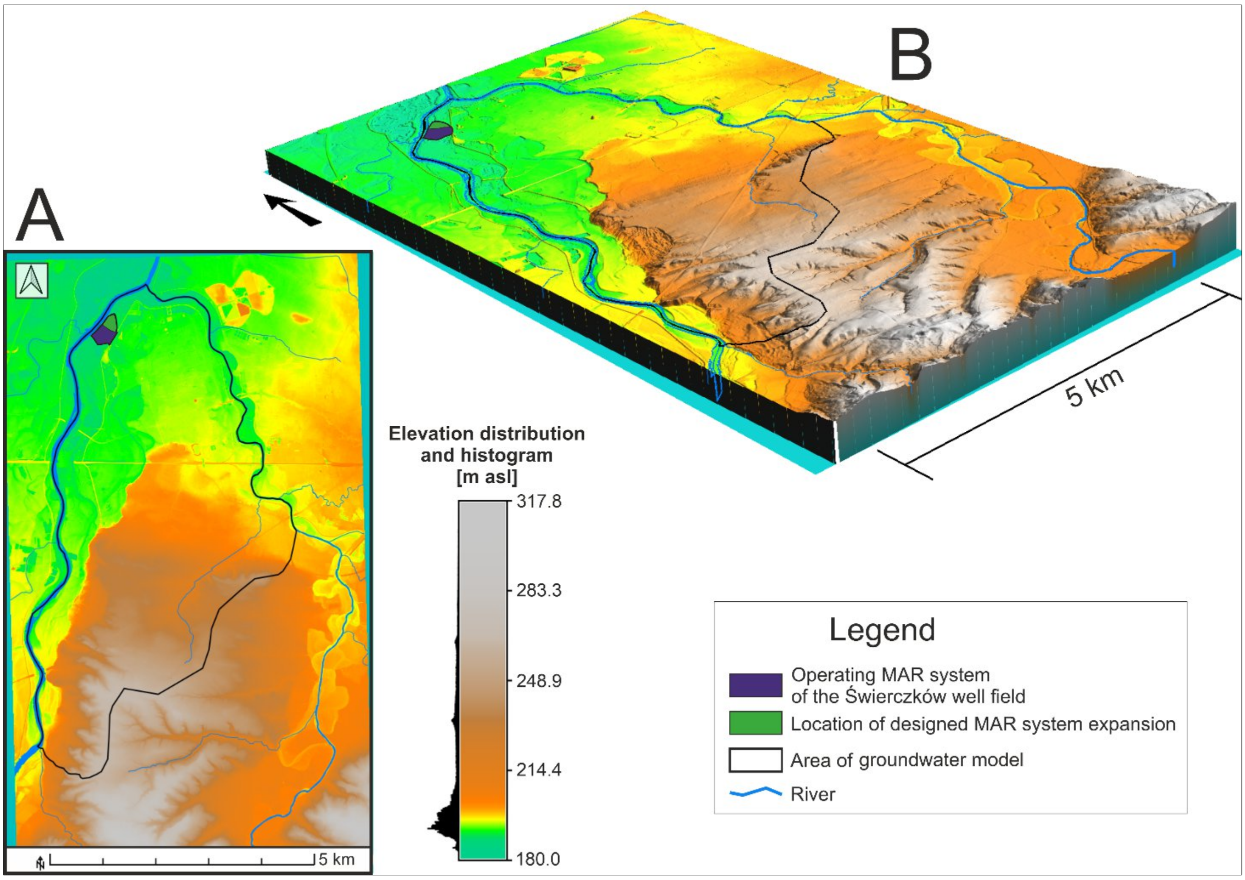


Fig. 4. 1. Morphology of the study area. A: **2D map,** B: **view of the surface in 3D.**

Table 4. 1. Distribution of land use in the study area (based on CLC 2018 database).

Land use type	area [km^2]	percentage share [%]
Transitional woodland-shrub	0.01	0.05
Water courses	0.73	2.69
Sport and leisure facilities	0.94	3.49
Mixed forest	0.96	3.55
Complex cultivation patterns	1.61	5.96
Broad-leaved forest	2.14	7.91
Land principally occupied by agriculture, with significant areas of natural vegetation	2.33	8.63
Pastures	2.35	8.70
Industrial or commercial units	3.51	12.99
Non-irrigated arable land	4.24	15.70
Discontinuous urban fabric	8.19	30.33
-	**27.02**	**100**

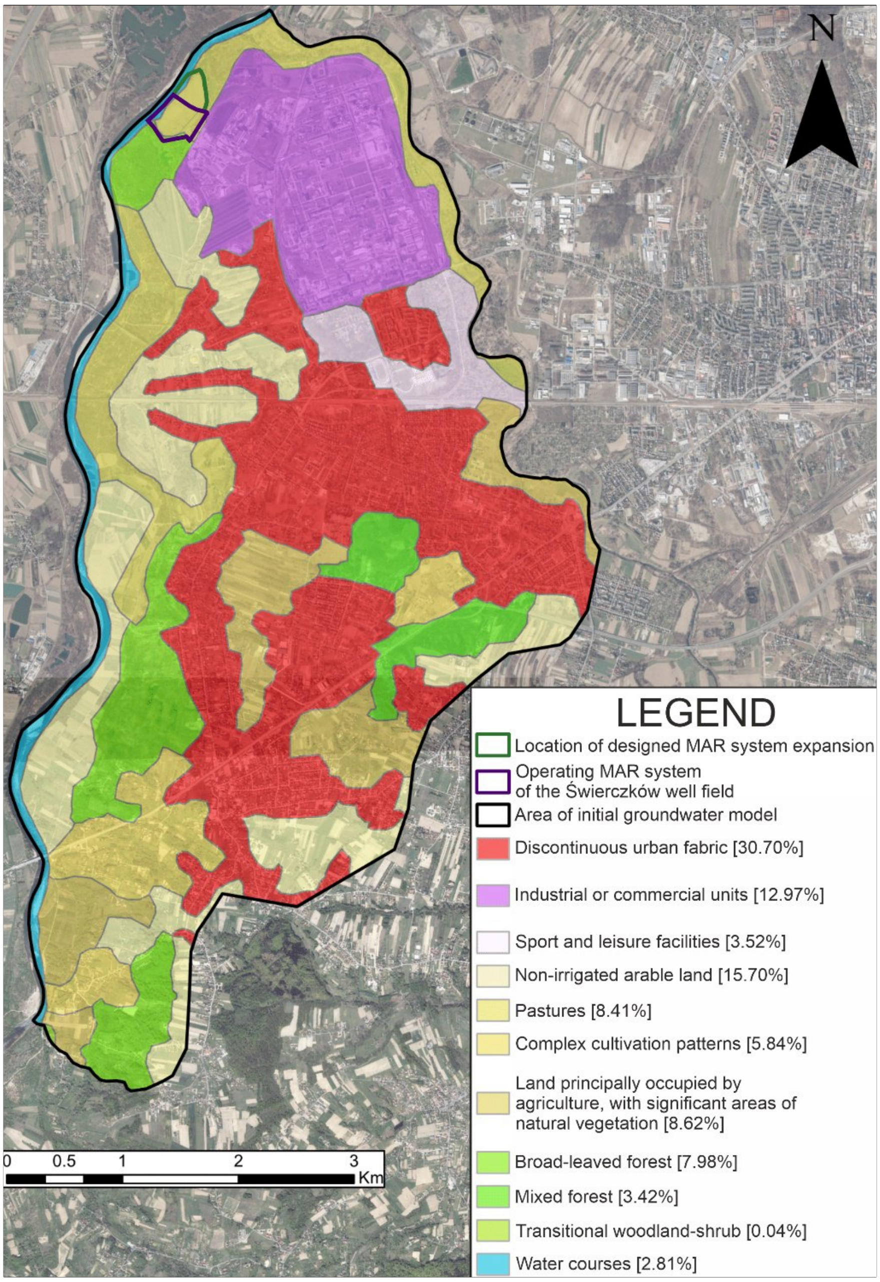


Fig. 4. 2. Land use map of the study area (Corine Land Cover, 2018).

In terms of climate, the study area is located in the Southern Lesser Poland climatic region according to Woś (2010) classification. This region is distinguished by the relatively frequent appearance of warm days. Moderately cool days with frosts are approximately 8. Also very cool, sunny days with frosts occur quite often, without any precipitation. The extreme precipitation above the daily total of 30 mm (1966-2018) has been occurring more frequent with is the result of climate change

The weather of the area is mostly shaped by the polar maritime air masses which occur with an annual frequency of 66%. The frequency of other air masses is much lower, reaching 18% for arctic air masses and 14% for polar continental air masses. The warm tropical air masses are noted during ca. 2-3% of days a year.

Another factor having an important impact on the local climate are the weather fronts that mark the transition zone between two air masses and lead to weather change and precipitation. The cold fronts have higher frequency than warm fronts. The analysis of long-term weather observations for Tarnów from 1966-2019 allows the conclusion that the average annual air temperature in this area is 8.9°C and it has been significantly rising since 1966, with the rate of 0.4°C per decade (DEEPWATER-CE, 2021a). Thus the climatic data for the Tarnów region clearly shows that the climate is warming up (Fig. 4.3). The general increase in mean air temperature is related to increased high air temperatures rather than changes in air temperatures below the freezing point. This region has the longest thermal summer in Poland - it lasts 114 days (the number of days with average daily temperature above 15°C). Tarnów annually receives an average of 725 mm of precipitation (1966-2019). The annual course of precipitation there is typically continental with a clear maximum in the summer months (July) and minimum in winter (February).

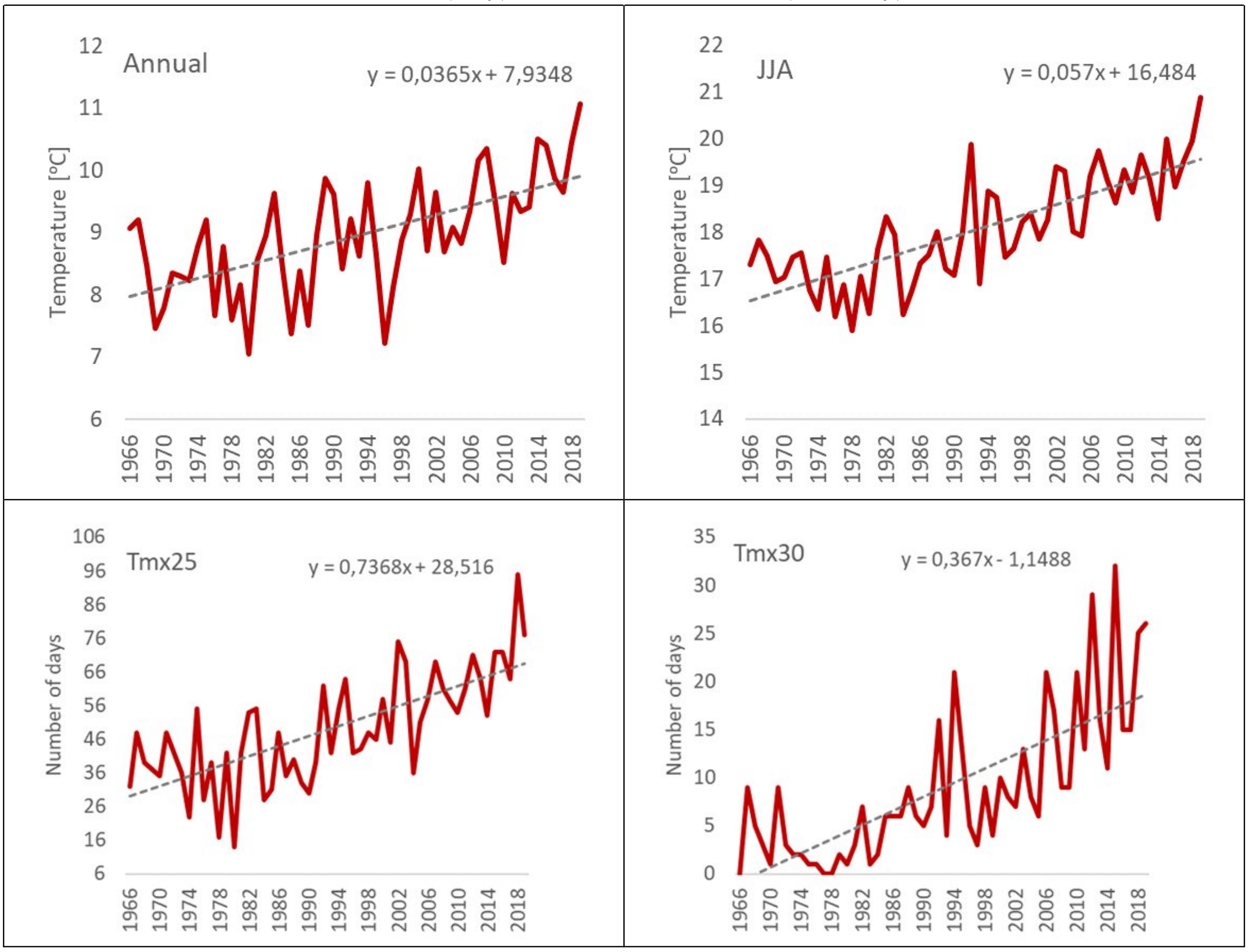


Fig. 4. 3. Long-term variability in annual and summer (June, July, August) air temperature and the numbers of summer (≥25°C) and heat (≥30°C) days in Tarnów, years 1966 - 2018.

The study area is located in the Baltic Sea drainage basin, the Vistula river basin, in the Upper Vistula water region, within the Regional Water Management Board in Cracow. It is situated at the fork of the Dunajec and Biała Tarnowska rivers and is located within two surface water bodies (SWB): the Dunajec river extending from the Czchów reservoir to the estuary (code PLRW20001921499) and the Biała river extending from Rostówka to the estuary (code PLRW200014214899) (Fig. 4.4). The western part of the research area, which belongs to SWB RW20001921499, is described as type no. 19 - a sandy-clay lowland river. Its length is 69.8 km, and the catchment area is 251,2 km^2 (Fig. 4.4).

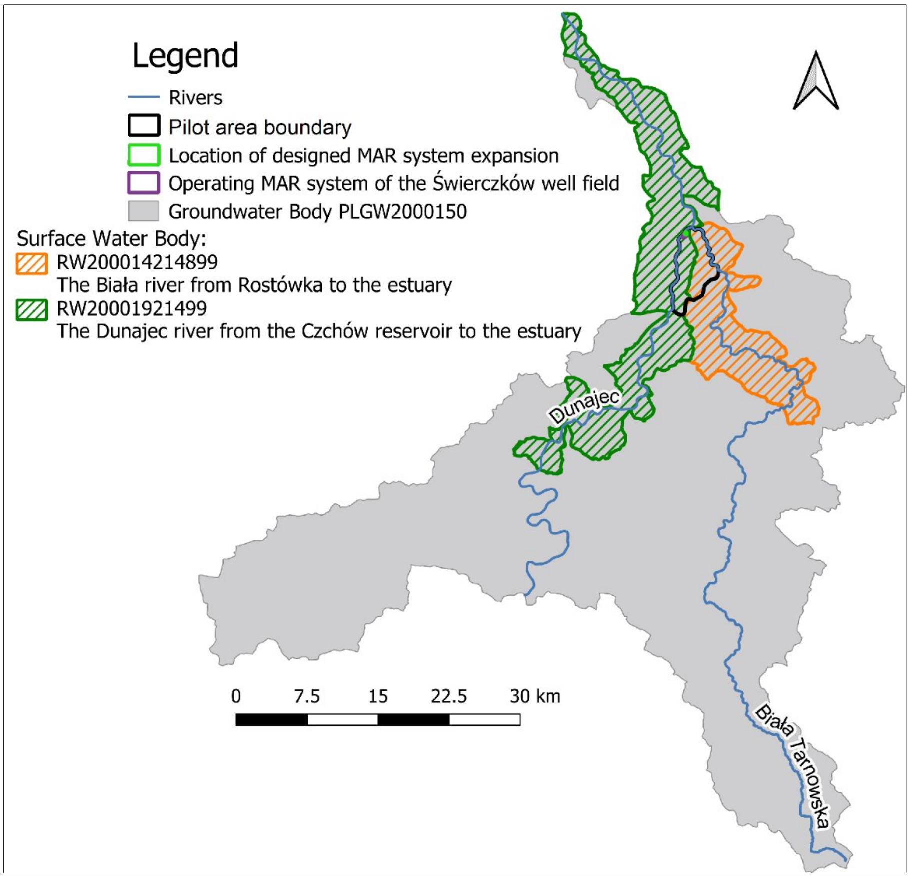


Fig. 4. 4. Location of the study area in relation to water bodies

Observed discharge rates of the Dunajec River at the water gauge station Zgłobice, located at km 38+560 (river kilometre - location of place on river calculated as distance from river mouth) of the river course, in the years 1981-2017 were as follows: the lowest 8.80 m^3/s, average low 18.7 m^3/s, average annual mean 77.4 m^3/s, average high 882 m^3/s, highest 2510 m^3/s. In the years 2016-2020: the lowest 20.8 m^3/s, average 80.07 m^3/s, highest 1030 m^3/s. The calculated base flow for the 2016-2020 period ranged from 20.8 to 124 m^3/s with a mean value of 40.44 m^3/s. The complete section of the Dunajec River in the study area belongs to a Natura 2000 protected zone (PLH120085 Dolny Dunajec). Subjects of protection are stones and gravel beds of mountain streams and fish populations.

The SWB code RW20001424899, named "Biała od Rostówka do ujścia" (eastern part of research area), belongs to type 14 - small flysch river. The Biała River is the right-bank tributary of the Dunajec River. The length of the water body is 34,4 km, the catchment area is 125,8 km^2 (Fig. 4.4). Discharge rates of the Biała River at the water gauge station IMiGW Koszyce, located in km 2+000 of the river's course, in the years 1971-2013 were: the lowest 0.60 m^3/s, average low 1.38 m^3/s, annual average 9.36 m^3/s, average high 282 m^3/s, highest 836 m^3/s and in the years 2016-2020: the lowest 0.92 m^3/s, average 7.68 m^3/s, highest 270 m^3/s. The calculated base flow for the 2016-2020 period ranged from 0.92 to 13.8 m^3/s with an average value of 3.68 m^3/s.

The Świerczków well field is located directly on the right bank of the Dunajec river. Such location is favourable for the development of IBF. Wells located directly at the Dunajec River can be fed by bank filtration.

The shallow geology deposits in the study area are of Quaternary and Miocene age (Fig. 4.5). The occurrence, form and thickness of the Quaternary sediments are mainly related to the glacial, fluvial and aeolian activities. Their thickness depends mostly on the morphology of the terrain and the relief of the Miocene's top. Generally, the first 10 - 20 m (for northern and southern part, respectively) below ground level are the Quaternary deposits.

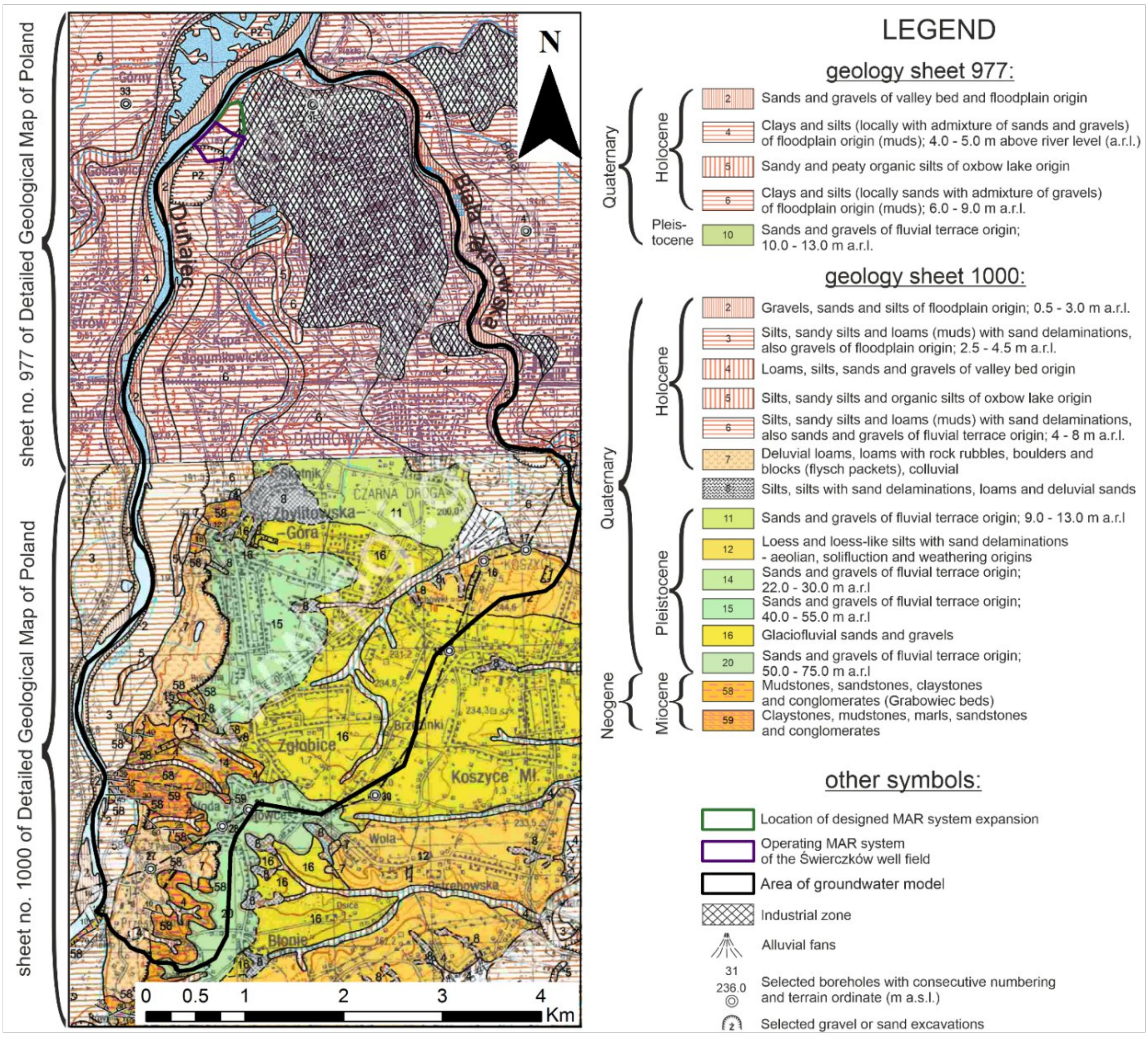


Fig. 4. 5. **Geological map of the study area (according to Purchla, 1991 and Marciniec et al., 2006).**

The Quaternary deposit consist of loams (muds), silts and organic silts or clays in the upper part of the profile (particularly in the northern part), and alluvial deposits in form of sands and gravels with a substantial fraction of pebbles in the lower part of the profile. Quaternary deposits lie on a clay Miocene bed (Wojtal et al., 2009; Kruk et al., 2017). The youngest sediments are represented by the so-called "Anthropocene": embankments, landfills and anthropogenically transformed land. Directly at the Świerczków well site, on the basis of data from hydrogeological well logs, the Quaternary deposits lies on an impermeable clay Miocene strata. The thickness of the Quaternary is about 8-10 m. The Quaternary aquifer consists of sands, gravels and pebbles. The aquifer lies on an impermeable clayey Miocene bed and is mostly covered with silts and loams. The depth to the aquifer varies from 2 to 5 m b.g.s. (on the southern upland, the depth increases to over 35 m b.g.s.) and its thickness is approx. 5 to 9 m (Fig. 4.6).

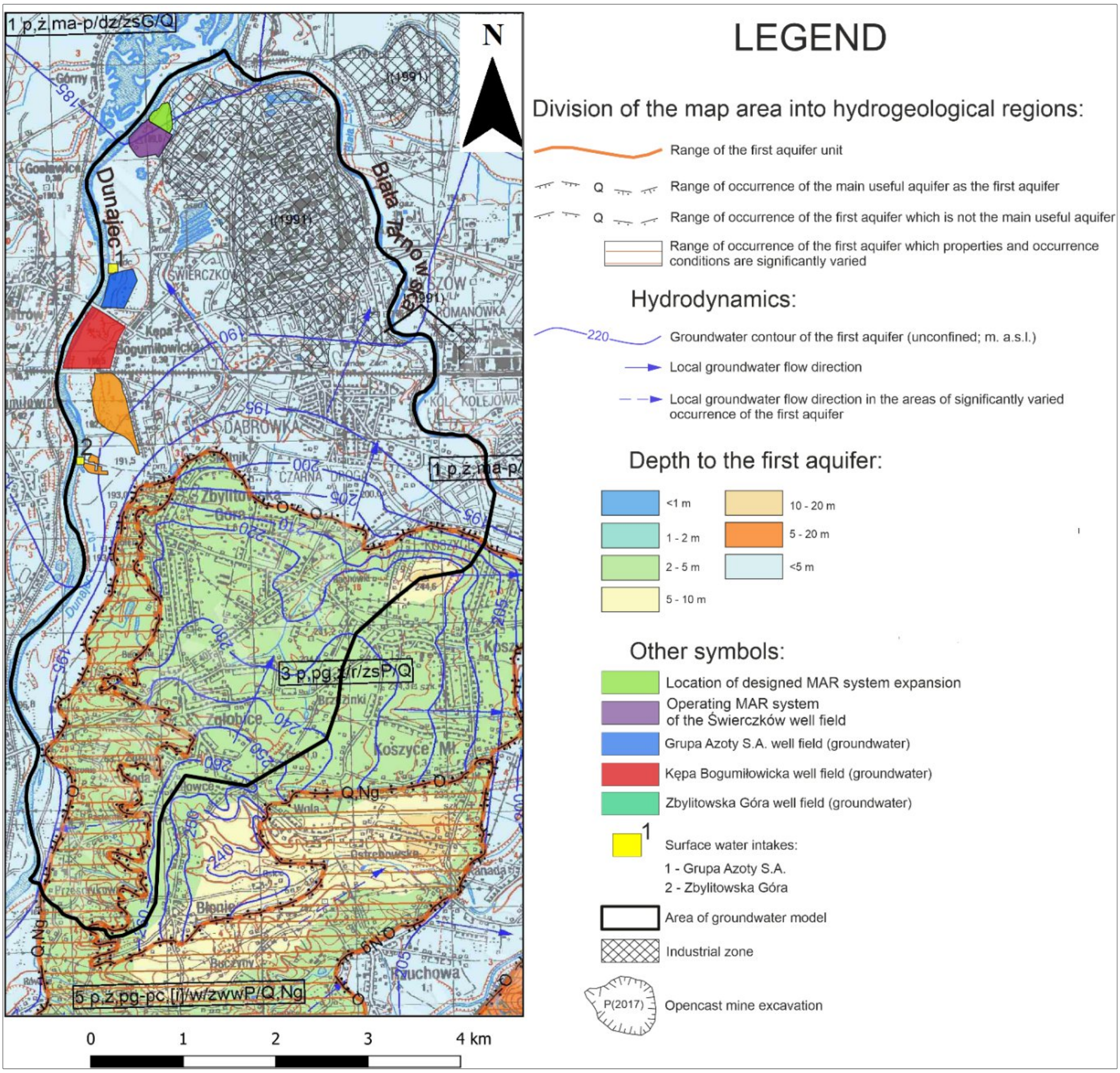


Fig. 4. 6. Hydrogeological map of the study area (based on Gorczyca, Gągólski, 2018; Gorczyca, Koziara, 2018)

The aquifer is mostly unconfined (Treichel et al., 2015). The depth to the groundwater table depends on the water level of the Dunajec and Biała Tarnowska rivers, the amount of groundwater abstraction, and the intensity of aquifer recharge from precipitation. The aquifer's recharge takes place in its entire catchment area by direct infiltration of rainwater and in the periods of high surface water levels also by infiltration from the rivers. The natural recharge based on the SWAT model for the year 2021 was determined to be 88-116 mm/year, which represents 13.5% of precipitation. Simulation scenarios for the following decades based on climate model data 2021-2091 vary between 11.5% (E-REP4.5) -18% (C-REP8.5) of total precipitation. The highest hydraulic conductivity of an aquifer occurs in the Dunajec valley, reaching up to several hundred m/d. The groundwater level varies from 185 (Dunajec riverbed) up to 260 m.a.s.l. in the south. The hydrodynamic system is typical for an interfluve area (Fig. 4.6). Groundwater flows in west and northwest directions towards the Dunajec river, and east and northeast directions towards the Biała Tarnowska river. The aquifer under natural conditions (without any abstraction of groundwater) is drained by these two rivers. During flood periods, the hydraulic gradient in the aquifer close to the rivers is reversed and the rivers become temporary losing-type and start to feed the aquifer. It should be noted that nowadays, the flow rate in the Dunajec is regulated by water discharge on the dam in Czchów (the well field is located about 30 km in a straight line from the dam). The Biała Tarnowska river is not regulated, therefore periodic floods can be more pronounced (Wojtal, 2013).

The groundwater flow directly at the Świerczków well field is more complex due to operating abstraction wells and artificial recharge by the infiltration ditches. In average, groundwater flows from SE to NW. The new monitoring scheme established within the DEEPWATER-CE project, thanks to new installed piezometers, will allow better recognition of the hydrodynamic conditions.

Existing infrastructure and MAR types in the pilot area

Drinking water as well as water for the industry and agriculture is supplied from surface and groundwater sources in the pilot area. Some of the existing well fields has been using MAR solutions (Table 4.2).

Table 4. 2. Existing well fields in the pilot study area.

Well field name (well field owner)	Type of abstracted water	MAR type	Max. abstraction due to the water permit (m^3/d)	Mean abstraction in 2020 (m^3/d)	Main aim of the water production
Świerczków (Tarnów Waterworks)	Groundwater	Infiltration ditches & IBF	8500	6505.85	drinking water
Kępa Bogumiłowicka (Tarnów Waterworks)	Groundwater	IBF	11500	9165.52	drinking water
Well field in Tarnów-Mościce (Grupa Azoty S.A.)	Groundwater	none	9864	1083.45	drinking water
Zbylitowska Góra (Tarnów Waterworks	Surface Water	none	40000	no data	drinking water
Mewa (Grupa Azoty S.A.)	Surface Water	none	79200	no data	process water

The most promising for implementing MAR seems to be well field Świerczków (Fig. 4.7). This well field, although adjacent to a large industrial zone threatening groundwater, provides, thanks to the existence of infiltration ditches and IBF methods, water of a quality that meets drinking water standards. In the DEEPWATER-CE project this was therefore of particular interest, where the process of improving groundwater quality by using MAR was investigated by means of targeted field work and research. In addition, analyses were also carried out on the possibility of expanding this area with additional wells and ditches, in the area immediately north of the Świerczków well field. The experience gained from this pilot action can also be used and applied in other areas in Poland or other Central European countries.

The Świerczków well field was established in 1910 as the main source of water for the city of Tarnów. The facility was expanded several times by increasing the number of wells; other wells were taken out of service. In the 1959, a system of enriching the aquifer through a system of infiltration ditches was implemented. Recharge water was taken directly from the Dunajec river until the end of 1970s. At that time a pumping station was installed on the bank of the Dunajec river, within the Świerczków well field area. In the 1970s, after locating ash dumps in the immediate vicinity of the well field area and constructing a sheet pile wall in the southern part of the well field (to avoid the leaching from the ash dumps), the artificial recharge duty was taken over by Zakłady Azotowe, currently Grupa Azoty S.A (GA S.A.).prior to its application at the well field Świerczków, the recharge water pumped from the Dunajec river is being passed through the sedimentation tanks, which significantly reduce the amount of suspended solids and thus reduce clogging of the infiltration ditches in the process. This system of artificial recharge is still operating. The amount of water pumped for recharge ranges from about 3,200 m^3/d (133 m^3/h) to about 4,900 m^3/d (about 204 m^3/h), which represents about 40% to >60% of the well field's current discharge. The infiltration ditches are cleaned (scraped) approximately every 3 years. Based on modeling studies, it was determined that more than 70% of water abstracted at the Świerczków well field comes from MAR, and the remaining portion from native groundwater.

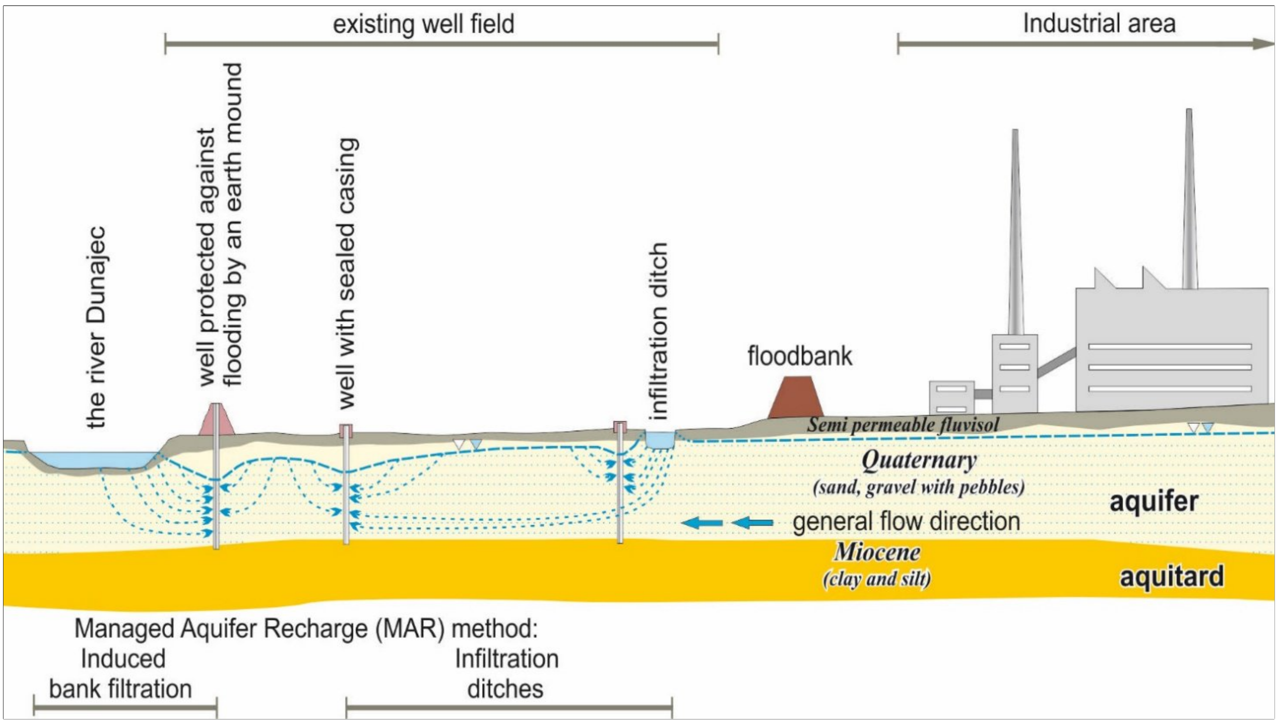


Fig. 4. 7. Scheme of MAR operation in the Świerczków well field.

The wells are connected to two siphon pipelines, the so-called southern and northern siphon. Both siphon pipelines feed water to the collection well located behind the flood bank, where the water is fed by low pressure pumps to a reservoir located at the pumping station of the well field. Before entering the water storage tank the water is treated with chlorine dioxide only for disinfection purposes. The water from the reservoir is then pumped by high-pressure pumps into the municipal network.

Originally, the water drawn from the well field was subject to de-ironing, and since 1967 de-ironing has been abandoned due to a decrease in iron concentration. Currently the well field consists of 17 wells (Fig. 4.8). In 2020, water abstraction from the well field varied from 152,854 m^3/month to 223,538 m^3/month. In the last 5 years, the average water abstraction has been about 6,910 m^3/d. The Świerczków well field has a water permit until 2033. According to the permit, the well field can extract water at a maximum hourly quantity of 380 m^3/h, an average daily quantity of 8500 m^3/d and maximum yearly quantity of 3 100 000 m^3/y.

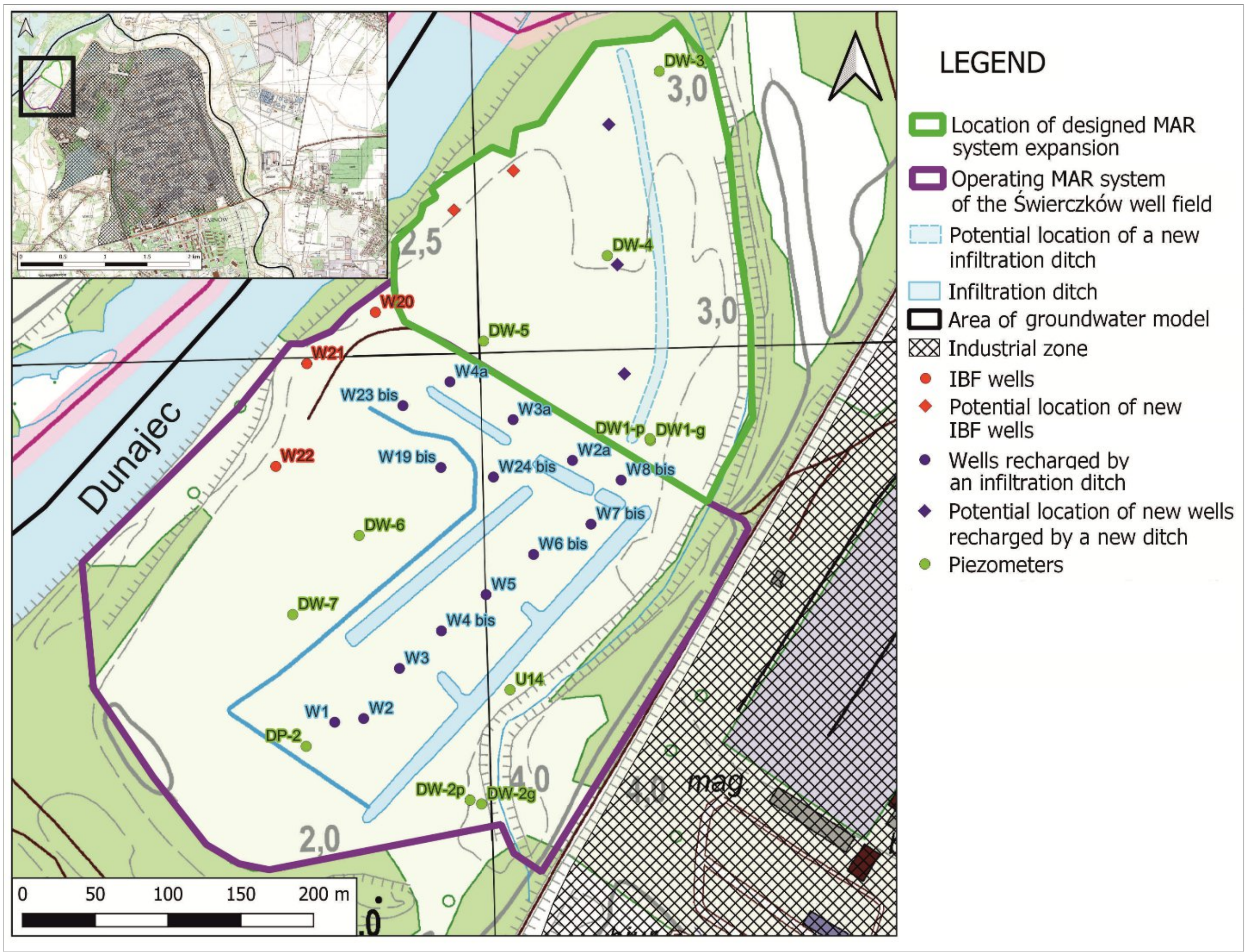


Fig. 4. 8. MAR system at the Świerczków well field and location of its potential expansion.

4.2. Methods

This chapter presents all the methods applied during the pilot feasibility study. It covers methods for geological, hydrogeological and water quality and pollution investigation.

The geological investigations in the pilot site were divided into geophysical survey, manual drillings, mechanical drillings, and sampling of sediments from infiltration ditches beds using two methods. The first field campaign was carried out in December 2019 and the investigation ended in the end of 2021.

Geophysical survey

Geophysical investigation conducted by means of ERT (Electrical Resistivity Tomography) aimed at a better recognition of geological and hydrogeological conditions at the pilot site . Measurements were performed using the LUND electrical imaging system with a Terrameter SAS 1000/4000 produced by ABEM Malå (Guideline Geo). This instrument measures voltage responses (between two potential electrodes) created by the transmitter current (between two current electrodes), while rejecting both DC voltage and noise. The LUND electrical imaging system consists of 41 electrodes, where each electrode is used as a current and potential electrode. The ratio V/I (voltage to current) is automatically calculated, displayed and recorded by the Terrameter. The transmitter was operating at 500 mA with a resolution of 0.02 mW for a single reading. The measurements were supplemented using the Wenner-Schlumberger electrode configuration with 3 m electrode separations. This particular array was used because it is moderately sensitive to both horizontal and vertical structures, and has better horizontal coverage and signal strength than other arrays.

Data were interpreted with RES2DINV software (Geotomo Software), which uses an iterative smoothness-constrained least-squares method to create a model of resistivity of the subsurface. The resulting models were based on 112 – 330 points for shorter profiles and 539 – 1035 points for the longer profiles. The root-mean-squared error (RMS), which indicates the differences between the calculated and measured values of apparent resistivity in the model, varied from 2.4 to 6.1%.

Drillings

Mechanical and manual boreholes were drilled in the pilot area to collect soil and water samples for testing, and to establish a monitoring network (mechanical boreholes). The specific objectives of this work and a description of the methods are described below.

Hand drillings

Manual drillings were done using Dutch auger, also known as mud auger (Fig. 4.9). The main aim of manual drillings was to collect data necessary for preparing a map of infiltration time through the vadose zone in the poorly identified northern part of the study area. The northern part of the well field is an area of a planned expansion of existing MAR system. Hydrogeological and geological information on the uppermost few metres is very important for an appropriate estimation of natural recharge (expressed by the effective infiltration rate) and will facilitate the planning of potential MAR implementation.

Moreover, to the south of the Świerczków well field, from the area of the recultivated ash dump, fly ash samples were collected in order to examine their chemical composition and to conduct batch leaching tests. Batch leaching tests allow to determine the mass of eluted substances from the sediment sample per kg of dry mass of the sample. Sampling of sediments and assessment of their quality was based on the Regulation of the Minister of Environment of 1 September 2016 on the manner of conducting assessment of contamination of the earth surface (Journal of Laws 2016, item 1395), pursuant to the Act of 27 April 2001 - Environmental Protection Law (Journal of Laws 2020, item 1219).

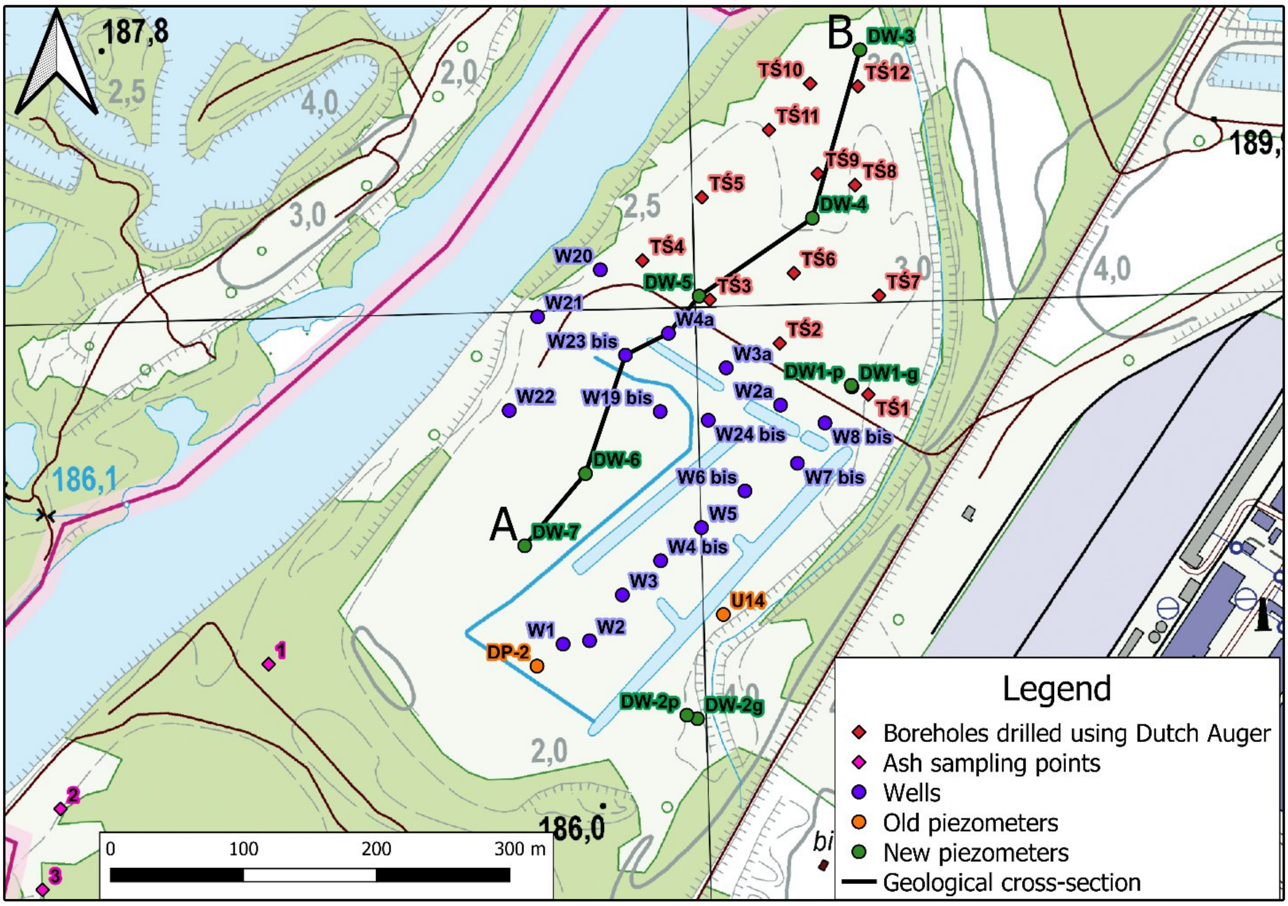


Fig. 4. 9. Map showing the location of new research boreholes drilled as part of the DEEPWATER-CE project along with the location of existing wells and piezometers.

In order to collect ash samples from the waste disposal site located to the south of the pilot area, 3 shallow boreholes were drilled (Fig. 4.9). Ash samples were collected at depth intervals of 0.5 m and then averaged. Analysed parameters were the same as in the case of sediments collected at well field. The chemical composition of collected sediments was analysed and batch leaching tests were conducted on them in accordance with the PN-EN 12457 standard. Application of the standard made it possible to determine the types and mass of leached components per 1 kg of dry mass. Considering the fact that the tests were performed on waste, the obtained results were evaluated in accordance with the Regulation of the Minister of Economy of 16 July 2015 on allowing waste to be stored in landfills (Journal of Laws 2015 Item 1277).

Another objective of this part of fieldworks was also collection of sediments from the bottom of the ditches. Investigation of the grain size distribution may help to determine whether clogging is taking place in the ditches. Samples were subjected to grain size analyses using two methods (Rutkowski, 2021) laser particle analyser using Fritsch particle analyser model Analysette 22 MicroTec plus and pipette analysis. Another objective of the hand drilling was sampling of sediments from the bottom of the ditch in order to investigate chemical and mineralogical composition of the sediments and to conduct batch leaching tests, as it was performed for fly ashes. Mineralogical analyses of fine fractions obtained from sediment samples were performed using the XRD method (X-ray powder diffraction).

Mechanical drilling of new observation wells (piezometers)

An important part of the geological field work was drilling of nine observation wells, thus creating a network for groundwater monitoring points for the shallow Quaternary aquifer (Fig. 4.9). The monitoring network was created on the basis of a geological operation project and a supplement to this project. After the completion of all observation wells, a geological documentation was written in accordance with the Polish legislation. All documents were approved by the Marshal's Office. The new monitoring network allows for several monitoring types at MAR sites, as described in the Australian Guidelines (NRMMC-EPHC-NHMRC, 2009): baseline monitoring on the undeveloped, northern part, and for the operational and validation monitoring on the southern part where MAR is already operating. The drilling was carried out using a self-propelled drilling rig of the UGB 50 typ. The PVC well screen in each piezometer has a diameter of 110 mm. Once installation of new piezometers was completed, after purification pumping, representative samples of groundwater for chemical analysis were taken. During the pumping of each piezometer (at a constant flow rate), basic hydrogeological measurements were made such as drawdown and rise of the groundwater table. For mineralogical investigation of the aquifer sediments, 15 samples were taken during drilling from the 4 piezometers. The samples were taken from different depth intervals: DW-1g (0,5-1,5m; 1,5-2,5m; 2,4-4,0m; 4,0-6,0m; 9,0-10,0 m), DW-4 (0,0-0,5m; 0,5-2,5m; 2,5-3,0m; 5,0-6,5m), DW6 (0,0-0,3m; 0,3-2,0m; 2,0-2,5m; 3,0-4,0m; 7,0-8,0m) and DW 7 (7,5-9,0m). For each sediment sample, the fraction below 0.5 mm was recovered using a sieve, then observed under a Zeiss Stemi 508 binocular microscope. All measurements were made using a PANalytical X-ray diffractometer, X'Pert Pro MPD PW3040/60 model (Table 4.3). The obtained diffractograms were processed in the HighScore + computer program by Panalytical (version 4.9). For quantitative calculations, the ICSD database standards (version 3.5, 2015) and COD (Crystallography Open Database, March 2021) were used, containing structural data for all matched patterns. The calculations were carried out using the Rietveld module.

Table 4. 3. XRD measurement parameters.

Radiation	**Co Ka1 (l=1,789010 Å)**
	Fe Kb absorption filter
X-ray tube tension	40 kV
X-ray tube current	40 mA
Range	5°- 90° 2Q
Step size	0.02° 2Q
Time limit	300 sec
Detector	X'Celerator with Real Time Multiple Strip technology (RTMS), active strip length = 2.122°2Q

Hydrogeological investigations

Hydrogeological field investigations started at the pilot site in September 2020. Since then, monthly measurements in all wells and piezometers at the well field have been carried out using an electric water level meter. On January 27, 2021, three types of dataloggers (1 barologger, 3 level-temperature-conductivity loggers, 2 level-temperature loggers) and 1 multiparameter sonde were installed in selected production wells, piezometers and one infiltration ditch (Fig. 4.10). A sixth datalogger (water level and temperatrue) was installed in the field on May 27 2021. According to Table 4.4, dataloggers recorded continuously, in 1-hour frequency, different ranges of parameters such as the level of water table (water pressure above the data logger), atmospheric pressure, water temperature, electrical conductivity (EC), nitrate and ammonium concentration. After several months of initial observations, a decision was taken to rellocate 2 dataloggers to other observation points - to the new piezometers DW-1p and DW-3. An overview of the observation periods at the given observation points along with the logger type is shown in Table 4.4.

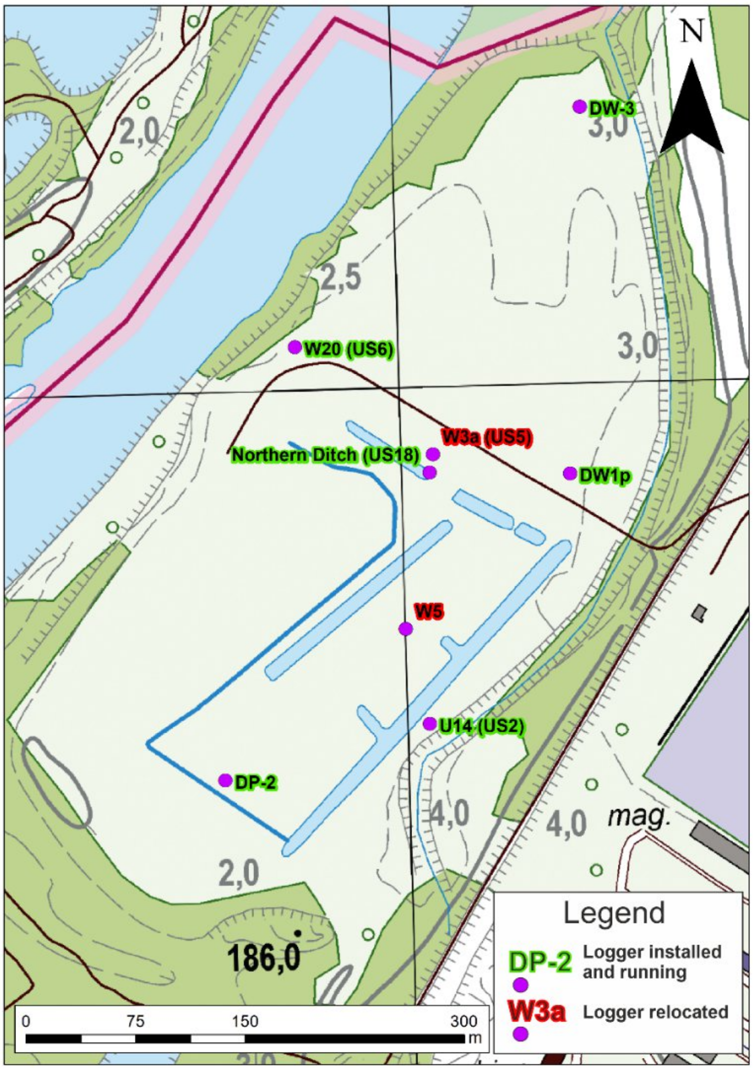


Fig. 4. 10. Location of the installed dataloggers.

Table 4. 4. Overview of dataloggers installed at the pilot site.

Observation point	Observation period	Logger type	Parameters measured
W20 (US6)	from 27.01.2021	LTC	water table, temperature, EC
U14 (US2)	from 27.01.2021	Junior and Aqua TROLL 600 probe	water table, temperature, concentration of nitrate and ammonium ion
W3a (US5)	27.01.2021 - 29.04.2021	Junior	water table, temperature
Northern Ditch (US18)	from 30.04.2021	Junior	water table, temperature
DP2	from 27.01.2021	LTC and Barologger	water table, temperature, EC, atmospheric pressure
W5	27.01.2021 - 19.02.2021	LTC	water table, temperature, EC
DW3	from 30.04.2021	LTC	water table, temperature, EC
DW1p	from 27.05.2021	Junior	water table, temperature

For the purpose of this report, the results of the groundwater table measurements were supplemented with the data from the neighbouring well fields and groundwater monitoring sites. On the basis of the obtained data, a groundwater table contour map was made in order to determine the direction of groundwater flow within the study area. In the process of creating this map, data on water withdrawals from several other groundwater and surface water supply sites located in the vicinity of the Świerczków well field were also considered.

Water quality investigation

The study on water quality comprised analyses of surface water, groundwater and precipitation samples. The investigation included measurements of physicochemical parameters of water, concentration of inorganic N ions (ammonium, nitrite and nitrate) and stable isotopes of water (δ^2H and $\delta^{18}O$) performed on a monthly basis for one year, from September 2020 to September 2021. Concentrations of major ions, Fe, Mn, total organic carbon and pharmaceutical residues were measured 4 times per year (3 times for pharmaceuticals) to study seasonal changes in water chemistry. Additionally, organic pollutants and microplastic were investigated once to investigate groundwater and surface water contamination with specific substances. For comparison, groundwater samples from two production well located south of the Świerczków well-field (US11 and US12) were collected 4 times per year. All methods applied in the pilot feasibility study were described in the report D.T3.4.2 (DEEPWATER-CE, 2021b). Sampling points of surface water and groundwater are presented in Table 4.5 and Fig. 4.11.

Table 4. 5. Sampling points for the water quality investigation.

No.	Symbol	Type	Local name
1	US1	River	Dunajec River
2	US2	Piezometer	U14
3	US3	Infiltration ditch	Eastern ditch
4	US4	Abstraction well	W8bis
5	US5	Abstraction well	W3a
6	US6	Abstraction well	W20
7	US7	Abstraction well	W22
8	US8	Abstraction well	W7bis
9	US9	Abstraction well	W4bis
10	US10	Abstraction well	W2
11	US11	Abstraction well	S-40
12	US12	Abstraction well	S-30
13	US13	Abstraction well	W2a
14	US14	Abstraction well	W6bis
15	US15	Abstraction well	W4a
16	US16	Abstraction well	W19bis
17	US17	Abstraction well	W24bis
18	US18	Infiltration ditch	Northern ditch
19	US19	Abstraction well	W21
20	P1	Precipitation	Precipitation
21	DW1p	Piezometer	DW1p
22	DW1g	Piezometer	DW1g
23	DW2p	Piezometer	DW2p
24	DW2g	Piezometer	DW2g
25	DW3	Piezometer	DW3
26	DW4	Piezometer	DW4
27	DW5	Piezometer	DW5
28	DW6	Piezometer	DW6
29	DW7	Piezometer	DW7

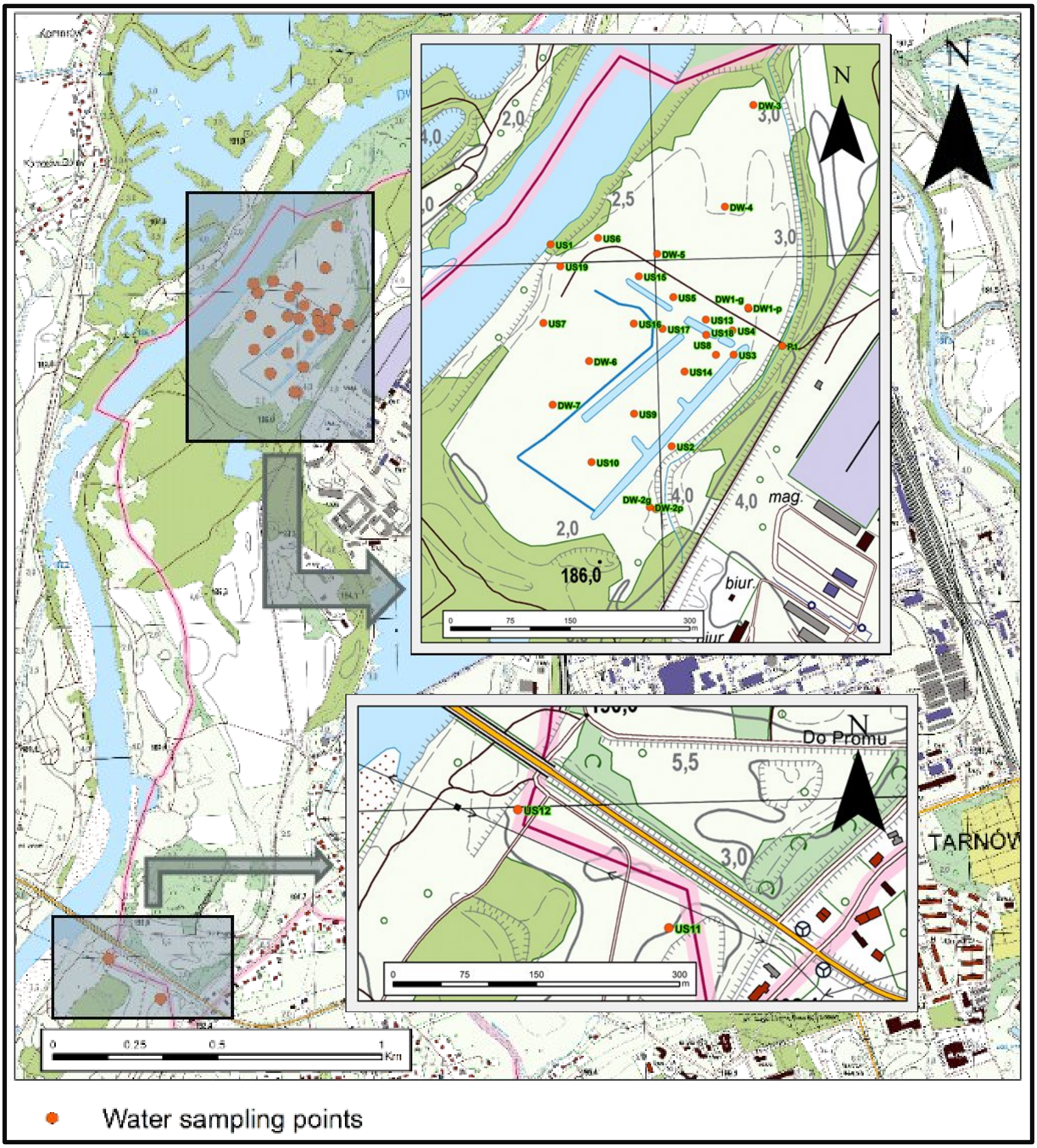


Fig. 4. 11. Location of the surface water and groundwater sampling points.

4.3. Water demand and supply, water source for MAR

The analysis of changes in water abstraction volumes and the assessment of emerging trends was based on archival data from 1998-2019 obtained from Statistics Poland, in regular time intervals (years 1998, 2005, 2010, 2015, 2019) (Table 4.6). The data were analysed for the city of Tarnów (according to the administrative division in Poland, the city of Tarnow has the rights of a commune [Polish: gmina] and a municipal county [Polish: powiat grodzki]), Tarnów commune adjacent to the city of Tarnów and Tarnów land county [Polish: powiat ziemski] (excluding the city of Tarnów) (Fig. 4.12). It should be noted that the communes of Tarnów land county use their own small water intakes or are supplied with water by Tarnów Waterworks [Wodociągi Tarnowskie], which is the largest water supply company in the pilot area. The selected administrative units completely cover the pilot area, which is the subject of a detailed study within the DEEPWATER-CE project (Fig. 4.12).

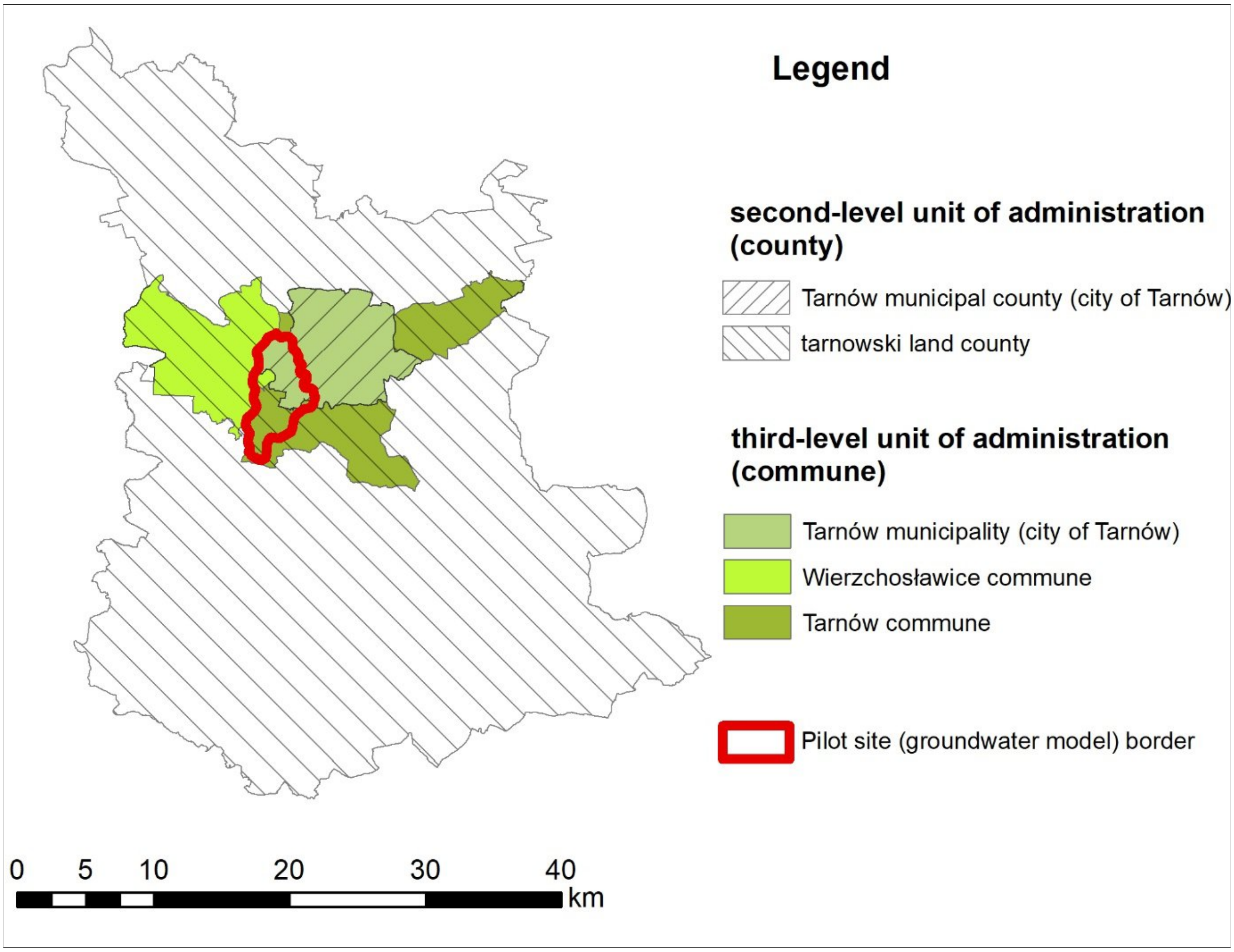


Fig. 4. 12. Location of the pilot area and administrative boundaries.

The analysis of the total water abstraction in 1998-2019 reveals a large decreasing trend for the city of Tarnów (Tarnów municipality) from 30252.6 dam^3 to 15894.1 dam^3 (1 cubic decametre, dam^3, equals 1000 m^3), with a reduction of water consumption by 47% (from 249 m^3/pers. to 146.5 m^3/pers.). In the case of Tarnów commune and Tarnów land county, in turn, there are clear upward trends, respectively: from 674.9 dam^3 to 1346.6 dam^3 (an increase of water consumption by 100%) and from 3273.3 dam^3 to 5070.3 dam^3; an increase of water consumption by 55%. There is a clear contrast between total water consumption per person, especially between the city of Tarnów and the Tarnów land county (in 1998, respectively, 249.0 m^3/pers. and 18.6 m^3/pers., and in 2019, respectively, 146.5 m^3/pers. and 25.2 m^3/pers.). This large difference is most likely due to unrecorded groundwater abstraction in areas outside the city.

The total water abstraction from 1998 to 2019 comprises: water consumption by industry, operation of the water supply system (drinking water) and water consumption by agriculture and forestry (Table 4.6).

The largest water user has been the Tarnów city industry, although it gradually reduced water consumption from 19014.0 dam^3 in 1998 to 10540 dam^3 in 2019, which represents a 45% reduction in water consumption. When it comes to industrial water consumption in Tarnów commune and Tarnów land county, we also observe a general decrease in water consumption (from 86 dam^3 in 1998 to 26 dam^3 in 2019 and from 393 dam^3 in 1998 to 149 dam^3 in 2019, respectively), although there was a slight increasing trend after 2015.

The analysis of the operation of the water supply system shows the same change trends as in the case of the total water consumption in 1998-2019. For the city of Tarnów there was a large decrease in water abstraction from the water network from 10048.6 dam^3 to 5354.1 dam^3; a reduction of water consumption by 47% (from 82.7 m^3/pers. to 49.4 m^3/pers.). In the case of Tarnów commune and Tarnów land county there are clear upward trends, respectively: from 588.9 dam^3 to 970.6 dam^3; an increase of water consumption by 65% (from 29.0 m^3/pers. to 37.0 m^3/pers.) and from 2041.3 dam^3 to 4313.3 dam^3;an increase of water consumption by 211% (from 11.4 m^3/pers. to 21.4 m^3/pers.). There is a clear contrast between total network water consumption per person, especially between the city of Tarnów and Tarnów land county (in 1998 respectively 82.7 m^3/pers. and 11.4 m^3/pers., and in 2019 respectively 49.4 m^3/pers. and 21.4 m^3/pers.). It should be emphasized, however, that in rural areas there still is a considerable number of private wells providing water for animals or watering gardens, etc. However, this part of water abstraction is dispersed and not monitored, so the amount of water used in this way is unknown.

The amount of water withdrawn by agriculture and forestry is negligible compared to water consumed by industry. For the city of Tarnów, the amounts are from 1190 dam^3 (1998) to 350 dam^3 (2019), while for the Tarnów land county they are from 893 dam^3 (1998) to 606 dam^3 (2019) (Table 4.6).

In order to fully assess the analysed trends of changes in water abstraction in the discussed region and their causes it is necessary to analyse the population changes occurring in the area (e.g. migration from the city to the suburbs, migration in the opposite direction - from the countryside to the city, cultural changes and changes in the standard of living). While this would go beyond the scope of this project, a more detailed analysis was done concerning the observed changes in water abstraction within the water supply system of Tarnów Waterworks. This company operate the water supply network of the Tarnów region (Fig. 4.13). All of Tarnów Waterworks' well fields are located in the pilot project area, and the communes supplied with water are shown in Fig. 4.6.

Table 4. 6. Water abstraction in the Tarnów region in 1998-2019.

Administrative unit	Year				
	1998r.	2005r.	2010r.	2015r.	2019r.
total					
City of Tarnów $[dam^3]$	30252.6	20236.5	18596.5	16340.1	15894.1
City of Tarnów $[m^3/person]$	249.0	172.1	162.9	147.7	146.5
Tarnów commune $[dam^3]$	674.9	677.3	830.3	878.7	1346.6
Tarnów commune $[m^3/person]$	33.2	29.5	34.2	34.4	51.4
Tarnów land county $[dam^3]$	3327.3	3680.7	3916.0	4345.7	5070.3
Tarnów land county $[m^3/person]$	18.6	19.0	19.8	21.7	25.2
industry					
City of Tarnów $[dam^3]$	19014	12519	11140	10451	10540
City of Tarnów $[m^3/person]$	156.5	106.5	97.6	94.5	97.2
Tarnów commune $[dam^3]$	86	26	35	21	26
Tarnów commune $[m^3/person]$	4.2	1.1	1.4	0.8	1.0
Tarnów land county $[dam^3]$	393	146	205	128	149
Tarnów land county $[m^3/person]$	2.2	0.8	1.0	0.6	0.7
exploitation of water network system					
City of Tarnów $[dam^3]$	10048.6	6527.5	6266.5	5939.1	5354.1
City of Tarnów $[m^3/person]$	82.7	55.5	54.9	50.1	49.4
Tarnów commune $[dam^3]$	588.9	651.3	795.3	857.7	970.6
Tarnów commune $[m^3/person]$	29.0	28.4	32.8	33.6	37.0
Tarnów land county $[dam^3]$	2041.3	2844.7	3281.0	3794.7	4313.3
Tarnów land county $[m^3/person]$	11.4	14.7	16.6	18.9	21.4
agriculture and forestry					
City of Tarnów $[dam^3]$	1190	1190	1190	350	350
City of Tarnów $[m^3/person]$	10	10	10	3	3
Tarnów commune $[dam^3]$	0	0	0	0	0
Tarnów commune $[m^3/person]$	0	0	0	0	0
Tarnów land county $[dam^3]$	893	690	430	430	606
Tarnów land county $[m^3/person]$	5	4	2	2	3

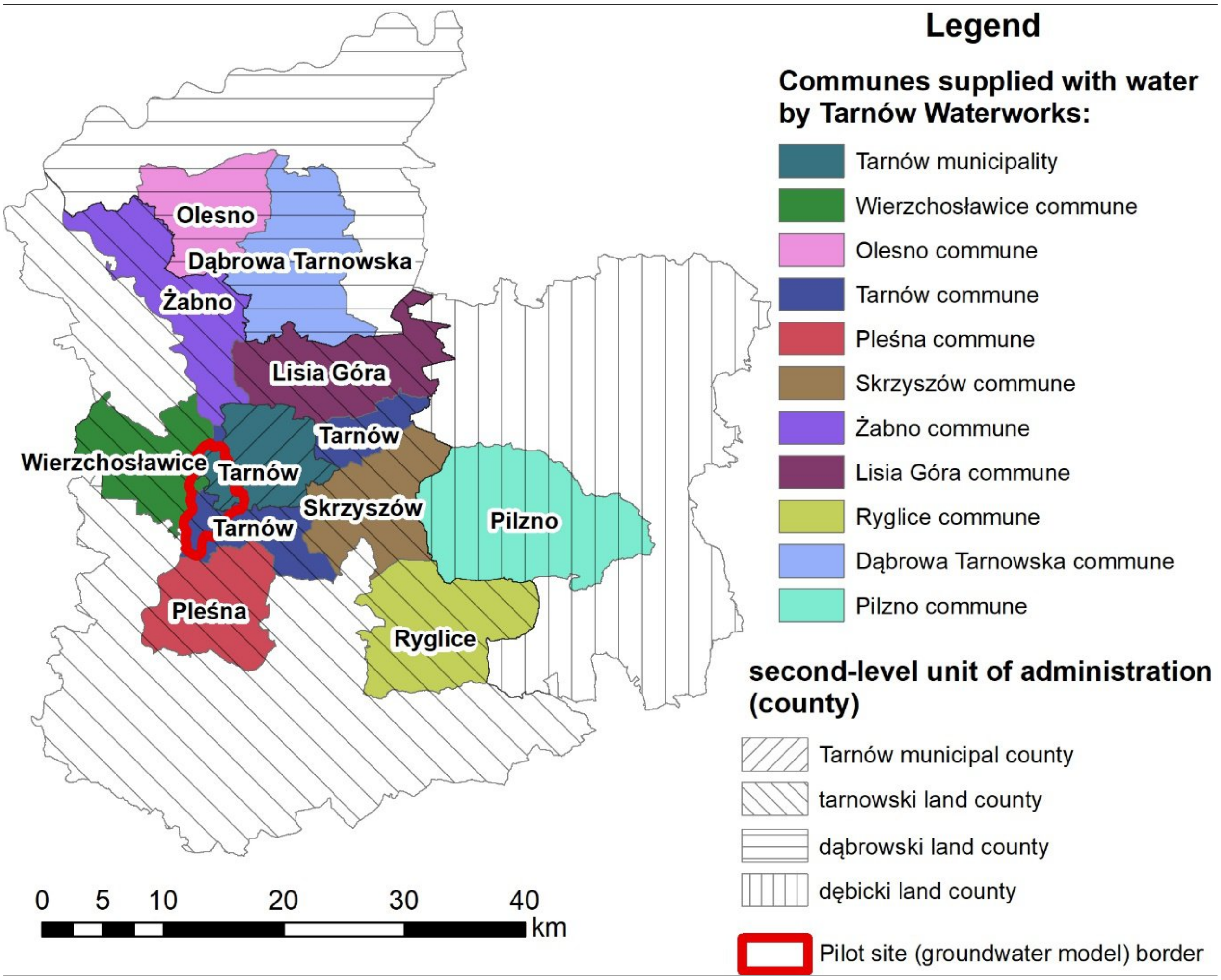


Fig. 4. 13. Municipalities supplied with water by Tarnów Waterworks.

The obtained statistical data indicate that in the entire area in question (3 administrative units jointly, i.e. the city of Tarnów and Tarnów land county together with Tarnów commune) tap water consumption in the analysed period (1998-2019) varied and fluctuated from 9.33 million m^3 in 2015 to 12.09 million m^3 (in 1998) (Table 4.7). In 2019, the consumption was 9.66 million m^3. This shows a decrease of about 2.4 million m^3 (more than 20%) between 1998 and 2019. At the same time, the population increased from 320718 to 336169 (about 5%). In the last 5 years (2015-2019), there has been a slight increase in water consumption of 0.33 million m^3 (about 3.5%). On the other hand, during this 5-year period, there was a decrease in population from 336801 to 336169 (by 632 people or about 0.2%). In the analysed period, the distribution abstraction water and the share of particular administrative units also changed. In 1998, the City of Tarnow's abstraction was 83% of the total, while in 2019 it was only 55%. At the same time, the share of Tarnów land county (including Tarnów commune) in the total regional abstraction increased from 17% to 45% (Table 4.7).

Table 4. 7. **Changes in the volume of water abstraction from the water supply system in individual administrative units in 1998, 2015 and 2019.**

Administrative unit	Water abstraction from the water supply network in millions of m^3 (% of total abstraction)			Changes in abstraction	
	1998	2015	2019	1998/2015	2015/2019
City of Tarnów	10.05 (83%)	5.54 (ca. 60%)	5.36 (>55%)	decrease by ca. 45%	decrease by ca. 3.5%
Tarnów commune	0.59 (5%)	0.86 (>9%)	0.97 (10%)	increase by >45%.	increase by ca. 13%
Tarnów land county (Tarnów commune excluded)	1.45 (12%)	2.93 (31%)	3.34 (35%)	increase by ca. 100%	increase by ca. 14%
Total	12.09 (100%)	9.33 (100%)	9.66 (100%)	decrease by ca. 23%	increase by ca. 100%

The significant changes in the abstraction structure presented here are, in part, due to changes in the population of each administrative unit (Table 4.8). Between 1998 and 2019, the city of Tarnów saw a >11% decrease in the number of residents, so that their share in the total population of the study area decreased from 38% to 32%. At the same time, the population of Tarnów land county increased by more than 12.5% and accounted for 60% of the region's population (it was 56% in 1998). During the analysed period the population of Tarnów commune also increased (by about 28%) and its share in the total population increased from 6 to 8%. A comparison of the changes in water abstraction volume and structure with the population changes indicates their relationship, but the reasons for changes in abstraction are certainly more complex and multifaceted.

Table 4. 8. **Population changes in individual administrative units in 1998, 2015 and 2019.**

Administrative unit	Population - persons (Percentage of total population)			Changes in number of residents	
	1998	2015	2019	1998/2015	2015/2019
City of Tarnów	121494 (38%)	110,644 (33%)	108470 (32%)	decrease by ca. 10%	decrease by ca. 2%
Tarnów commune	20298 (6%)	25557 (7.5%)	26202 (8%)	increase by ca. 25%	increase by ca. 2.5%
Tarnów land county	178926 (56%)	200600 (59.5%)	201497 (60%)	increase by ca. 12%	increase by ca. 0.4%
Total	320718 (100%)	336801 (100%)	336169 (100%)	increase by ca. 5%	decrease by ca. 0.2%

The overall rate of abstraction change does not correspond fully with the rate of population change. The quoted data, however, clearly show a relative stabilization of abstraction during the analysed 5-year period (2015-2019). The decrease in total water abstraction, which has been noted for several years, has been stopped. The observed increases in water abstraction in Tarnów land county and Tarnów commune are compensated by decreases in the abstraction of the city of Tarnów (Table 4.7). All the above data comes from the Statistics Poland online yearbook and represents statistics that often do not reflect the complex mechanisms regarding the structure of abstraction and the share of dispersed abstraction, which is difficult to record reliably. Important issues in the context of the project are the current volume of water abstraction by Tarnów Waterworks, the assessment of observed temporal changes in water abstraction and the forecasting of abstraction for the near future. They are particularly important given the planned extension of the well field. This well field is the primary study area for the project, where the detailed studies described in report D.T3.4.2 (DEEPWATER-CE, 2021b) were performed.

According to Tarnów Waterworks, for the last few years the volume of water sold by the company has stabilized at the level of about 8 million m^3/year, with the volume of water abstracted from all surface and groundwater sites reaching 10 million m^3/year. Of this amount 24% (2.4 m m^3/year) came from the well field.

The water abstraction from the Świerczków well field in 2020 varied from 152,854 m^3/month (5095 m^3/d) to 223,538 m^3/month (7451 m^3/d). The average water abstraction from the well field during this period was about 6,500 m^3/d. In the last 5 years, the average water abstraction has been about 6,910 m^3/d (ca. 290 m^3/h). These data indicate that, considering the maximum daily abstraction in 2020 of about 7451 m^3/d, there is currently a water abstraction reserve of about 1050 m^3/d.

It should be noted, however, that there are considerable annual fluctuations in the amount of daily water abstraction from the network, ranging from approximately 20,000 m^3/d to over 40,000 m^3/d. Assuming the maintenance of the current proportions of the percentage share of individual intakes (24% from Świerczków), with the maximum daily abstraction amounting to over 40,000 m^3/d, the water abstraction from the Świerczków well field should amount to approximately 9600 m^3/d exceeding the permissible amount of water to be drawn (8,500 m^3/d). An increased demand for water is typically recorded during the summer months, during periods of rainless weather with sustained high temperatures. Some increase in water demand during these periods is probably due to the use of water for, among other things, irrigation systems or for gardening purposes, while the record-breaking consumption, exceeding 40,000 m^3/d, observed in recent years can probably be associated with the increasing popularity of backyard swimming pools. The filling of pools taking place commonly in the first hot period of the year leads to a situation that puts the water supply system to a serious test. In this situation, the planned increase of the capacity of the Świerczków well field to about 400 m^3/h (9600 m^3/d) will increase the security of water supply for the inhabitants of the Tarnów agglomeration, especially during the peak consumption periods.

It should be added, however, that the planned extension of the well field and the increase in water abstraction to 400 m^3/h will exceed the currently permitted abstraction of 380 m^3/h. Therefore, it would be necessary to obtain a new water permit for this well field. In addition, the increase in water abstraction at the Świerczków well field must be accompanied by an expansion of the MAR system in order to significantly reduce the abstraction percentage of polluted groundwater from industrial areas.

In the future, in the area of Tarnów Waterworks operation small but constant increase in demand for water should be expected, the opening of new connections with other functioning communal water supply systems planned for the coming years will significantly improve the security of water supply in these areas which, however, already have their own water abstraction sites and supply infrastructure. A certain impulse to increase water supply by Tarnów Waterworks may be the takeover by the company of some areas where water supply is currently based on own sources of water, e.g. the area of Grupa Azoty S.A in Tarnów Mościce or the development of industrial plants where water is an important raw material for production (e.g. food industry).

The climatic data for the Tarnów region (1966-2018) clearly shows that the climate is warming up as a result of negative climate changes. The solutions proposed in the DEEPWATER-CE project consisting in additional water storage in aquifers by means of manged aquifer recharge solutions may result in mitigation of negative effects of climate change in Tarnów region and help in situations as described above where significant increase in water demand is recorded during the summer days with hot weather. The over-exploited aquifer in summer period could be recharged during the winter months when water demand is lowest using appropriate MAR methods like tested in Tarnów for example infiltration ditches.

Increases in water demand associated with climate change are also projected in longer term. Various climate change projection scenarios carried out in the DEEPWATER-CE project indicate that also in the next decades the analysed area will be exposed to increased water demand. As shown in the climate exposure maps (https://ggis.un-igrac.org/maps/2171/view) for periods 2021-2050 and 2071-2100 this exposure may be moderate (optimistic scenario) to extreme (pessimistic scenario).

There are certain changes in land use planned for the Tarnów water intake area that can potentially pose a threat to the water abstraction sites. One of such projects is the construction of a freeway connector passing through the Kępa Bogumiłowicka well field and its indirect protection zone. According to hydrogeological documentation (Cieślak et al., 2021), the main threat associated with the planned project is the possible deterioration of groundwater quality due to infiltration of contaminants from the land surface into the aquifer supplying the Kępa Bogumiłowicka well field. The Quaternary aquifer is characterized by a high susceptibility to contamination (lack of a layer isolating it from the surface and relatively shallow water table). Taking into account the possibility of contamination of the abstracted water and a temporary limitation of water abstraction from this well field, the possibility of increasing water abstraction by other water abstraction sites, including the Świerczków well field, should be taken into consideration.

Another project to be implemented in this area is the construction of a weir on the Dunajec River. The structure, however, is not expected to have a negative impact on the operating well fields. On the contrary, it may stop the bed erosion and lead to the river maintaining its current channel, as well as improve working conditions of the induced bank filtration at the Kępa Bogumiłowicka site and deep wells located here as a result of raising the river's water table.

In the Polish pilot area due to its specificity described in detail in report D.T3.4.1 (DEEPWATER-CE, 2021a) the only source of water for MAR may be the river Dunajec. To analyse the potential impact on surface water quality and quantity, particular attention was paid to the characteristic flows in the Dunajec river, from which water is pumped to the current Świerczków well field and will also be pumped to the planned extended area. The current water abstraction situation at the existing well field was also analysed. The data contained in the report D.T3.4.1 (DEEPWATER-CE, 2021a) show that the flow rate of the Dunajec river at the water gauge station Zgłobice, located at km 38+560 of the river's course, in the years 1981-2017 was: the lowest 8.80 m^3/s, average low 18.7 m^3/s, average annual mean 77.4 m^3/s, average high 882 m^3/s and the highest 2510 m^3/s. In the years 2016-2020, the lowest was 20.8 m^3/s, average 80.07 m^3/s and the highest 1030 m^3/s. The calculated base flow for the 2016-2020 period ranged from 20.8 to 124 m^3/s with a mean value of 40.44 m^3/s.

The amount of water pumped from the Dunajec river to supply the infiltration ditches at the Świerczków well field currently varies from about 3200 m^3/d (133 m^3/h) to about 4900 m^3/d (204 m^3/h). Concerning the lowest, mean and highest annual flow rate of the Dunajec river at the Zgłobice water gauge station for the period 1981-2017 and compering the highest water withdrawal to the flow rate in Dunajec it constitutes respectively: 0.64%, 0.07% and 0.002% of the river flow rate.

The already operating Świerczków well field has a water permit based on the decision of the President of Tarnów dated 13 June 2013, valid until 13 June 2033. According to the well field permit, water can be drawn at: 1) a maximum hourly volume rate of 380 m^3/h, 2) a daily average amount of 8,500 m^3/d, 3) a maximum annual volume of 3,100,000 m^3/year.

It should be noted that the aforementioned water permit refers to both groundwater and water originating from MAR (infiltration ditches and river bank filtration). If we compare the water abstractions permitted with the flow rate of the river Dunajec, we obtain proportions as described in the following.

With respect to the lowest, annual average and highest flow rate of the Dunajec River at the water gauge station Zgłobice in the period 1981-2017, the maximum hourly amount (380 m^3/h) constitutes respectively: 1.20%, 0.13% and 0.004% of the flow rate in the river. With respect to the lowest, mean annual and highest flow rate of the Dunajec River at the Zgłobice water gauge station during 1981-2017, the mean daily amount (8,500 m^3/d) represents respectively: 1.10%, 0.13% and 0.004% of the river flow rate. With respect to the lowest, mean annual and highest flow rate of the Dunajec River at the Zgłobice water gauge station during 1981-2017, the maximum annual amount (3,100,000 m^3/year) represents respectively: 1.12%, 0.13% and 0.004% of the flow rate in the river. Similar results would be obtained for the lowest, mean annual and highest flow rate of the Dunajec River at the Zgłobice water gauge station in 2016-2020.

The analysis of the potential impact on the quantity of surface water during the operation of the Świerczków MAR, led to the conclusion that it is insignificant and that the water abstraction from the Świerczków well field does not exceed 1.5% of the Dunajec flow rate in the most unfavourable variant, which will not result in adverse changes in surface water quality.

In terms of water quality in the Dunajec River according to the Regulation of the Minister of Maritime Affairs and Inland Navigation of 11 October 2019 on the classification of ecological status, ecological potential and chemical status and the method of classifying the status of surface water bodies, as well as environmental quality standards for priority substances, in terms of physicochemical elements, the water of the Dunajec River can be classified as class I and class II surface water quality, depending on the month of testing. Only nitrite nitrogen does not meet the requirements for quality class II in summer at high temperatures, then the water of the Dunajec should be classified as quality class III.

Compared to groundwater flowing from the south-eastern part of the Świerczków well field, water from the Dunajec river is characterized by much better physical and chemical parameters. First of all, its electrical conductivity, indicating salinity of water, is within the range of 254-396 µS/cm, whereas groundwater 951-1050 µS/cm in the south-eastern part and up to 1970 µS/cm in the northern part in piezometer DW3. At no sampling point does the conductivity value exceed the permissible value for human consumption (2500 µS/cm) according to the Regulation of the Minister of Health of 7 December 2017 on the quality of water intended for human consumption. The groundwater is characterized by low oxygen content, even below 1 mg/L, while the water in the Dunajec River, depending on the month, is characterized by oxygen concentrations in the range of 5.17 - 11.21 mg/L, most often above 7 mg/L.

Nitrogen compounds in the Dunajec water are also present in much lower concentrations, with ammonium nitrogen ranging from <0.01 to 0.06 mg/L, while in groundwater in the SE part of the well field from 6.4 to

9.8 mg/L, and in the N part of the well field from 0.03 to 3.7 mg/L. The maximum concentration of ammonia nitrogen acceptable for human consumption is about 0.35 mg/L, which means that most groundwater flowing into the intake does not meet the standard for $N\text{-}NH_4$. Nitrate nitrogen in the Dunajec River ranges from 0.7 to 1.73 mg/L, while groundwater in the SE part of the well field ranges from 1.9 to 4.72 mg/L, and up to 7.9 mg/L in the N part. The maximum concentration of nitrate nitrogen acceptable for human consumption is about 11 mg/L, so no monitoring point showed exceedances in this range.

Dunajec River waters are characterized by low alkalinity and Ca and Mg contents. HCO_3 concentration ranges from 124 to 193 mg/L, Ca from 39 to 59 mg/L, and Mg from 7.3 to 13 mg/L. In the groundwater on the SE side, HCO_3 concentrations vary from 369 to 464 mg/L, Ca from 110 to 140 mg/L, and Mg from 16 to 20 mg/L. Groundwater in the N side of the intake has HCO_3 concentrations ranging from 315 - 442 mg/L, Ca from 99 to 246 mg/L, and Mg from 15 to 33 mg/L.

A distinct difference in chemical composition can be seen in the Cl concentrations. In the Dunajec river concentrations of Cl ranged from 10 to 27 mg/L, whereas in groundwater flowing into the well field from the SE side concentrations ranged from 40 to 145 mg/L. In the N part of the well field chloride concentrations were the highest, ranging from 119 to 368 mg/L. The permissible concentration of chloride in drinking water is 250 mg/L, which means that in the northern part of the well field area this parameter does not meet the requirements at several monitoring points. Also, Na concentrations are the highest in groundwater in the N part of the Świerczków well field, ranging from 81 to 288 mg/L. In the SE part of the well field, Na concentrations did not exceed 80 mg/L, while the Dunajec River waters have low Na concentrations, ranging from 8.2 to 13 mg/L. The permissible concentration of sodium in water intended for drinking is 200 mg/L, so exceedance of permissible concentrations in groundwater was noted only in the N part of the intake.

Similar pattern has been observed for sulphate; water from the Dunajec River was characterized by concentrations ranging from <5 to 20 mg/L, while groundwater in the SE part of the well field contained concentrations ranging from 42 to 128 mg/L, and in the N part of the well field SO_4 occurred in concentrations ranging from 85 to 180 mg/L. At no sampling point sulphate concentrations exceeded the drinking water limit (250 mg/L).

Taking into account the flow rate and quality parameters of water in the Dunajec River, it can be concluded that its use as a source of groundwater recharge at the MAR facilities in a quantity similar to that at the Świerczków well filed will not cause any significant quantitative or qualitative changes in the river, but will improve the quality of groundwater quantity.

4.4. Hydrogeological and aquifer characteristics

In order to carry out MAR feasibility studies for the two tested MAR methods, i.e. induced bank filtration and ditches, it is necessary to precisely determine geological and hydrogeological conditions of the aquifer and the overlying sediments. In the DEEPWATER-CE project, at the Polish pilot site it was done and describe in two reports D.T3.4.1 (DEEPWATER-CE, 2021a) and D.T3.4.2 (DEEPWATER-CE, 2021b). The former report is based on analyses of archival material and the latter describes the necessary field investigations carried out for the MAR feasibility study.

Recognition of the investigated geological framework and hydrogeological parameters characterising aquifer storage and groundwater flow dynamic are an important part affecting the efficiency and success of MAR implementation projects. Therefore, the following field research was conducted as part of the MAR feasibility study research at the Polish pilot site.

Geophysical survey

The first geological investigation conducted at the pilot site was a geophysical survey using an ERT (Electrical Resistivity Tomography) method for better recognition of geological and hydrogeological conditions and for the purpose of establishing a new monitoring network of a shallow Quaternary aquifer (Fig. 4.14).

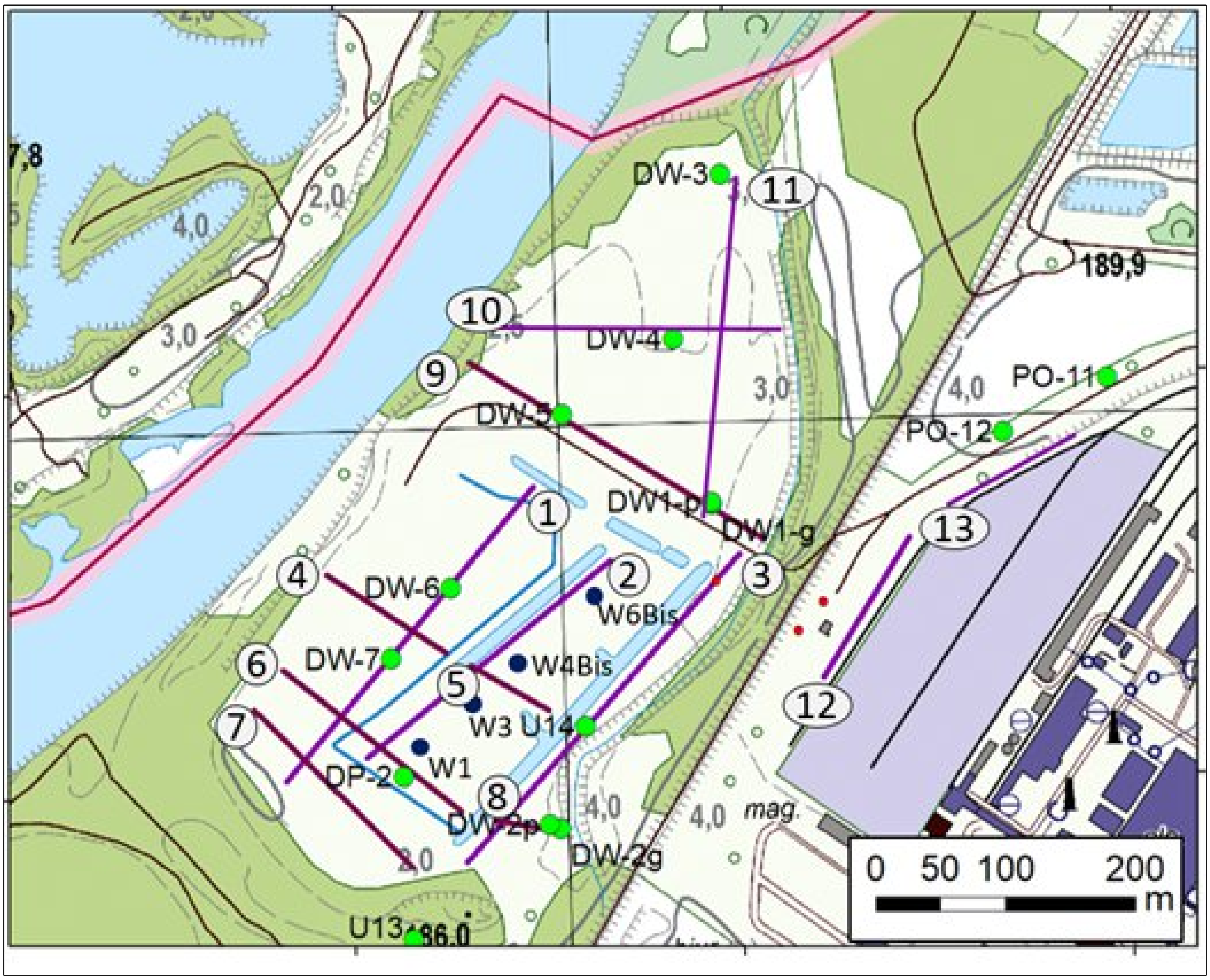


Fig. 4. 14. Location of 13 profiles obtained using electrical resistivity tomography (purple lines). Green dots represent location of the observation wells. Light purple area represent coal storage yard.

Thirteen ERT profiles, from 54 m up to 315 m in length, depending on the area's geometry, were carried out during the fieldwork in December 2019 (ERT1-ERT8), January 2020 (ERT9, ERT 12) and September 2021 (ERT_10-11, ERT_13) (Table 4.9).

Table 4. 9. **Parameters for field data acquisition for ERT survey.**

Profile no.	Data points	RMS (%)	Depth of penetration (m)	Profile length (m)
ERT_1	859	6.2	23.6	290
ERT_2	774	4.3	23.6	240
ERT_3	1035	2.8	23.6	315
ERT_4	330	3.0	23.6	110
ERT_5	158	3.0	12.9	66
ERT_6	546	2.6	23.6	171
ERT_7	539	2.7	23.6	171
ERT_8	112	2.4	9.56	54
ERT_9	872	3.6	23.6	260
ERT_10	702	1.8	23.6	216
ERT_11	818	2.7	23.6	260
ERT_12	325	3.7	23.6	120
ERT_13	329	2.4	23.6	120

ERT_1 – ERT_8 were carried out in the southern part of the research area (existing MAR site, Fig. 4.14, Fig. 4.15) and ERT_9-ERT_11 were performed in the northern part (the area of the potential MAR, Fig. 4.14, Fig. 4.16). ERT_12 and ERT_13 were conducted at the border between the coal storage yard and the surrounding soil in order to determine the effect of coal storage pile on soils and groundwater in the vicinity of the CHP plant (Fig. 4.14, Fig. 4.17) belongs to the Grupa Azoty S.A. nitrogen plant.

Detailed description of geophysical survey results are presented in chapter 4.1.1, report D.T3.4.2 (DEPWATER-CE, 2021b). Here we would like to present selected examples of created profiles in order to demonstrate the usefulness of the ERT method for determining the geometry and thickness of the aquifer. Knowledge of the size and thickness of the aquifer is essential for estimating the storage capacity of the reservoir, which may determine the viability of MAR.

With ERT profiles we were able to better identify the thickness of the areation and saturation zone (Table 4.10). In addition, the ERT method proved to be useful in defining a zone of elevated electrical conductivity, which indicates the presence of a zone of contaminated water in the area close to the coal storage yard (Fig. 4.14) .

Table 4. 10. Parameters of the unsaturated and saturated zones based on the ERT cross-sections.

Profile no	Depth of the unsaturated zone (m)	Thickness of the saturated zone (m)	Depth of the aquitard (m)	Maximal depth (m)	Profile length (m)
ERT_1	3.5-5	5.5-7	9-13	23.6	290
ERT_2	4-5	5-7	9-12	23.6	240
ERT_3	4	5-7	9-12	23.6	315
ERT_4	3-5	3-5	9-13	23.6	110
ERT_5	3-5	3-6	9-11	12.9	66
ERT_6	3-5	4-7	12-15	23.6	171
ERT_7	3-5	4-7	11-13	23.6	171
ERT_8	2-4	5	8-9	9.56	54
ERT_9	4	4-7	12-15	23.6	260
ERT_10	2-4	5-7	11-12	23.6	216
ERT_11	2-4	4-7	11-12	23.6	260
ERT_12	-	-	12-14	23.6	120
ERT_13	-	-	12-13	23.5	120

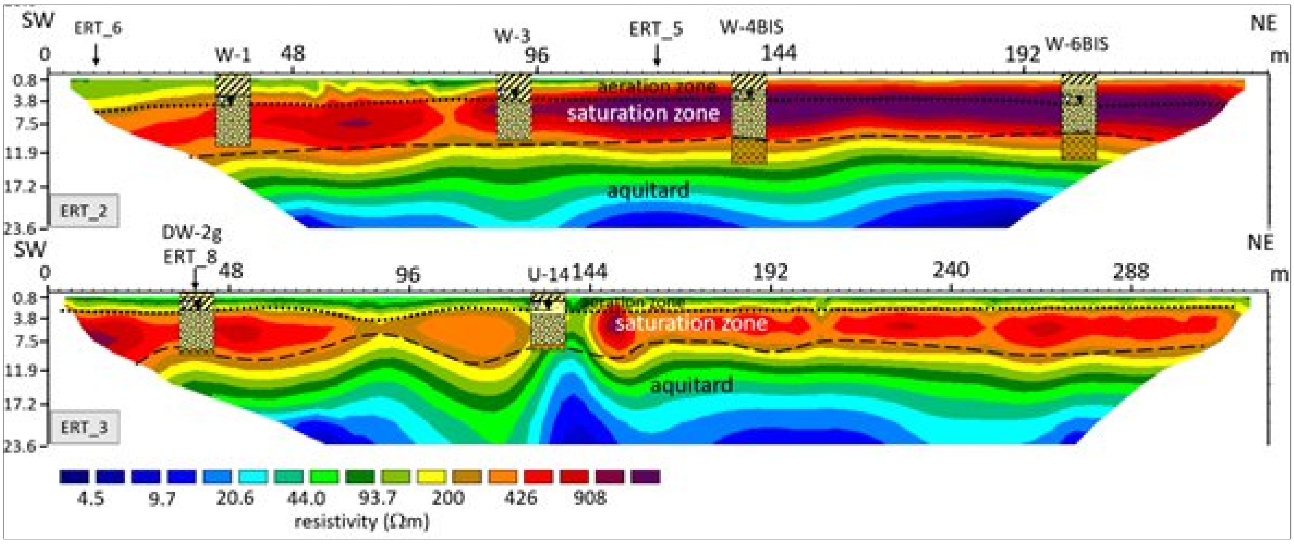


Fig. 4. 15. Inversion results of ERT_2 and ERT_3 measurements and shallow boreholes conducted near ERT profiles at existing MAR site. For all ERT profiles the dotted line indicates the boundary between the unsaturated and the saturated zone; the dashed line indicates the boundary between the saturated zone and the aquitard. The hatched areas on the shallow boreholes from the top signify respectively for: W-1 (soil, sandy loam, sand with gravel and pebbles); W-3 (sandy loam, sandy gravel and pebbles); W4BIS (silt, medium sand, coarse gravel with pebbles, silt), W6Bis (silt, fine sand, coarse gravel with pebbles, silt); DW-2g (soil, sandy loam/sandy silt; saturated gravel with pebbles and coarse sand, silty clay); U-14 (soil, silty loam; fine sand; saturated gravel with pebbles; silty clay).

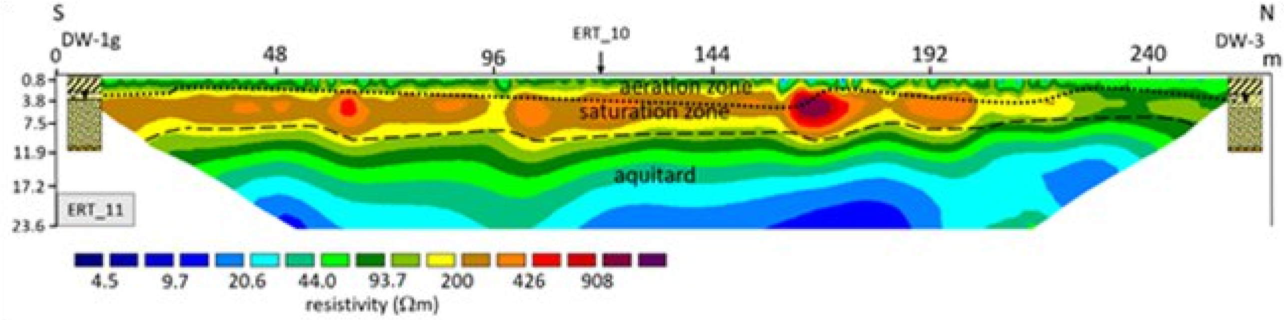


Fig. 4. 16. Inversion results of ERT_11 measurements and shallow boreholes conducted near ERT profiles at the potential MAR site. The hatched areas on the shallow boreholes from the top signify respectively for: DW-1g (soil, silt/sandy silt, loamy sand layered with pebbles, saturated gravel and pebbles with coarse sand, silty clay); DW-3 (soil, silt, loamy gravel with pebbles, saturated gravel with pebbles and coarse sand, clay).

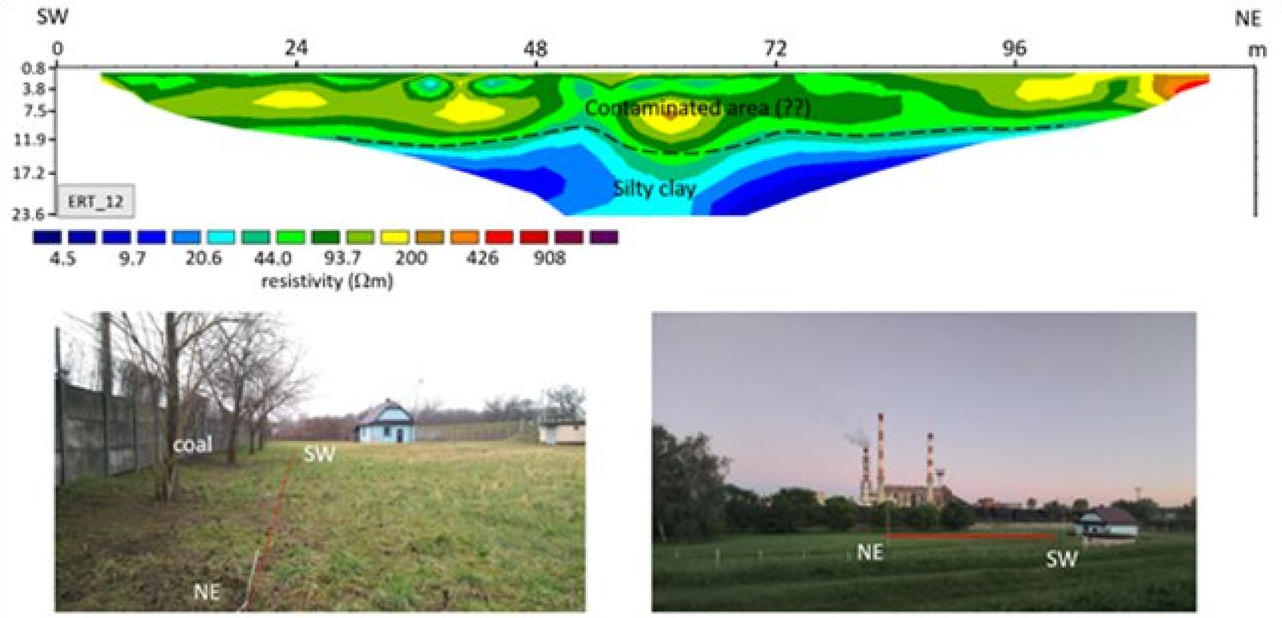


Fig. 4. 17. Inversion results of ERT_12 measurements conducted on the boundary with a coal storage yard of Grupa Azoty S.A.

Drillings

Hand drilled boreholes have been completed for more detailed identification of properties: 1) aeration zone deposits and 2) ash from the reclaimed waste disposal located to the south of the MAR site.

Near-surface sediment samples (areation zone)

Collected near-surface sediments (Fig. 4.9) were used to calculate the time of vertical seepage through the aeration zone, in the northern part of the pilot site and thus assess the natural potential of the near-surface sediments for natural groundwater recharge from precipitation. This can indirectly provide information on groundwater vulnerability to surface pollution. Vulnerability of the Quaternary aquifer was assessed by calculating the mean residence time of water (MRT), by evaluating results using vulnerability classes for the uppermost aquifer (Herbich, Skrzypczyk, 2008) and mapping obtained points. As a result of this work, Fig. 4.18 presents the northern part of well field (orange), indicating high vulnerability (MRT<10 years) of the Quaternary aquifer to contamination coming from the surface. This information gives an outline of the situation in terms of a threat to an aquifer exploited by the wells. It can be concluded that the potential expansion of MAR to this area has a high degree of vulnerability to surface contamination and, therefore, should be taken under special consideration in order to protect it against the risk of contamination. The isolation through poorly permeable formations is not sufficient enough to fully protect groundwater (Bugla, 2021).

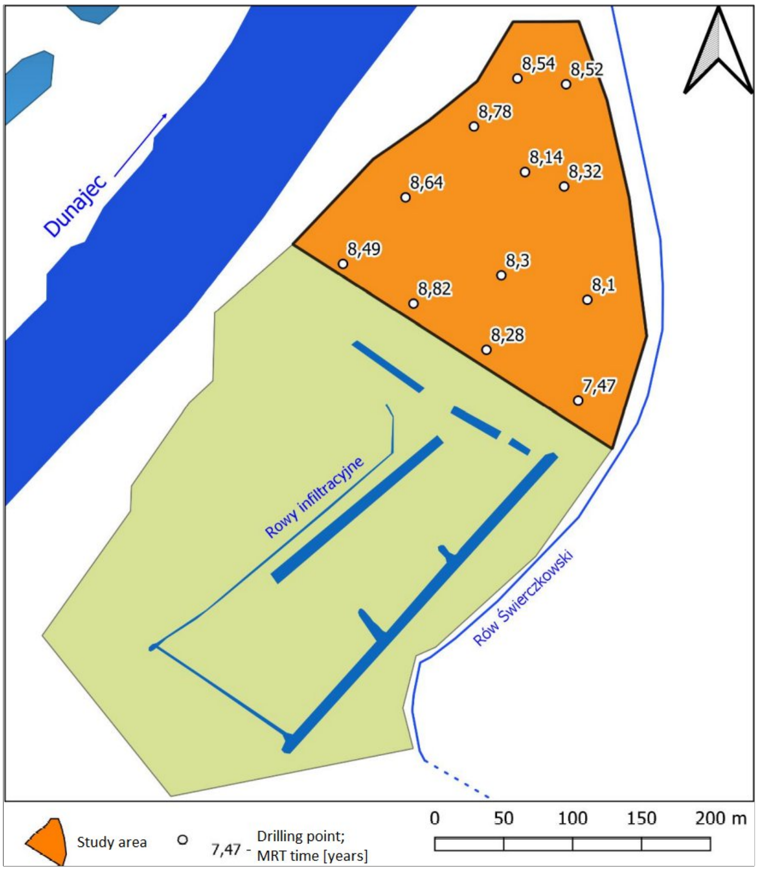


Fig. 4. 18. Calculated vertical seepage times (mean residence time of water MRT) through the unsaturated (vadose) zone in the northern part of the pilot site, as part of an engineering thesis (Bugla, 2021).

Ash samples

The Polish pilot area, unlike the other pilot areas in the DEEPWATER-CE project, is located in the vicinity of industrial zone. One of the hazards that may have a negative impact on groundwater quality is fly ash deposited in old post-mining pits north and south of well field. In order to collect fly ash samples from the waste disposal site located to the south of the pilot area, 3 shallow boreholes were drilled (Fig. 4.9). The first borehole did not show the presence of wastes, however ashes were present at the second borehole, with a thickness of about 1.1 m (a layer of sands was drilled below), and in the third borehole a layer of ash with a thickness of >2.1 m was found. The simplified logs are presented in Table 4.11.

Table 4. 11. **Simplified logs and coordinates of boreholes drilled to take fly ash samples.**

Sample no.	Geographical coordinates	Geological profile [m bgl]
1	50°1'40,33632"N; 20°53'51,08568"E	0-0,5 sands; 0,5-1,25 sands and gravels
2	50°1'36,02964"N; 20°53'43,26288"E	0-0,3 sands; 0,3-1,4 ash of grey colour; >1,4 sands and gravels
3	50°1'34,60343" N; 20°53'42,6804"E	0-0,4 sands; 0,4-2,5 ash, of grey colour and liquid phase in the bottom

Results of analytical research (determination of selected parameters of chemical composition and performance of batch leaching tests) are summarized in the following for soil samples (Table 4.12) and for ash samples (Tables 4.13-16). The chemical composition in soil samples is dominated by silicates and aluminium silicates. The content of trace elements for soils, expressed in ppm, is presented in Table 4.14.

The main leaching component is calcium, with concentrations of 170-208 mg/kg dry mass [DM]. The second most soluble element is Mg, leaching at amounts about ten times lower. Of the other analysed components, Al, Ba and B are characterized by the high elution. No leaching of Cd, Hg and Sn was found. The chemical composition of the analysed fly ash waste is dominated by silicates and aluminosilicates. The content of selected heavy metals in the investigated fly ash is presented in the Table 4.14.

Table 4. 12. **Leaching of selected chemical elements from soil samples in the Świerczków well field.**

Analyte	Ca	Mg	Na	K	Cr	Ba	Al	B	Ni	Co	Mo	Cu	Pb	Zn	As
unit	mg/kg DM				μg/kg DM										
mean	188,6	25,9	3,7	10,4	11,4	174,9	744,3	115,7	5,7	0,6	7,0	64,7	10,9	109,1	14,0
min	170,4	17,1	2,4	4,2	8,0	122,0	360,0	90,0	2,0	0,2	3,0	36,0	5,0	20,0	9,0
max	208,1	33,7	6,4	22,5	17,0	278,6	2050,0	180,0	10,0	1,3	11,0	94,0	25,0	544,0	22,0
stand. dev.	11,4	5,6	1,3	6,2	3,2	49,7	586,5	29,9	3,0	0,4	3,1	23,9	6,7	192,2	4,8

Table 4. 13. **Chemical composition of ashes deposited in the neighbourhood of the Świerczków well field.**

Analyte	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
Unit	%	%	%	%	%	%	%	%	%	%	%
mean	51,66	26,47	5,91	2,15	2,23	0,64	2,97	1,02	0,40	0,07	0,02
min	50,51	23,51	5,59	2,05	1,86	0,55	2,77	0,95	0,32	0,06	0,02
max	53,10	27,44	6,17	2,24	3,08	0,81	3,06	1,06	0,45	0,09	0,03
standard deviation	0,99	1,66	0,28	0,09	0,49	0,10	0,12	0,04	0,05	0,01	0,00

Table 4. 14. **Contents of selected trace elements in fly ashes deposited in the neighbourhood of the Świerczków well field.**

Analyte	Cr	Ba	Co	Sn	Mo	Cu	Pb	Zn	Ni	As	Cd	Hg
Unit	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM
mean	83,47	1072,6	27,28	7,00	0,86	33,12	22,42	47,00	23,14	25,22	0,20	0,25
min	78,68	929,0	25,90	7,00	0,50	29,70	17,60	37,00	21,00	21,10	0,20	0,19
max	88,95	1174,0	28,50	7,00	1,40	42,70	29,20	61,00	27,40	29,10	0,20	0,32
stand. dev.	4,59	96,6	1,04	0,00	0,35	5,41	4,32	9,17	2,50	3,36	0,00	0,05
limit value*	300	300	30	30	30	150	100	300	100	20	3	3
limit value**	500	600	50	50	50	300	300	500	200	50	5	5

*for soils with a permeability > 10^{-7} m /s, located in agricultural and forest areas, ** for land with a permeability <10^{-7} m/s, located in agricultural and forest areas.

Based on batch leaching tests, various amounts of pollutant loads were found in the fly ash deposited in the vicinity of the Świerczków well field. Ca and SO_4 are two dominant ions. The load of leached sulphate is close to the limit value for non-neutral and non-hazardous waste (Table 4.15).

Table 4. 15. Leachability of selected elements from fly ashes deposited in the neighbourhood of the Świerczków well field [mg/kg DM].

Sample name	Ca	Mg	Na	K	SO_4
2/1	198,3	59,3	12,1	35,7	270
2/2	449,1	7,7	24,7	128,9	990
3/1	129,4	40,92	9,381	13,37	119,8
3/3	58,84	114,7	17,88	67,83	179,8
3/4	302,4	15,4	17,3	86,9	630
limit value for neutral wastes*	- -	- -	- -	- -	1000

* on the basis of the regulation of Journal of Laws.2015, Item. 1277

Calculated masses of leached components in waste (ash) samples show that due to the leaching of As, Sb and Se, it is not possible to consider the waste as posing no threats to the environment. At the same time, the magnitude of loads being washed out is very low, compared to the limit values (Table 4.16), indicating that they are non- hazardous waste (Table 4.16).

Table 4. 16. Leachability of selected trace elements from fly ashes deposited in the neighbourhood of the Świerczków well field [μg/kg DM].

Sample name	As	Ba	Cr	Cu	Mo	Pb	Sb	Se	Zn
2/1	170	783	42	81	339	7	140	85	36
2/2	237	682	10	9	93	2	244	246	6
3/1	361	971	52	5	35	3	112	25	2
3/3	510	857	26	4	91	3	134	269	
3/4	196	845	96	7	65	2	93	87	10
limit value for neutral wastes*	500	20000	500	2000	500	500	60	100	4000
limit value for other than neutral and other than hazardous wastes*	2000	100000	10000	50000	10000	10000	700	500	50000

* on the basis of the regulation of Journal of Laws 2015, Item 1277

Analyses showed a clear release of other components as well: Al (up to 30.2 mg/kg dm), B (up to 33.08 mg/kg dm), Li (0.789 mg/kg dm), Si (21.998 mg/kg dm), Sr (6.277 mg/kg DM) and V (1.386 mg/kg DM).

These listed ingredients are not included in the regulation of Journal of Laws 2015, Item 1277.

The conducted studies indicate that the waste located in the vicinity of the Świerczków well field may constitute a real threat to the soil and water environment. For this reason, a sheet piling separating the landfill of fly ashes from the wells is of key importance for the protection of the well field.

Collection of sediments from ditches beds

From the point of view of MAR efficiency, one of the most common problems with the infiltration ditch MAR method is clogging. The cause of this process can be physical, chemical, biological or any combination of these. The effect is a continuous reduction of infiltration rate of recharge water from the ditch beds into aquifer. Therefore, in September 2020, 8 sediment samples were collected from the beds of four infiltration ditches, using two types of samplers: Van Veen sampler and Dutch auger.

Sediments collected from the bottom of the infiltration ditches were subject to laboratory analyses in order to determine grain size distribution. The results of laser measurements carried out on samples no. 1-8 are presented in Fig. 4.19. The grain size of 10 - 45 µm is the most abundant and it reaches almost 50%. The 5 - 10 µm grain size is the second most abundant one.

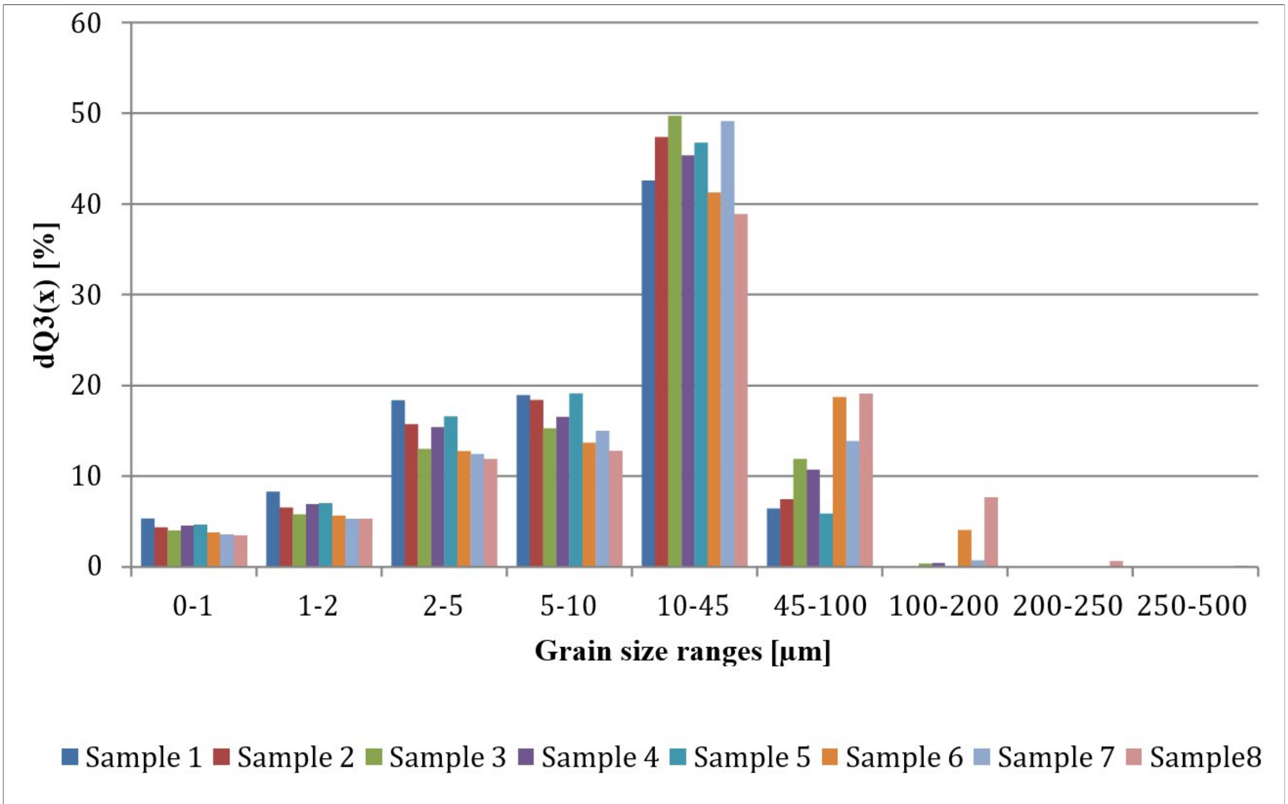


Fig. 4. 19. **Percentage grain content of sediment samples from the bottom of infiltration ditches, determined with a laser particle analyser.**

By means of pipette analysis, it was possible to classify the sediment samples no. 1-8 as loams, silty loams and silty clays. Sediments show medium and high cohesion for loams and the highest cohesion for clays.

Results of the chemical and mineralogical analyses of the sediments from the

ditches

The chemical composition of the sediments collected from the bottom (Tables 4.17-18) of the infiltration ditches is dominated by silicates and aluminosilicates.

Table 4. 17. **Chemical composition of samples taken from the bottom of the infiltration ditches.**

Analyte	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
Unit	%	%	%	%	%	%	%	%	%	%	%
mean	68,15	11,74	4,10	1,62	2,28	1,40	2,15	0,69	0,16	0,07	0,02
min	61,61	9,67	3,16	1,14	0,90	1,12	1,78	0,53	0,12	0,03	0,01
max	76,44	13,35	4,76	1,95	3,60	1,62	2,44	0,77	0,19	0,16	0,02
standard deviation	6,20	1,51	0,68	0,35	1,03	0,19	0,29	0,09	0,03	0,04	0,00

Table 4. 18. **Content of selected trace elements in the bottom sediments from the infiltration ditches.**

Analyte	Cr	Ba	Ni	Co	Sn	Mo	Cu	Pb	Zn	As	Cd	Hg
Unit	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM
mean	55,2	367,8	45,3	11,7	2,6	0,4	22,3	16,1	69,8	4,8	0,3	0,1
min	41,1	323,0	29,0	8,1	2,0	0,3	15,7	10,8	43,0	4,0	0,2	0,0
max	61,6	420,0	62,0	14,7	3,0	0,5	27,7	20,6	87,0	5,6	0,4	0,1
standard deviation	7,2	29,3	11,3	2,6	0,5	0,1	5,1	3,9	17,0	0,6	0,1	0,0
limit value */**/***	150-300-500	200-400-600	100-150-300	20-30-50	10-20-40	10-25-50	100-150-300	100-250-500	300-500-1000	10,0	2-3-5	2-4-5

*/**/*** - light and very light soils with a FG02 fraction content of 10-20%/ medium and heavy soils with a FG02 fraction content greater than 35%/heavy mineral soils with a FG02 fraction content greater than 35%.

The sampling method influenced concentration of the eluted components - in the case of main ions, the samples from the Van Veen sampler are characterized by greater leaching. For example, the leachability of Ca and SO_4 in the probe samples is 328-574 and 88-539 mg/kg DM (dry mass), respectively, while the leachability of these ions from the hand probe is 167-179 and 61-90 mg/kg DM, respectively. The mean values for the main ions are presented in the Table 4.19.

Table 4. 19. **Leachability of main ions and silica from sediments collected from the infiltration ditches of the Świerczków well field [mg/kg DM].**

Analyte	Ca	Mg	Na	K	Cl	SO_4	SiO_2
Unit	mg/kg DM						
mean	364,5	54,92	22,93	23,47	34,69	247,41	43,30
min	167,3	23,51	13,73	8,879	19,98	60,54	8,01
max	574,6	87,21	42,29	39,82	49,4	539,46	95,25
standard deviation	141,9	22,96	9,491	9,962	20,8	168,8757	30,34

The concentrations of selected trace elements eluted from the sediments are presented in the Table 4.20.

Table 4. 20. **Leachability of trace elements from bottom sediments collected from the infiltration ditches of the Świerczków well field [µg/kg DM].**

Analyte	As	B	Ba	Br	Cd	Co	Cr	Cu	Mo	Ni	Pb	Sn	Zn	Al
Unit	µg/kg DM													
mean	39	327	689	204	2	3	18	135	15	28	20	3	172	314
min	8	160	196	70	1	0	10	37	11	4	8	2	50	110
max	81	470	1025	603	5	10	34	341	20	81	35	6	438	1033
standard deviation	25	103	287	179	2	3	9	104	3	29	9	3	130	303

The results of a mineralogical analysis of sediments from the ditches by XRD method are presented in Figure 4.20.

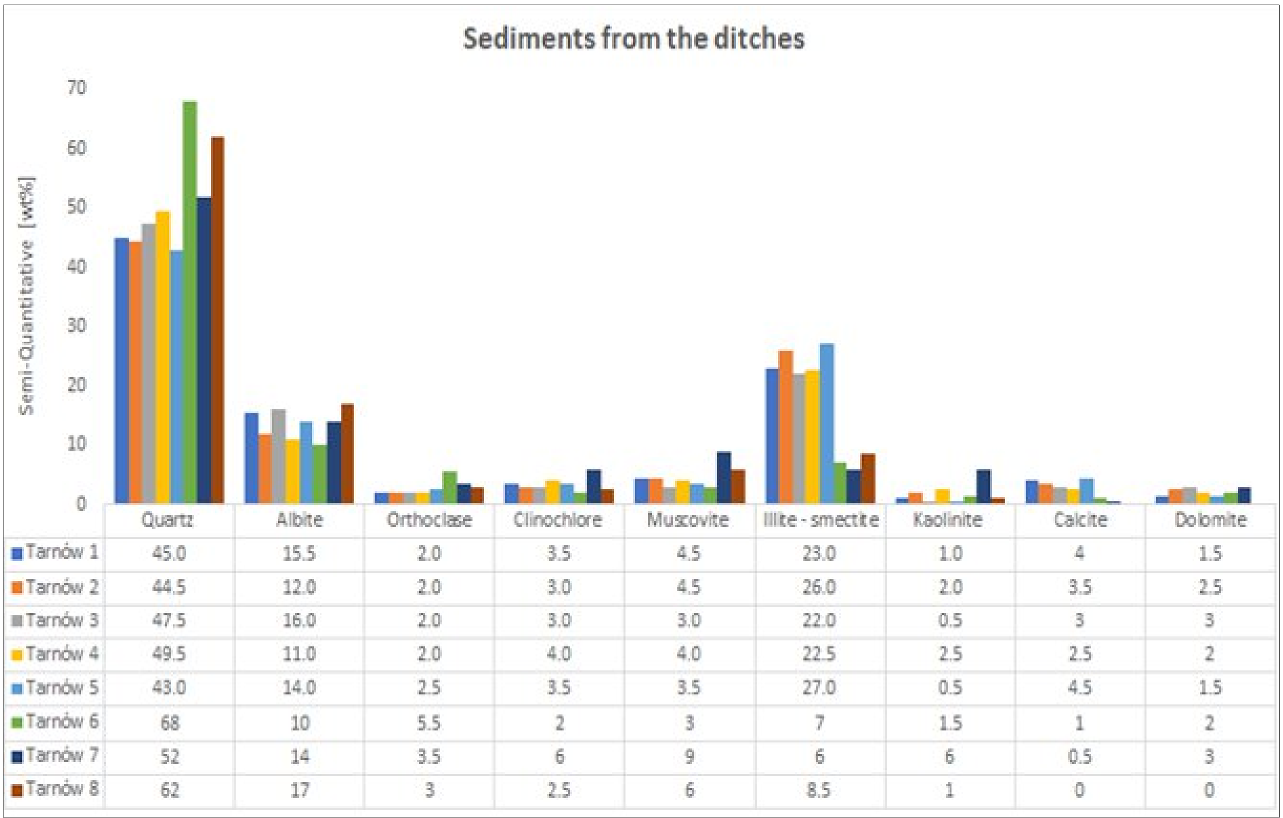


Fig. 4. 20. **Results of XRD mineralogical analysis of 8 samples of bed sediments from the ditches.**

The results show the dominance of Quartz in the mineralogical composition of all bed sediments from infiltration ditches (ranging from 43 to 68 wt%). High contents of Illite - smectite have been observed in samples 1-5 (ranging from 22 to 27 wt%). The third mineral present in relatively high content was Albite (from 10 to 17 wt%). It is interesting that carbonate minerals (Calcite and Dolomite) were found in almost all samples (reaching 4.5 wt%).

Drilling of new observation wells

All the geological works, such as the installation of new piezometers, purification pumping as well as reclamation of the area, were performed in March 2021. A summary of technical features of installed piezometers are shown in Table 4.21.

Table 4. 21. Technical features of new piezometers installed in March 2021.

Piezometer name	X coordinate [EPSG:2180]	Y coordinate [EPSG:2180]	Design depth [m]	Depth achieved [m]	Well screen [m bgl]
DW-1p	242001,38	636316,92	8,00	8,00	6,0 - 7,0
DW-1g	242002,73	636317,03	12,50	10,50	8,5 - 9,5
DW-2p	241749,82	636190,67	6,50	6,50	4,5 - 5,5
DW-2g	241750,49	636192,14	12,00	9,00	7,0 - 8,0
DW-3	242253,20	636319,88	10,50	11,00	6,0 - 10,0
DW-4	242128,58	636284,37	10,50	10,50	5,5 - 9,5
DW-5	242070,94	636198,88	10,50	11,50	6,5 - 10,5
DW-6	241934,01	636114,64	12,00	11,00	4,0 - 10,0
DW-7	241880,12	636068,93	12,00	11,00	4,0 - 10,0
Total [m]	-	-	94,50	89,00	-

Based on the hydrogeological profiles of observation wells, a hydrogeological cross-section was prepared (Fig. 4.21). The line of geological cross-section is marked on Fig. 4.9.

Mineralogical analyses of fine fractions obtained from sediment samples from new piezometers were performed using the XRD method (X-ray powder diffraction). As a result of the experiments, for each sample an X-ray diffraction pattern was obtained, showing the diffraction of X rays on the crystal lattice of minerals present in the sample. Due to its unique structure, each mineral shows a characteristic set of diffraction lines, which can be considered as a fingerprint. The calculations carried out with the HighScore + program, which allowed for a qualitative and semi-quantitative analysis of the mineral composition.

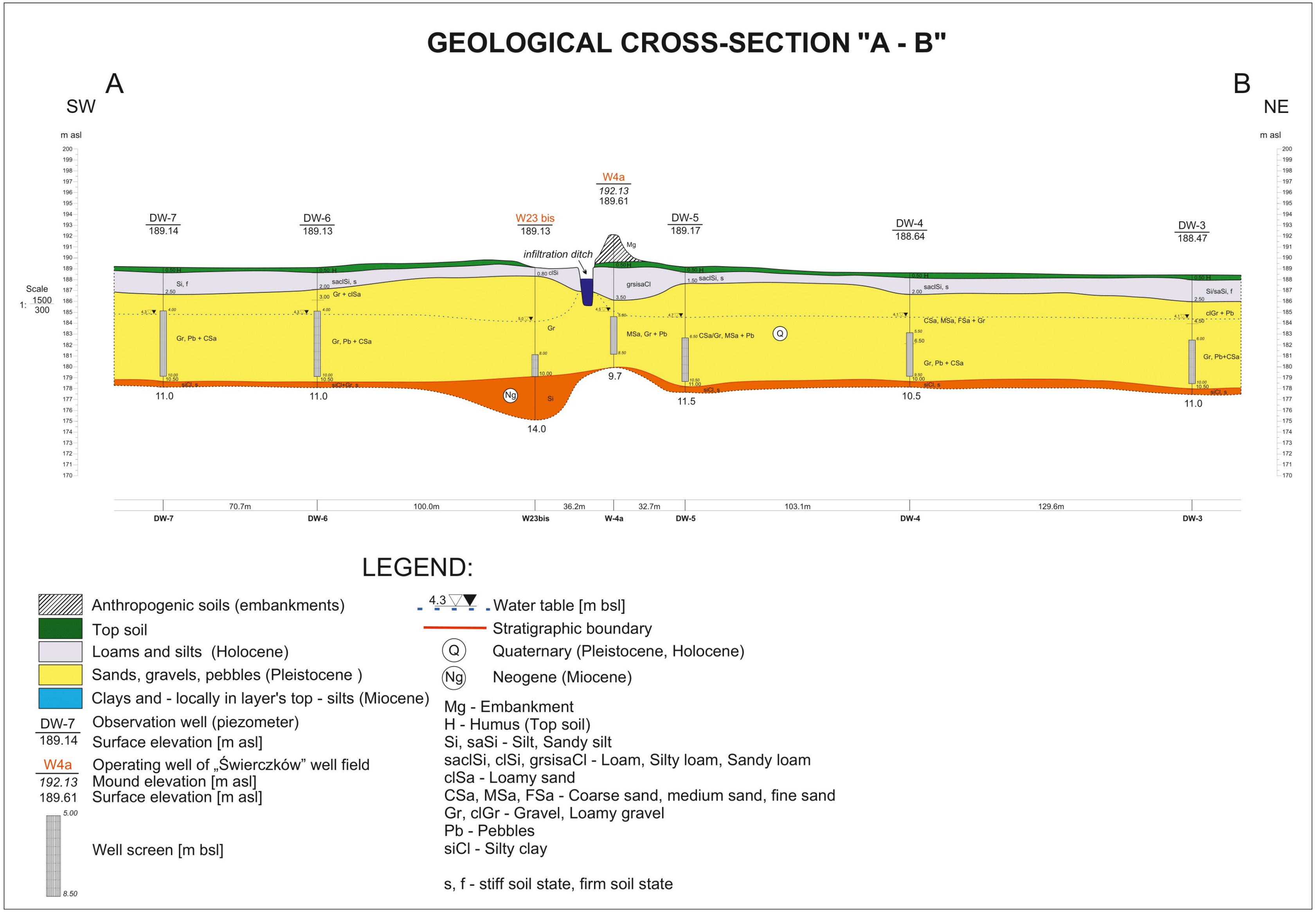
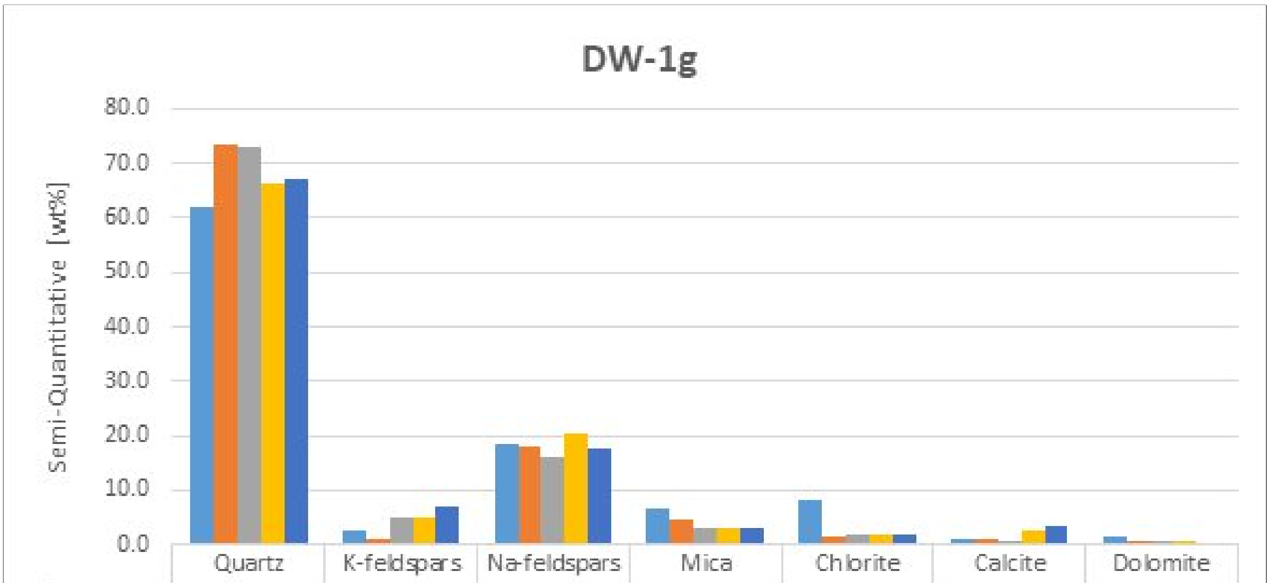


Fig. 4. 21. Geological cross-section “A-B” through the well field based on data collected during drilling new piezometers.

All samples are characterized by a similar mineral composition, with relatively small quantitative differences. The main mineral phase is quartz, which is marked on the diffraction patterns by all diagnostic peaks. The strongest quartz peak is present at 31°2Theta. The feldspar peaks of both potassium (microcline, orthoclase) and sodium (mainly albite) varieties are very well visible on the obtained scans. In the low angles range, reflections of layered silicates represented by chlorites (clinochlore) and mica (muscovite) were observed. Chlorite peaks show broadening and are asymmetric, which may be the result of mixed layer structures with smectite interlayers. In some samples, the presence of carbonate minerals - calcite and dolomite - is visible. The main peaks (3.035 Å for calcite and 2.877 Å for dolomite) are well marked on the diffraction patterns.

The example of quantitative mineral composition calculated by the Rietveld method is presented in Figure 4.22. Correlation in the mineral composition was observed depending on the depth and grain size distribution of the samples, i.e. the presence of fine or coarse fractions in the grain framework. Samples from smaller depths, characterized by a predominance of fine fractions (silt and clay), show higher contents of clay minerals, and lower contents of quartz and K-feldspar.

Accessory minerals do not appear on the obtained scans because their amount does not exceed 1% by weight. For a low concentration, even the main peaks of these minerals do not stand out from the background, which makes their determination by XRD impossible. Depending on the type of a given phase, the detection limits vary from 1.0% to 0.3% by weight for the measurement conditions used.



	Quartz	K-feldspars	Na-feldspars	Mica	Chlorite	Calcite	Dolomite
0,5-1,5	62.0	2.5	18.5	6.5	8.0	1.0	1.5
1,5-2,5	73.5	1.0	18.0	4.5	1.5	1.0	0.5
2,5-4,0	73.0	5.0	16.0	3.0	2.0	0.5	0.5
4,0-6,0	66.5	5.0	20.5	3.0	2.0	2.5	0.5
9,0-10,0	67.0	7.0	17.5	3.0	2.0	3.5	0.0

Fig. 4. 22. Quantitative mineral composition of samples taken at different depths (0,5 to 10 m b.g.l.) from the drilling core of DW-1g piezometer.

Hydrogeological investigations

Water table measurements

Figure 4.23 shows water level recordings in groundwater wells (atmospheric pressure-compensated), ditch N and the Dunajec river (the latter data were obtained from the Tarnów Waterworks). For each groundwater well, monthly measurements (using an electric water level meter) are compared to hourly data logger measurements. These results were used, among others, to create a water table contour map of the pilot site (Fig. 4.24).

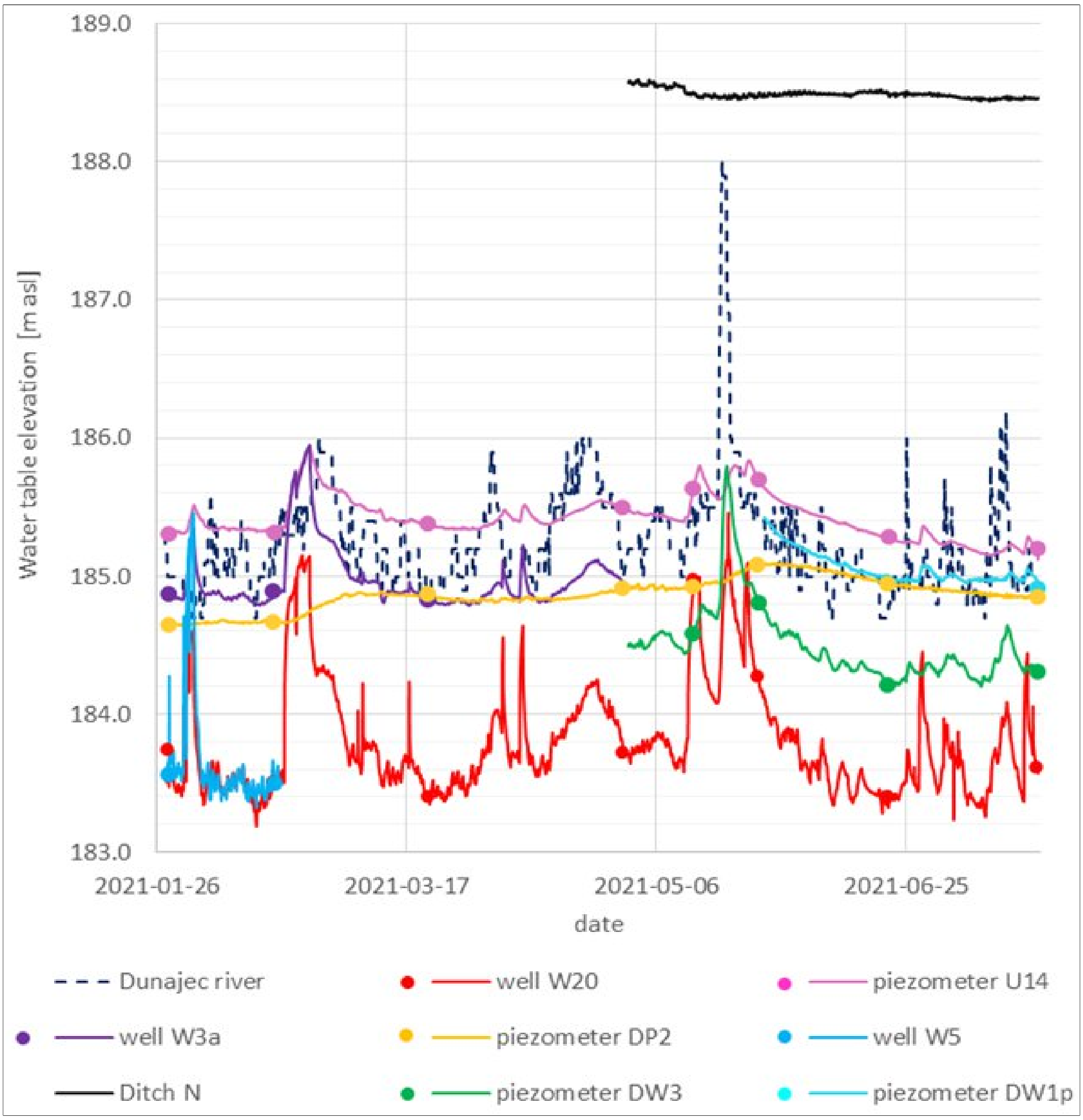


Fig. 4. 23. Water table elevation for selected observation points. Comparison of manual measurements (dots) with data from dataloggers (lines).

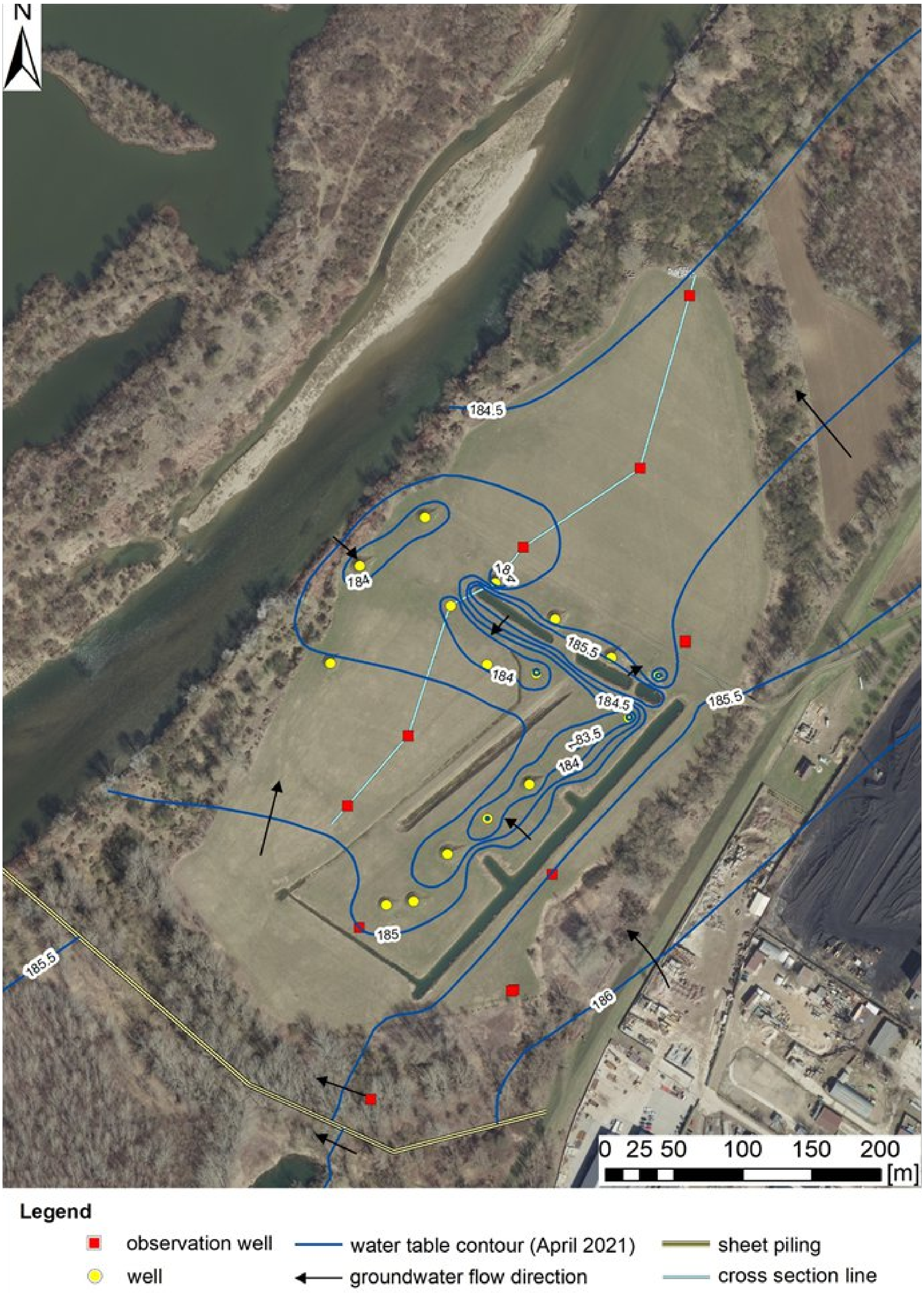


Fig. 4. 24. Groundwater table contour map of the pilot site based on model results and field measurements.

Apart from the water table, each data logger measured water temperature (Fig. 4.25), and three of them also measured electrical conductivity EC (Fig. 4.26). In addition, Fig. 4.25 presents water temperatures of the Dunajec river, obtained from Tarnów Waterworks.

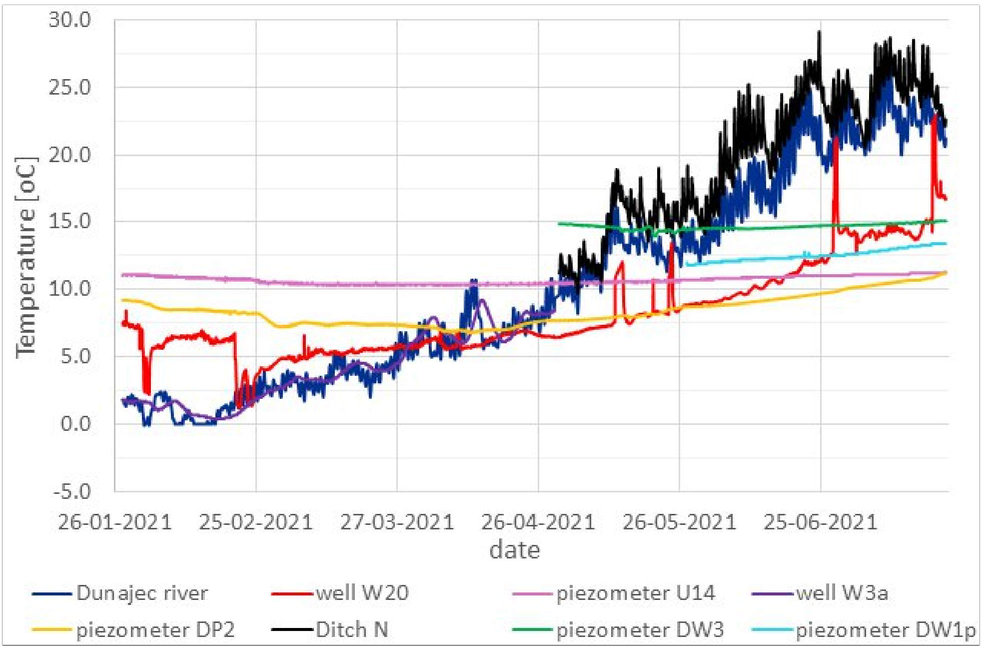


Fig. 4. 25. **Water temperature measurements at selected points at the pilot site.**

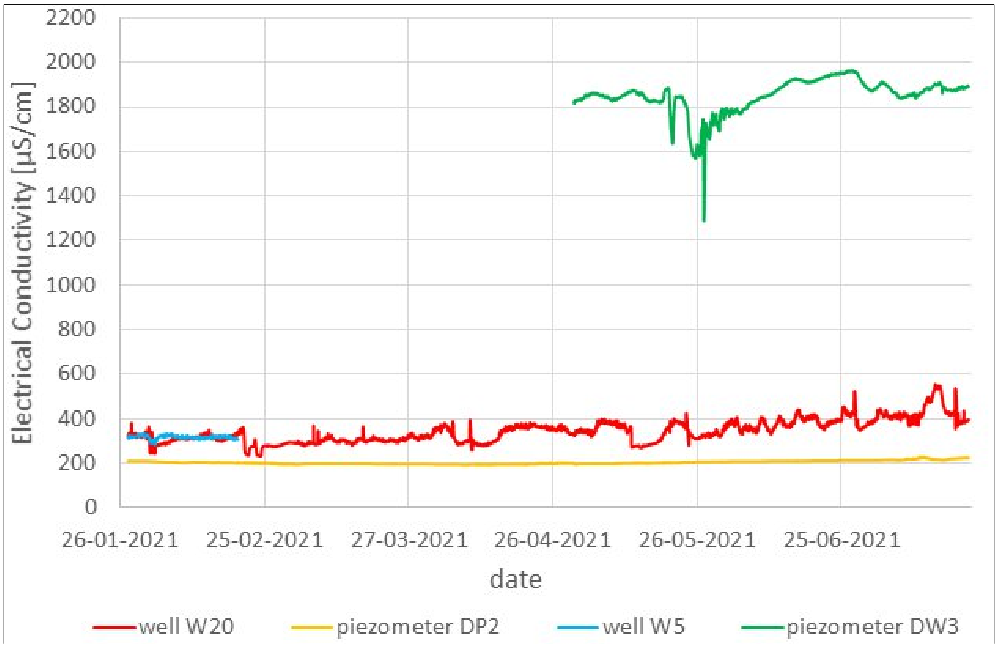


Fig. 4. 26. **Electrical conductivity measurements at selected points at the pilot site.**

4.5. Water quality

Monthly measurements of inorganic N ions and physical-chemical parameters of surface and groundwater showed relatively stable concentration of ammonium and nitrate during the year (eg. well US19 – Fig. 4.27), despite large spatial variation in their concentration across the well field area (Table 4.2.2, Fig. 4.28-29).

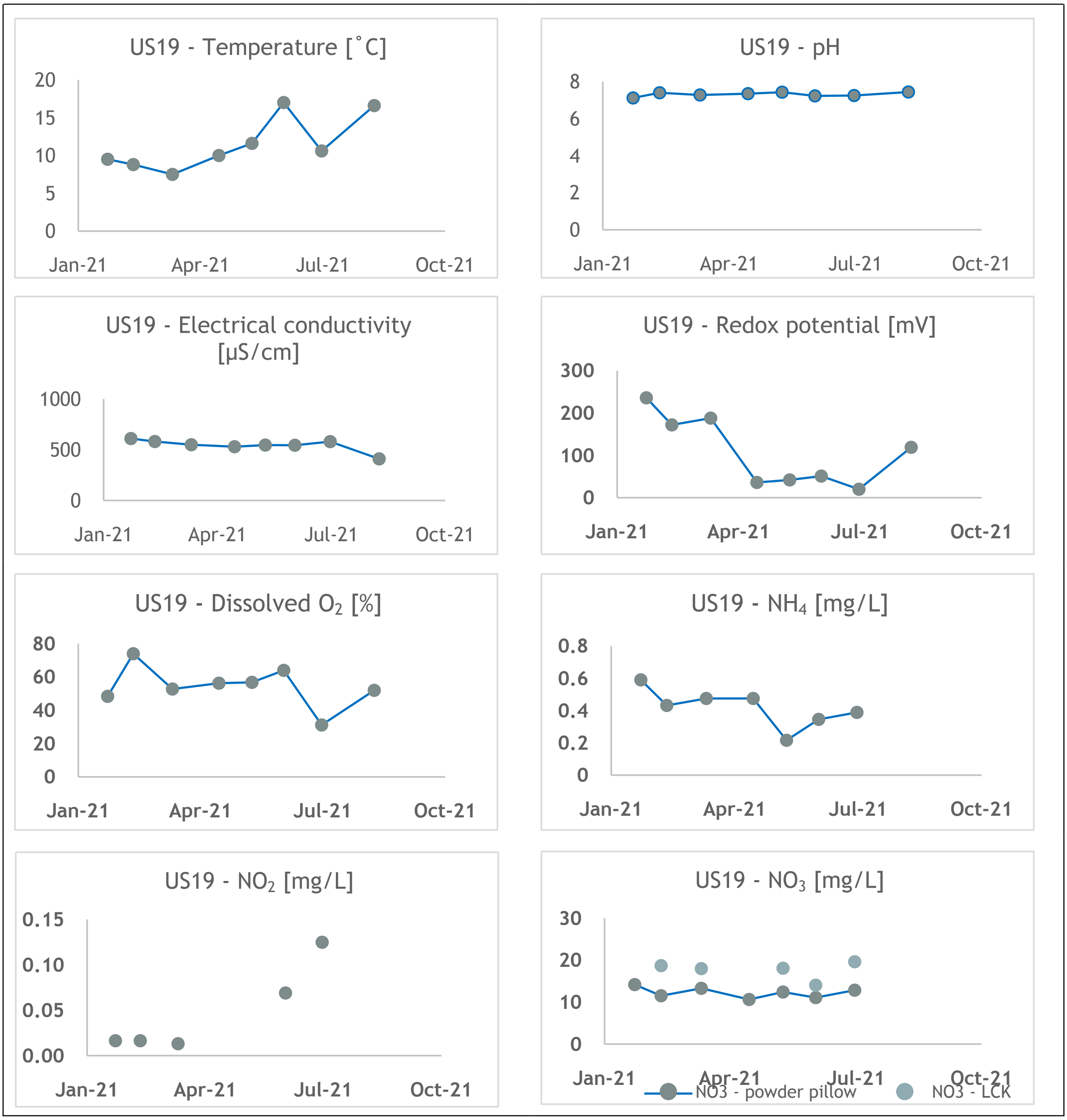


Fig. 4. 27. Time series of temperature, pH, EC, redox potential, dissolved O_2 and concentrations of NH_4, NO_2 and NO_3 in the sampled groundwater from the abstraction well - US19.

Table 4. 22. Physical-chemical properties of water samples taken on a monthly basis.

Type of water samples	Statistics	Temp	pH	PEW	Eh	O_2	O_2	NH_4	NO_2	NO_3 PP*	NO_3 LCK**
		˚C	-	µS/cm	mV	mg/L	%	mg/L	mg/L	mg/L	mg/L
Surface water	Minimum	0.3	6.86	247	-4	5.17	59.8	<0.0129	0.0131	3.10	4.60
	Maximum	24.7	8.56	417	238	12.19	113	0.0864	0.2300	8.85	7.66
	Average	12.0	7.88	327.1	127.2	8.94	84.7	0.027	0.0528	4.53	6.65
	Median	11.6	7.93	319.4	148	8.78	88.3	0.0144	0.0263	4.43	6.91
Precipitation	Minimum	0	5.29	13.9	26	4.78	51.3	0.0432	0.0460	3.10	1.33
	Maximum	27	8.78	38.9	263	11.14	92.2	5.04	0.2136	8.85	7.53
	Average	12.3	7.03	26.7	131.6	7.74	73.5	1.848	0.1253	4.53	3.82
	Median	15.2	7.03	29	132	8.04	76.2	1.584	0.1084	4.43	3.28
Groundwater	Minimum	0.1	6.2	305	-32	0.38	3.6	<0.0129	0.0099	2.21	2.21
	Maximum	22.4	8.04	1970	253	11.68	87.6	14.112	0.2990	27.00	43.83
	Average	11.9	7.25	656.2	108.0	5.20	49.1	2.043	0.0748	9.20	14.19
	Median	12.2	7.23	582.2	97	5.01	48.5	0.3456	0.0263	8.41	12.57

* Powder pillows reagents NitraVer5, ** LCK339 couvette tests

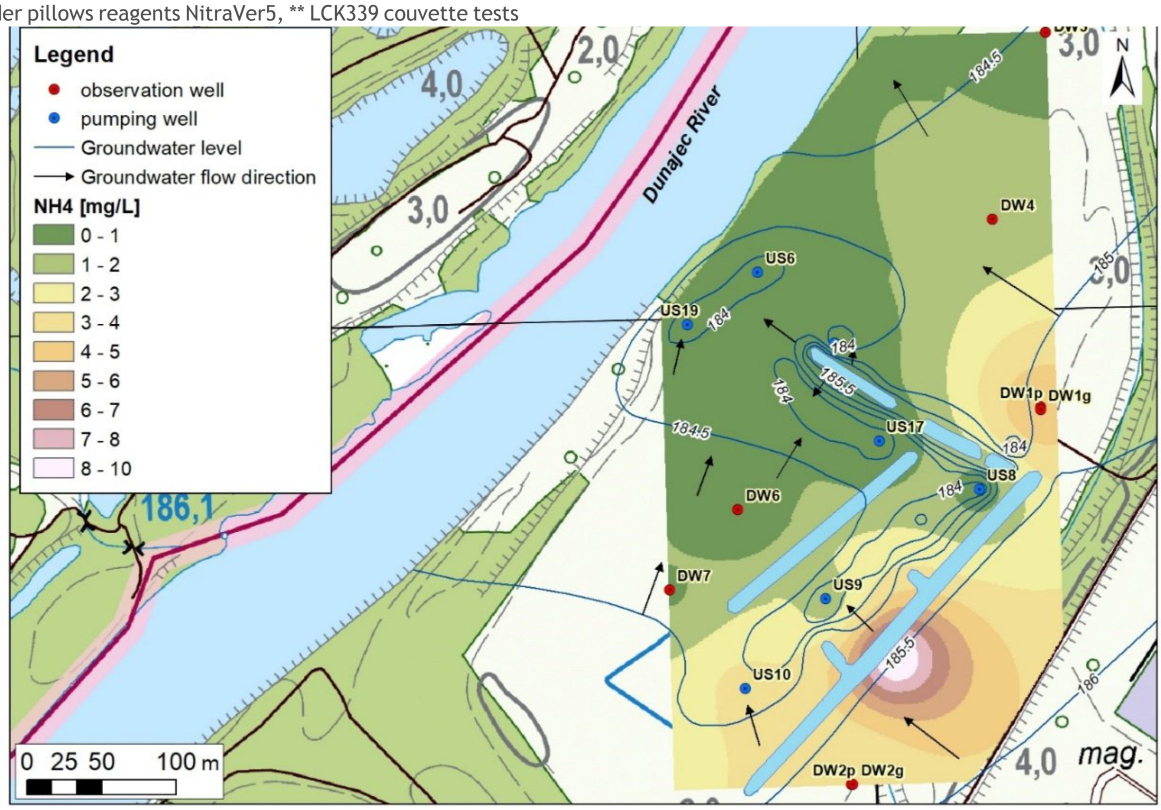


Fig. 4. 28. Spatial distribution of NH_4^+ concentration in groundwater in the area of the Świerczków well field based on the field campaign in July 2021.

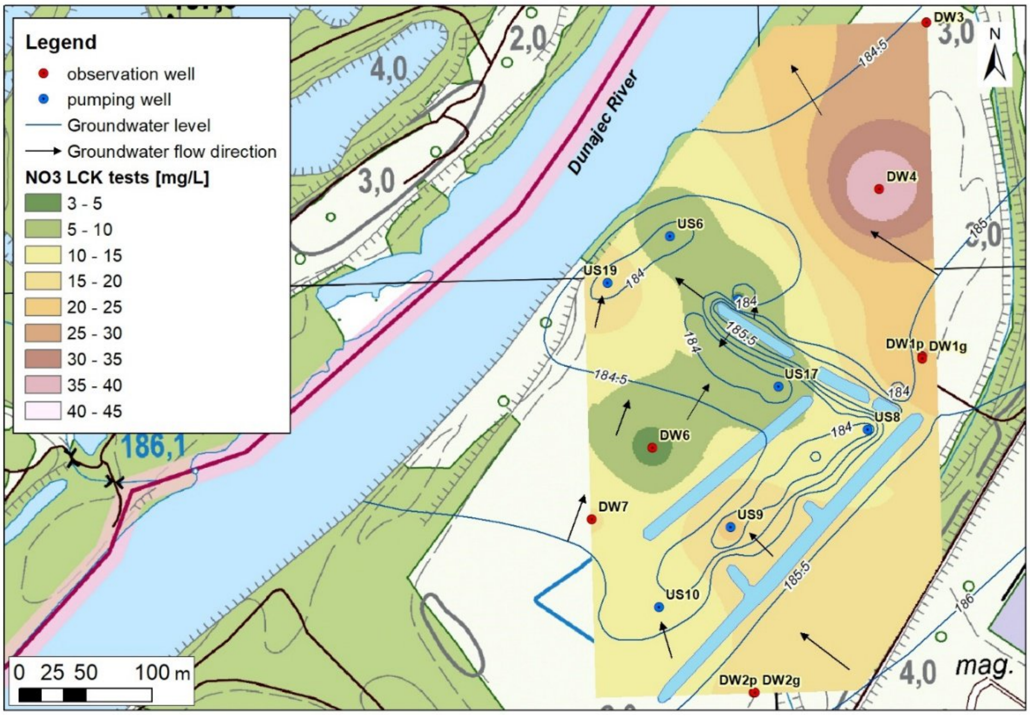


Fig. 4. 29. Spatial distribution of NO_3^- concentration in groundwater in the area of the Świerczków well field based on the field campaign in July 2021.

Nitrite concentrations were low in all water samples during cold seasons and increased up to tenfold during the summer. Temperature, redox potential and oxygen concentration varied significantly during the one-year study, while pH and electrical conductance remained stable. Concentrations of major ions revealed large variation within the Świerczków well field (Table 4.23, Fig. 4.30).

Table 4. 23. Ion concentrations measured in surface water, groundwater and precipitation water samples based on 4 sampling campaigns.

Type of water samples	Statistics	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+
		mg/L						
Surface water	Minimum	120	19	<5	32	6.4	8.2	2
	Maximum	193	28	17	59	13	13	3.5
	Average	147	22.27	10.7	51.1	11.01	10.8	2.9
	Median	151	21	10	53	12	11	3
Precipitation	Minimum	<12	<10	<5	1.6	0.29	<1	<1
	Maximum	<12	<10	<5	1.7	0.46	2.7	<1
	Average	<12	<10	<5	1.7	0.40	1.3	<1
	Median	<12	<10	<5	1.7	0.45	1.3	<1
Groundwater	Minimum	130	5	9	42	8.9	9	2.3
	Maximum	464	180	368	246	33	288	21
	Average	288.9	67.8	54.9	106.7	16.9	46.3	6.4
	Median	298	52	20	99	16	20	4.9

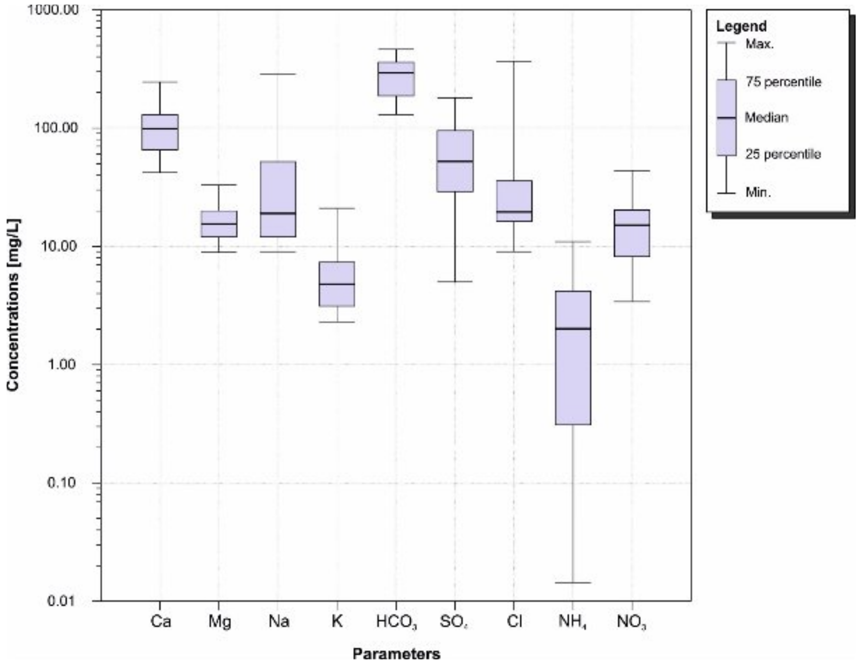


Fig. 4. 30. Ion concentrations in groundwater samples based on 4 sampling campaigns from 09.2020-07.2021.

In general, the highest values were observed in the south-eastern part of the well field, at the inflow of contaminated groundwater. Water infiltrating from the ditches dilutes ions concentration in groundwater and changes its physical-chemical parameters. The pattern presented by spatial distribution of electrical conductivity of groundwater (Fig. 4.31) was more or less followed by temperature, pH, NO_3, SO_4 or HCO_3. In the case of Na and Cl, the highest concentrations were observed in the north-eastern part of the study area, where groundwater is not diluted by infiltration ditches.

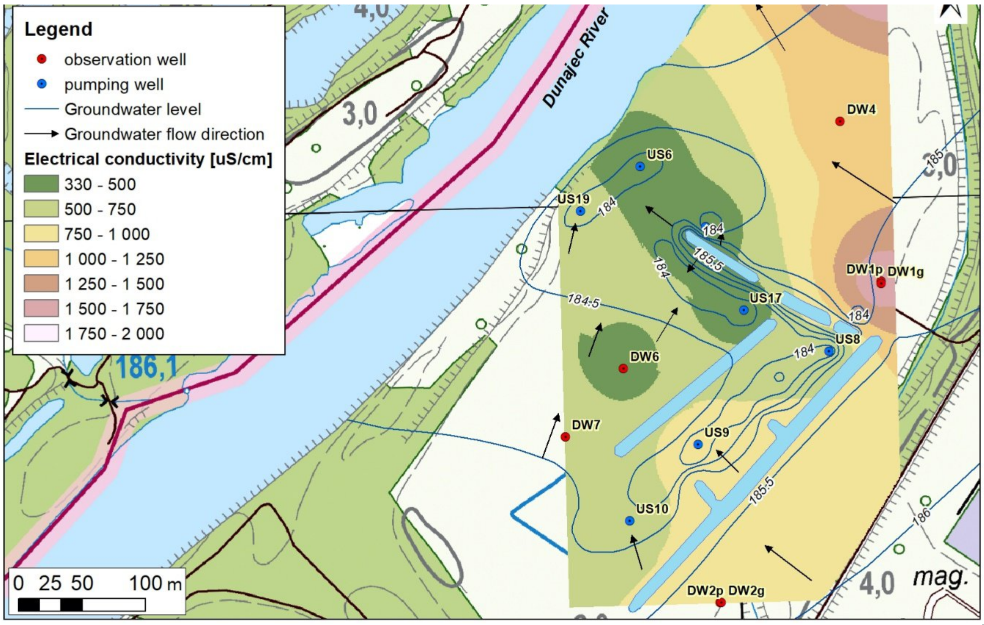


Fig. 4. 31. Spatial distribution of electrical conductivity in groundwater in the area of the Świerczków

well field based on the field campaign in July 2021.

Interesting results were obtained from the isotopic investigation of water. A clear difference was found between the isotopic composition of contaminated groundwater coming from the industrial site towards the well field and surface water infiltrating from the ditches into the aquifer. It allowed to see the proportion of infiltrating water and contaminated groundwater in the water abstracted by the wells (Fig. 4.32). In the case of the wells located closest to infiltration ditches and the Dunajec (US6, US15, US19), their composition of stable isotopes of water are consistent with values observed in the river (US1) and ditch (US18).

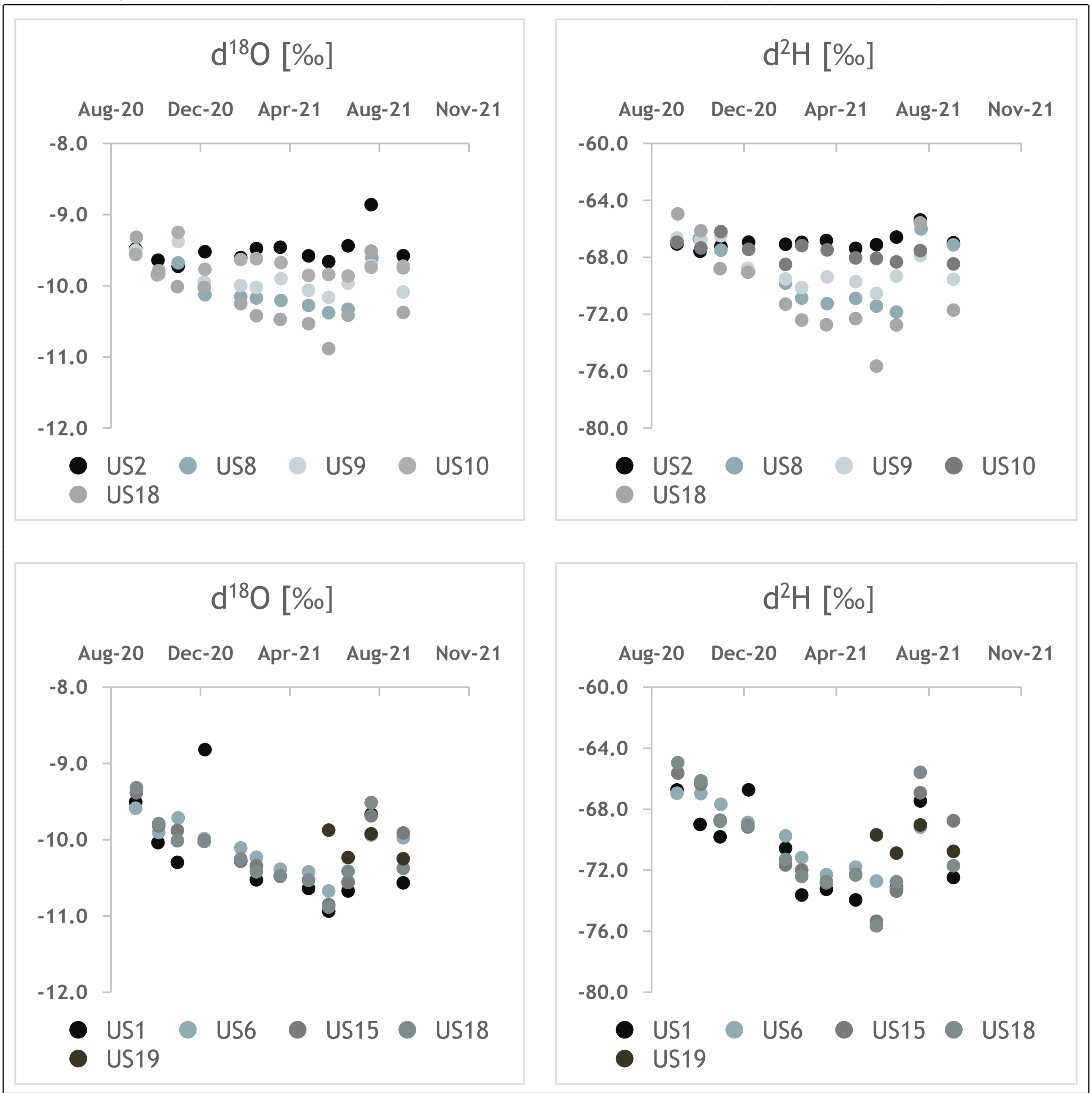


Fig. 4. 32. Time series of $\delta^{18}O$ and $\delta^{2}H$ in groundwater and surface water in the area of the Świerczków well field.

Analyses of organic pollutants (including polycyclic aromatic hydrocarbons, PAH) and microplastic in surface water and groundwater samples did not reveal any contamination. In contrast, research on pharmaceutical and personal care products (PPCPs) showed the presence of a couple of pharmaceutical residues in surface water samples (e.g., metformin, iohexol, iopromide, iomeprol, telmisartan) in ng/L concentrations, and trace concentrations in groundwater. Surface water infiltration is regarded as the only source of pharmaceuticals in sampled groundwater.

Furthermore, substances belonging to personal care products and pharmaceutical metabolites were observed in groundwater samples (e.g. caffeine, saccharin, paraxanthine, oxypurinol) (Fig. 4.33). In groundwater collected from some of the wells, concentrations of several substances (e.g., oxypurinol, saccharin) were higher compared to surface water. This may result from the fact that the migration of contaminants from surface water to an aquifer takes some time. Therefore, substances occurring in the aquifer could also be present in water from a river or infiltration ditches in the past. Cumulation of some microcontaminants in the aquifer should be considered, especially in favourable conditions occurring in the groundwater environment, for example, conditions preventing oxidation of chemical compounds. It is noteworthy that higher concentrations of the mentioned substances were reported for wells abstracting groundwater in the area of more reducing conditions (manifested by higher concentration of NH4 and lower concentration of dissolved O2) in comparison to other wells.

Some substances were typical for industrial sites, i.e. fluorosurfactants and corrosion inhibitors. Fluorosurfactants could have migrated from industrial areas located on the west of the Świerczków well field, as PFOS and PFOA were also detected in groundwater from the US2 (U14) piezometer. The source of corrosion inhibitors is not clear because these substances are widely used in the maintenance of metal surfaces. The highest concentrations were detected in groundwater taken from the US6 (W20) well, where the aquifer is recharged by both river and infiltration ditches. In surface water samples, corrosion inhibitors were detected in all sampling campaigns.

During the first sampling campaign for PPCP analysis, relatively high concentrations were observed for caffeine (a substance occurring in coffee and tea) and paraxanthine (a metabolite of caffeine) in one production well of the Świerczków well field and one well of the Kępa Bogumiłowicka well field. Bisphenol S was also detected in concentrations substantially exceeding the quantification limit in these samples. This substance was not found in other water samples, regardless of the sampling campaign. The presence of this compound suggests possible contamination during sampling. Bisphenol S is a compound used in the production of plastic containers and tin cans. As many everyday products are stored in such packages, the contact of a sampler with this substance and then sample contamination cannot be excluded. The presence of bisphenol S and elevated concentrations of caffeine and its metabolite (paraxanthine) seems to confirm this assumption. Similarly, the results of DEET (an insect repellent) obtained in the last sampling campaign revealed that this substance was present in every water sample in very high concentrations, reaching several thousands of ng/L, which is typical for wastewater rather than natural waters. In this case, the application of insect repellents by a team members conducting field measurements was responsible for water samples contamination with this compound. Therefore, samples for which results suggested their contamination during sampling were excluded from outcomes presented in Fig. 4.33.

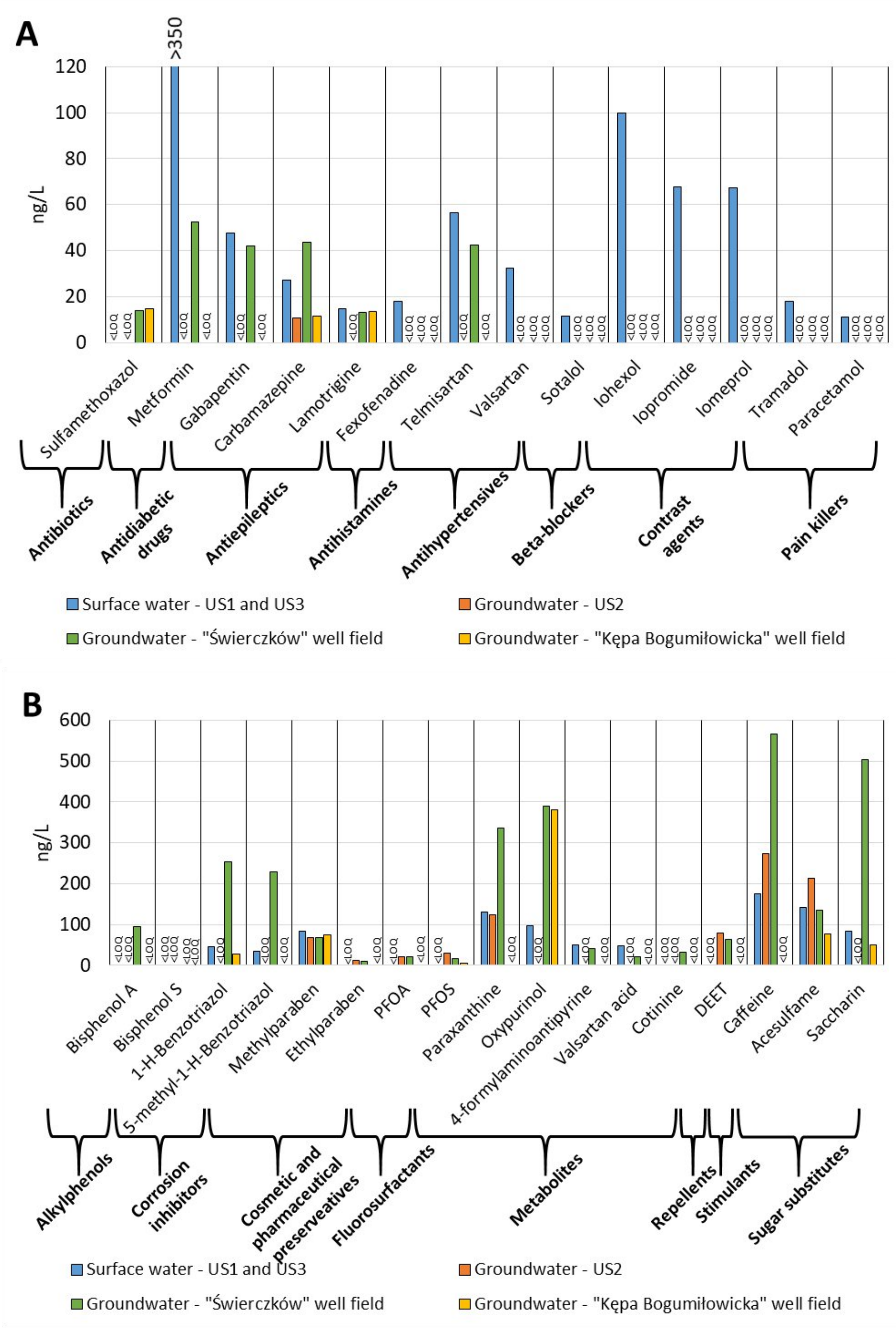


Fig. 4. 33. Maximum concentrations of detected PPCPs in water samples. A – pharmaceuticals; B – personal care products and others; <LOQ – below the limit of quantification.

As part of the study, an attempt of creating a geochemical model was made to better understand processes controlling groundwater geochemistry within the Świerczków well field. PHREEQC code was applied to perform calculations. Several types of geochemical models have been created and the best results have been obtained for mixing of groundwater and surface water (Table 4.24). The model 1 assumed mixing of groundwater taken from DW7 piezometer and surface water from the Dunajec river in proportion 37.5% : 62.5%, respectively. The mixing proportion was pre-determined based on chloride concentrations, assumed its conservative behaviour in water environment. Model 2 assumed, in addition to mixing in the proportions mentioned above, the oxidation of organic carbon contained in the Dunajec water. The results of modelling were compared with groundwater sampled from the US19 well (W21).

Table 4. 24. Comparison of two PHREEQC model scenarios results with chemical composition of 3 samples taken from well, piezometer and the river.

Water sample	pH	Alkalinity	NH_4^+	NO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	SiO_2
	mmol/L										
Dunajec river	7.82	2.11	0.005	0.124	0.22	0.28	0.97	0.30	0.36	0.054	0.086
DW7 piezometer	7.31	4.95	0.064	0.216	0.48	0.51	2.15	0.49	0.61	0.079	0.101
US19 (W21)	7.43	4.34	0.012	0.290	0.46	0.42	1.95	0.45	0.57	0.084	0.090
Model 1	7.37	3.89	0.042	0.181	0.38	0.42	1.71	0.42	0.51	0.070	0.095
Model 2	7.20	3.94	0.042	0.128	0.38	0.42	1.71	0.42	0.51	0.070	0.095

The results of the geochemical models are consistent with the chemical composition of groundwater taken from the US19 well. The only noticeable difference was observed for alkalinity and sulphate concentration – the modelled values were lower compared to the observed ones. This may result from the fact that other processes, not included in our models, were present in the aquifer and modified chemistry of the groundwater, e.g., oxidation of sulphide minerals coupled with denitrification.

5. Risk management

Within the report D.T3.4.3 (DEEPWATER-CE, 2021c), an attempt to describe suitable risk management plan for the well field "Świerczków" was performed. Świerczków is a Polish pilot site, where the expansion of existing and operating MAR system (infiltration ditches and IBF) is being considered. Chosen methods were selected based on the developed Common Methodological Guidance For DEEPWATER-CE MAR Pilot Feasibility Studies report (DEEPWATER-CE, 2020b).

The main study objective was to illustrate the risks that could affect the pilot site and what the consequences may be if none preventive measures were taken. Thus, the risk treatment methods were also proposed to manage or to reduce potential risks to an acceptable level. All the risks were classified into 12 groups (Table 5.1) and listed in four summary tables, covering design-construction and operational phases for technical and non-technical aspects. The tables contained risks description, rating and treatment.

Risks that may severely affect the quality and continuity of MAR functioning were identified. This was evidenced by the high likelihood of these risks in pair with their serious impact on the MAR system. Authors of the D.T3.4.3 report have concluded that MAR facility owners in Tarnów should establish a comprehensive risk management plan (or rather keep enhancing and updating the plan already in place) in order to function properly, principally after the planned expansion. The results presented in this report can constitute an initial step in the process of developing a more exhaustive risk management solution at the MAR site under question.

Table 5. 1. Created risk groups divided into technical and non-technical risk (modified from Rodríguez-Escales et al., 2018).

Non-technical risks
legislation risks
governance risks
economic risks
social risks (unacceptance)
Technical risks
not enough water recharged due to low input water quality
water scarcity risks
hydraulic and hydrogeological risks
lack of infrastructures risks
structural damages due to environmental events or human activity (civil work failures)
clogging risks
risks connected to unacceptable quality of water at sensitive location (MAR)
specific targets risks

5.1. Risk identification

The starting point in identifying risks during our study was the set of various risks prepared in another MAR-related project: the EU FP7 project MARSOL (Rodríguez-Escales et al., 2018; http://www.marsol.eu/6-0-Home.html). It was decided to use this list because it formed the calculations basis in one of the two methods used in our analysis: MAR-RISKAPP, a Microsoft Excel® macro developed under the aforementioned project (see next Chapter), based on fault tree principles.

Firstly, all the risks that may anyhow lead to an examined MAR failure were listed and analysed for two viability phases: design-construction and operational. This set of 65 risks, originally created by the MARSOL team, was based on a literature review of 51 MAR facilities worldwide, an expert knowledge and the data gathered during the project itself (Rodríguez-Escales et al., 2018). Research in the MARSOL project focused on the Mediterranean region, thus for the purposes of our risk analysis in Poland the list of risks had to be modified, in order to adapt them to the specificities of our pilot site. Risk groups names created by the team working on the original version of MAR-RISKAPP have been modified by us to better fit risk groups proposed in the earlier report D.T3.2.5 (DEEPWATER-CE, 2020b), and few new risks were added to the analysis. The employees of the Associated Partner of the DEEPWATER-CE project, Tarnów Waterworks, were involved in this process of modifying the original list of risks. Conclusively, total of 12 risk groups (Table 5.1) were described by 74 distinctive risks (53 technical and 21 non-technical) that may potentially affect MAR viability (Table 5.2).

Some of the risks analysed that played a role in the MARSOL study region certainly do not appear in southern Poland (eg. desalination plant failure). When preliminary work on a given risk showed that its probability of occurrence in the research area is zero or close to zero, this risk was not taken for further consideration. Of all the risks analysed, 32 were not further analysed in detail (Table 5.3) (DEEPWATER-CE, 2021c).

Table 5. 2. **All identified risks divided into technical and non-technical.**

Non-technical risks	
European territorial constraints	Low price of water
National territorial constraints	High installation cost
Regional/Local territorial constraints	High maintenance cost / maintenance requirements
Health legislation	Lack of private /public funding
Others	Health risk perception by society
Lack of coordination	High cost perception by society
Non-technical knowledge	Behavioural requirements
Macroeconomic constraints	Children surveillance
Not enough water to recharge due to industrial use	Fair distribution of treated water
Not enough water to recharge due to agricultural use	Perception of effectiveness by society
Not enough water to recharge due to domestic use	

Technical risks	
Right of access from State Water Holding "Polish Waters"	**Pipe or/and filter fails (water diverted from deposition ponds)**
Risk of low water storage	**Residence time (water diverted from deposition ponds)**
Risk of low infiltration rate	Source fine particles (generation inside MAR facility)
High thickness and not shallow aquifer	Deposition (transport of solids into the aquifer, sedimentation at the infiltration ditch bed)
Regional hydrogeology and hydrochemistry	Erosion (transport of particles from infiltration ditch slope)
Lack of potential available land	Bioclogging
Lack of structure for capturing the water	Evaporation (excess) (chemical clogging)
Lack of water pre-treatment infrastructures	Water mixtures (chemical clogging)
Lack of recovery wells	Microbial population catalysis
Flooding	Compaction
Natural hazards (e.g. earthquake)	Generation of gas - Physical Motives
Vandalism	Generation of gas - Bacterial processes
Slope stability	Generation of gas - Inappropriate design
Pipe breakage	Elevated geochemical background (due to vicinity of industrial site)
Aquifer dissolution (e.g. in karstic aquifer)	Emerging organic compounds (as the result of inefficient natural attenuation)
Others	Nutrients (as the result of inefficient natural attenuation)
Sanitary/biological restrictions (e.g. due the pathogens)	Nitrogen cycle (NO_2^-, N_2O… as a product of metabolite generation)
Turbidity/particles	Emerging organic compounds (as a product of metabolite generation)
Metals (e.g. arsenic, manganese)	Other nutrient cycles (e.g. H_2S)
Salinity and sodicity	Metals mobilization
Nutrients (nitrogen, phosphorous)	Seawater barrier risk
Organic chemicals (pollutants, EOCs)	Protected water body risk
Radionuclides (regarding input water)	Water level - spring
Droughts and rainfall event periodicity	Water level - wetland
Waste water treatment plant failure	Water level - river
Desalination plant failure	Water level - groundwater
River regulation	

Table 5. 3. Identified risks which were not taken into further consideration/analysis.

Non-technical risks	
Not enough water to recharge due to industrial use	Lack of private /public funding
Not enough water to recharge due to agricultural use	Health risk perception by society
Not enough water to recharge due to domestic use	High cost perception by society
Children surveillance	Behavioural requirements
Fair distribution of treated water	Perception of effectiveness by society
High installation cost	
Technical risks	
River regulation	Compaction
Lack of potential available land	Generation of gas - Physical Motives
Natural hazards (e.g. earthquake)	Generation of gas - Bacterial processes
Slope stability	Generation of gas - Inappropriate design
Aquifer dissolution (e.g. in karstic aquifer)	Other nutrient cycles (e.g. H_2S)
Radionuclides (regarding input water)	Metals mobilization
Waste water treatment plant failure	Seawater barrier risk
Desalination plant failure	Protected water body risk
Evaporation (excess) (chemical clogging)	Water level - spring
Water mixtures (chemical clogging)	Water level - wetland
Microbial population catalysis	

Detailed descriptions of each of the risks presented in the above tables can be found in the aforementioned report D.T3.4.3, fully devoted to risk analysis (DEEPWATER-CE, 2021c) .

5.2. Risk assessment

The risk assessment for the pilot site in study was performed using on two methods: 1. Qualitative Risk Analysis Matrix (e.g. Nadebaum et al., 2004, Swierc et al., 2005) and 2. Probabilistic Risk Assessment method - Fault Tree Analysis; PRA-FTA (e.g. Rodríguez-Escales et al., 2018).

The risk analysis matrix (Table 5.4) was used to assign each identified risk (listed in the previous Chapter) as low, medium or high. By classifying risks in this way it was possible to establish a hierarchy of risks, which is an essential element while determining priorities for risk management. The level of risk was estimated by determining the likelihood of it's occurrence and identifying the impact severity of each hazardous event. In the qualitative risk factor matrix, the authors decided to set five likelihood ranges (maybe give them: or reference Table 5.4), providing information on how often an unwanted event can happen in the pilot site. In terms of consequences severity of a given risk, three categories were distinguished (low, medium and high).

After matching every risk to the risk factor matrix by assessing the likelihood of its occurrence and its foreseen consequences, the values in the rows and columns of the matrix were multiplied. Scores below 6 points were considered as low risks, 6-12 points - medium risks and above 12 points -high risks. Such numerical rankings provide a relative indication of likelihood and consequence of the event, therefore it is important not to assume their accuracy in absolute terms. It should also be added that this method is highly subjective and its accuracy depends greatly on the knowledge and experience of the authors conducting it. The results from the risk matrix are shown in Table 5.5.

Table 5. 4. **Risk Factor Matrix used to conduct the risk assessment.**

RISK FACTOR MATRIX	Severity of Consequences		
Likelihood	Low impact [1]	Medium impact [3]	High impact [5]
once a year or more [5]	5	15	25
1 to 5 years [4]	4	12	20
5 to 10 years [3]	3	9	15
10 to 20 years [2]	2	6	10
> 20 years [1]	1	3	5
Risk score	<6	6-12	>12
Risk rating	Low	Medium	High

The second used method focuses directly on MAR and is based on the development of a probabilistic risk assessment method (fault trees). The methodology evaluates the probability of MAR failure, taking numerous risks (technical and non-technical) into account at two viability stages: design-construction and operational (Rodríguez-Escales et al., 2018).

The first step of implementing this method was defining the concept of a potential system failure and determining the events that may affect the correct and continuous operation of MAR facility (the well field). The second step was creating an appropriate fault tree to avoid the situation when the events affecting MAR would be dependent on each other. It's worth noting that all events should be as independent from each other as possible. The third step was a mathematical fault tree expression, based on the Boolean algebra. The last step was determining the probability of individual events affecting the system, based on the fault tree results.

As mentioned in the previous chapter, the risk assessment for MAR facility located in Tarnów was done using PRA-FTA method, with an Excel macro "MAR-RISKAPP". The macro was used to evaluate the risk of MAR facility failure during design-construction and operational phases.

It should be noted that MAR failure, as defined in Rodríguez-Escales et al. (2018), is: "*The need to stop operation of the facility. The failure can be either complete or partial. Partial failure means that it is possible to mitigate the problem in a short period of time so that the facility can be put back to operation, where complete failure implies that the facility needs to undertake significant changes and reparations in order to work again (or even not working ever again after the failure)*".

In our study, the exposed failures were considered only as the partial failures. Reason for this is that the

Tarnów Waterworks staff is highly familiar with the long running system and it has been in operation for many years without any significant, long-standing problems.

The probabilities of occurrence on a scale of 0-1 (representing 0-100 %) were assigned in the MAR-RISKAPP to every risk of the risk group in question (listed in the previous Chapter and Table 5.5), based on the knowledge and experience of staff from Tarnów Waterworks and hydrogeologists from University of Silesia in Katowice. The starting point for assigning probability values between 0 and 1 to risks was an attempt to transpose the likelihood levels from the risk matrix, which was done as the first method. Likelihood values scored as 5 in the risk matrix were estimated as 75% (0.75) of the probability (risk value) of MAR failure in MAR-RISKAPP, and further 4 - 0.5; 3 - 0.25; 2 - 0.1 and 1 - 0.05, respectively. MAR failure was interpreted as the partial or complete need to stop the MAR operation. For the analysed MAR system, only partial failures that could be fixed or prevented were taken into account. During the ongoing work within the expert team, chosen of the initially assigned values for risks were changed. The proposed changes resulted from the fact that the "likelihood" values in the risk matrix only answer the question “how often can the risk occur?”, while the "risk value" in MAR-RISKAPP directs the user towards the answer to “how high is the probability of MAR failure due to the risk occurring within the selected time frame?”. The probability assignment was related to the determination of specific probability for each basic event at the bottom of the tree, based on expert knowledge but also using the Boolean algebra rules (a full description of which can be found in Report D.T3.4.3.), until the top of the fault tree (full system failure) is reached. The results obtained by this method are shown in the Table 5.5 and on the Fig. 5.1.

5.3. Risk treatment

MAR systems (especially those supplying shallow, unconfined, or poorly isolated aquifers) are exposed to a significant number of risks. These can be the risks that occur once in a while (e.g. floods, droughts or legislation changes) as well as frequently or nearly all the time (e.g. inflow of poor quality, contaminated groundwater or deposition of particles suspended in recharge water at the bed of an infiltration basin). As such, facility managers (implicitly Waterworks) are required to implement and continually improve systems to prevent, mitigate, or eliminate specific risks.

In the case of our study area we are dealing with a well field located on a floodplain where the probability of flooding is high and amounts to 10% (chance of flooding once in 10 years), see chapter 3.4.1. of the D.T3.4.1 - Report on the desk analysis of the pilot feasibility study for MAR deployment in porous aquifers located near industrial sites on contamination of aquifers (DEEPWATER-CE, 2021a). Moreover, the well field exploits a shallow (approx. 3.5 - 10 m b.g.l.) and poorly isolated aquifer of low thickness (approx. 7 m), which is exposed to:

(a) hazards emerging from the surface (e.g. inflow of highly contaminated flood water, infiltration of contaminated rainwater), but also **(b)** hazards of a hydrogeological nature originating from the industrial zone adjacent to the area in study to the south.

Tarnów Waterworks management has had many years to refine its methodology for handling the risk at MAR pilot site. The well field has been in operation since 1910 (MAR since the 1950s) (Wojtal et al., 2009) and today a number of measures, which are necessary for it to function properly in the face of the risks mentioned above, are implemented. Examples of such include:

- Older wells were made on about 5 m high mounds for flood protection.

- Newer wells (drilled in 2012) have modern and watertight closures which prevent floodwater from entering the aquifer.

- Despite the inflow of low quality groundwater from the industrial zone, the water abstracted by the wells is of relatively good quality due to its improvement by MAR (see report D.T3.4.2., DEEPWATER-CE, 2021b).

- Water intended for human consumption is subjected to a detailed laboratory tests and additional treatment processes (chlorination) before entering the municipal network.

- Infiltration ditches are periodically (at least once every few years) completely drained and meticulously cleaned in order to remove clogging caused by natural settling of particles and biological matter.

- The well field in a current state contains a grid of observation wells (piezometers), a significant portion of which were drilled as part of the DEEPWATER-CE project (DEEPWATER-CE, 2021b). They play a supportive role with further understanding of the aquifer nature, monitoring the correctness and effectiveness of infiltration ditches, and allow to study the amount of pollutant load transferred from the industrial zone.

Report D.T3.4.3 (DEEPWATER-CE, 2021c) presents (in tabular form) the suggested responses (treatment ideas) to each of the risks analysed, which would somehow reach our study area. A good part of these methods were inspired by the Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge (NRMMC-EPHC-NHMRC, 2009), which describe in a very thorough and meticulous way how to combat, counteract and minimize a number of different risks. Another document providing ways to deal with risks was WHO's "Water Safety Plan manual" (Bartram et al., 2009). Of course, an indispensable element of creating this table was also seeking opinions at the source - namely, multiple consultations with the employees of Tarnów Waterworks regarding the biggest technical and non-technical difficulties they face in their everyday work.

5.4. Common comparison of risks

Two methods were chosen to conduct the risk assessment in the Polish pilot site. This choice was dictated, among other things, by the desire to show greater objectivity in the analysis as well as to check whether the two methods would show similar or different results.

Table 5.5, shown below, provides a generalized comparison of both methods results. However, when analysing this table, one key difference between those methods should be kept in mind. The results from the risk matrix in the “risk rating” column are the final results of this method, which are the product of likelihood and severity of a given hazard. In turn, the "risk value" (used in MAR-RISKAPP) assigned to each risk is just one component of the higher part (branch) of the fault tree. Thus even if some lower level risks have low "risk values", the higher part of the fault tree can still have relatively high resulting value. Also it is enough for one of the component risks to happen for an event higher up in the fault tree to occur. This highlights that risks are interdependent.

Example: Non-technical risks during an operational phase, where "higher order" group "territorial risks" consists of 3 types of "lower level" risks: European, National and Regional (legislation changes) (Fig. 5.1).

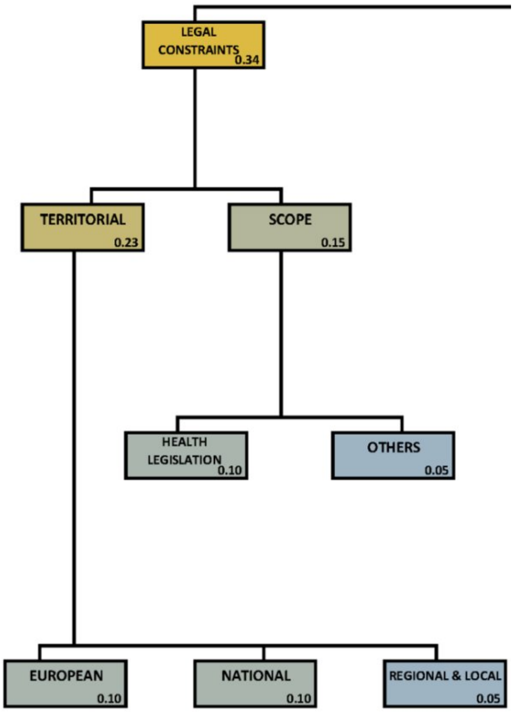


Fig. 5. 1. A part of the fault tree created for non-technical risks during the operational phase of MAR (DEEPWATER-CE, 2021c, based on Rodríguez-Escales at al., 2018).

Each higher hierarchical part of the fault tree is the result of a mathematical calculation using classical Boolean probability rules (Rodríguez-Escales at al., 2018).

As an example, the equation for the mentioned group of "territorial risks" was as presented:

$$0.1+0.1+0.05-(0.1*0.1)-(0.1*0.05)-(0.1*0.05)+(0.1*0.1*0.05) = 0.23$$

Table 5. 5. Comparison of the output "risk rating" from the risk matrix and the "risk value" component used in the MAR-RISKAPP macro calculations.

RISKS DURING DESIGN AND CONSTRUCTION OF MAR FACILITY: NON-TECHNICAL		
	Risk rating (Risk Matrix)	Risk value (MAR-RISKAPP)
Legislation risks		
European territorial constraints	Low	0,10
National territorial constraints	Low	0,10
Regional/Local territorial constraints	Low	0,05
Health legislation	Low	0,10
Others	Low	0,05
Governance risks		
Lack of coordination	Medium	0,10

Non-technical knowledge	Medium	0,05
Economic risks		
Macroeconomic constraints	Medium	0,1
Low price of water	Low	0,05
High installation cost	Low	0,10
High maintenance cost / maintenance requirements	Low	0,10
Lack of private /public funding	Low	0,05
Social risks (unacceptance)		
Health risk perception by society	Low	0,05
High cost perception by society	Low	0,05
Perception of effectiveness by society	Low	0,05
RISKS DURING OPERATIONAL PHASE OF MAR: NON-TECHNICAL		
Legislation risks		
European territorial constraints	Low	0,10
National territorial constraints	Low	0,10
Regional/Local territorial constraints	Low	0,05
Health legislation	Low	0,10
Others	Low	0,05
Governance risks		
Lack of coordination	Low	0,05
Non-technical knowledge	Low	0,05
Economic risks		
Macroeconomic constraints	Low	0,10
Low price of water	Low	0,05
High maintenance cost/maintenance requirements	Low	0,20
RISKS DURING DESIGN AND CONSTRUCTION OF MAR FACILITY: TECHNICAL		
Not enough water recharged due to low input water quality		
Sanitary / biological restrictions (e.g. due the pathogens)	Low	0,50
Turbidity / Particles (water entering MAR system)	High	0,75
Metals	Low	0,05
Salinity and sodicity	Low	0,05
Nutrients	Low	0,05
Organic chemicals	Low	0,05
Water scarcity risks		
Droughts and rainfall event periodicity	Medium	0,25
Right of access from State Water Holding "Polish Waters"	Low	0,05
Hydraulic and hydrogeological assessment of risks		
Risk of clogging	High	0,50
Risk of low water storage	Low	0,05
Risk of low infiltration rate	Low	0,05

High thickness and not shallow aquifer	Low	0,05
Regional hydrogeology and hydrochemistry	Medium	0,10
Lack of infrastructures risks		
Lack of structure for capturing the water	Medium	0,10
Lack of water pre-treatment infrastructures	Medium	0,10
Lack of recovery wells	Medium	0,10
RISKS DURING OPERATIONAL PHASE OF MAR: TECHNICAL		
Structural damages due to environmental events or human activity (civil work failures)		
Flooding	Medium	0,10
Vandalism	Low	0,10
Pipe breakage	Medium	0,25
Others	Low	0,10
Not enough water recharged due to low input water quality		
Sanitary/biological restrictions (e.g. due the pathogens)	Low	0,25
Turbidity/particles (water entering MAR system)	High	0,75
Metals (e.g. arsenic, manganese)	Low	0,05
Salinity and sodicity	Low	0,05
Nutrients (nitrogen, phosphorous)	Low	0,05
Organic chemicals (pollutants, EOCs)	Low	0,05
Water scarcity risks		
Droughts and rainfall event periodicity	Medium	0,25
Clogging risks		
Pipe or/and filter fails (water diverted from deposition ponds)	Medium	0,25
Residence time (water diverted from deposition ponds)	Medium	0,25
Source fine particles (generation inside MAR facility)	Low	0,10
Deposition (transport of solids into the aquifer, sedimentation at the infiltration ditch bed)	Low	0,05
Erosion (transport of particles from infiltration ditch slope)	Low	0,05
Bioclogging	Low	0,05
Risks connected to unacceptable quality of water at sensitive location		
Elevated geochemical background (due to vicinity of industrial site)	Medium	0,30
Emerging organic compounds (as the result of inefficient natural attenuation)	Low	0,05
Nutrients (as the result of inefficient natural attenuation)	Low	0,05
Nitrogen cycle (NO2-, N2O… as a product of metabolite generation)	Low	0,05
Emerging organic compounds (as a product of metabolite generation)	Low	0,05
Specific targets risks		
Water level - river	Medium	0,05
Water level - groundwater	Medium	0,10

According to the results of the “Qualitative Risk Analysis Matrix”, the most severe risks to MAR viability in Polish pilot site are:

1. The risk of wells and infiltration ditches clogging (together with too long residence time of surface water in settling tanks, from which it is derived to the infiltration ditches).

2. Too high turbidity (high amount of particles) of the water entering MAR system.

3. Flooding.

4. Lack of water available for recharge due to extreme climate events.

5. Regional hydrogeology and hydrochemistry problems.

6. Infrastructure problems (lack of necessary technology or failure like pipe breakage).

7. Also some of the non-technical risks like governance or macroeconomic constraints should be considered with greater emphasis (DEEPWATER-CE, 2021c).

The second method - “Probabilistic Risk Assessment method - Fault Tree Analysis” revealed that the greatest risk might derive from:

1.Low quality and quantity of recharge water (water from Dunajec) due to physical clogging or sanitary and biological aspects (the latter only for design phase).

2. Water scarcity as a result of extreme climate events that may harm MAR facility (e.g. structural damage as a result of a flood).

3. A unacceptable groundwater quality due to insufficient natural attenuation of groundwater.

4. Water disposition failure (pipe breakage, too long residence time of surface water in settling tanks).

5. Also based on this method results some of the non-technical risks should be considered with greater emphasis, e.g. economical and legislation (change) risks (DEEPWATER-CE, 2021c).

The results of this method, in contrast to the risk matrix, are presented in a percentage form. Thus, technical risks dominate (98% and 89% of failure for design and operational phases, respectively), but attention must be paid to non-technical constraints (such as economical or legal constraints) as well. For these, the probability of MAR-failure equals 68% for design and 59% for operational phase, if no preventive actions are taken (more detail are given in DEEPWATER-CE, 2021c).

5.5. Responsible for risk assessment

In Poland, the responsibility for risk assessment in context of MAR facilities is not regulated directly by legal acts. However, there are regulations (Water Law, Journal of Laws 2021, item 2233) which impose an obligation to perform risk analysis by the owners of the drinking-water well field for the purpose of assessment of health hazards, taking into account factors negatively affect water quality. The issue of risk analysis, assessment and management related to water supply has to be carried out in the context of determining whether there is a need to establish an intermediate protection zone for drinking water supply sites (Water Law, Journal of Laws of 2021, item 2233).

The second regulatory document that relates to the performance of risk assessments, also in the context of drinking water safety is Regulation of the Minister of Health of 07.12.2017 on the quality of water intended for human consumption (Journal of Laws of 2017, item 2294). This regulation defines risk assessment as a process consisting of hazard identification and risk analysis conducted on the basis of the PN-EN 15975-2 standard (PN-EN 15975-2:2013 Security of drinking water supply-Guidelines for risk and crisis management – Part 2: Risk management).

The PN-EN 15975-2 standard referred to the Regulation of the Minister of Health of 07.12.2017 is based on the fundamental elements of the approach described in the Water Safety Plans (Bartram, 2009). A risk management approach described in the standard is focused on elements of the drinking water supply chain including protection of sources, water abstraction, transport, treatment, storage and distribution.

5.6. Conclusions on the conducted risk analysis

After carrying out a risk analysis for the Polish pilot area, we may conclude that the methodology we chose proved to be effective and recommendable for the two types of MAR we analysed - Induced Bank Filtration (IBF) and infiltration ditches. The results of the two methodologies, as presented at the end of the previous chapter, are similar in terms of identifying the most significant risks that could negatively impact MAR performance in the study area.

The pilot site is located in a sensitive and unique location in several aspects, thus some of the identified risks may be called typical for such area. It is a well field located entirely on a floodplain, bordered on the west by the Dunajec river (source of water feeding MAR), on the northeast and southwest by a forest with reclaimed ash dumps (separated by a sheet piling), and on the east by one of the largest fertilizer-chemical industrial areas in Poland. Moreover, the exploited aquifer is of low thickness, shallow and covered by only a few meters thick layer of loams and silts on the top.

With this information in mind, it is not too surprising that both risk assessment methods portray the risks widely associated with flooding, clogging, poor water quality and insufficient water quantity, as well as local hydrogeological and hydrochemical problems in the worst light. All these risks can be classified as broadly technical risks, which dominate among the most harmful risks for the analysed MAR. In addition, however, both methods draw the attention to the non-technical risks, which can also threaten the proper functioning of the system. Such risks include, among others, mismanagement of the facility, macroeconomic problems, or significant changes in water legislation.

In the last section of our risk analysis report (DEEPWATER-CE, 2021c), we have also presented suggestions for an adequate monitoring of the MAR system in study (and systems similar to it), the so-called "risk management milestones" for four main risk categories. The most important groups of risks, requiring specifically planned and regularly (and some continuously) conducted monitoring, were identified as:

a) Groundwater and surface water quality deterioration, where 3 monitoring frequencies were separated: weekly, monthly and seasonal;

b) Clogging of the wells and infiltration ditches;

c) Extreme fluctuations of Dunajec water table and flow;

d) Extreme groundwater table fluctuations.

For a detailed description of each type of monitoring, as well as all other risk analysis aspects described in this document, see Report D.T3.4.3 - Compiled check list for the application of risk management protocol during the field works for MAR in Tarnów shallow aquifers (DEEPWATER-CE, 2021c).

6. Economic feasibility (CBA)

6.1. Introduction to CBA

Despite all advantages that MAR schemes can bring, it is nevertheless important to determine whether their benefits justify the anticipated costs. In this report, we outline the methodology and results of the cost-benegit analysis (CBA) study for the Polish pilot site. The aim of this study is to investigate whether the extension of the existing MAR scheme in Polish pilot site is economically feasible and whether the total economic value of the MAR scheme's extension (which includes both use and non-use benefits of it) meets or exceed the costs of putting this system in place and maintaining it.

It is also important to account for uncertainty in CBA studies. To incorporate this element in our analysis we develop scenarios with plausible variations of the main CBA parameters and check how sensible the net present value (NPV) of the MAR scheme's extension is to them. The report also includes an assessment of two dimensions of socio-economic risks associated with the MAR scheme: their probability and the magnitude of their consequences. Based on the conducted analysis we provide policy recommendations for implementation of the MAR scheme's extension in the Polish pilot site from a socio-economic perspective.

6.2. Materials and methods

Cost analysis

Main groups of initial investment and capital costs associated with extension of the MAR scheme include: i) investigation costs (geophysical surveys, physicochemical analyses of water, modelling studies together with forecasting simulations); ii) cost of wells (drilling a borehole, installation of well, pumping tests, geodesic surveying); iii) cost of piezometers (drilling a borehole, installation of a piezometer and protective casing), and iv) infiltration ditch (excavation and ground levelling), v) cost of connecting new infiltration ditch and wells to the existing system. A detailed breakdown of the total values of initial investment and capital costs is provided in Appendix A. The project timeline foresees that the investigation and installation of the piezometers can be conducted during the first year of the project, while the wells and infiltration ditch installation and connection to the existing system can be implemented in the second year of it.

Since the MAR scheme is already functioning and there is a historical data on operation and maintenance costs, corresponding costs associated with the extension can be calculated using the ratio of the extension's size to the size of the MAR system in place. The current MAR scheme includes 17 working wells and 3 infiltration ditches while the planned extension will consist of 5 wells and 1 ditch. Thus, all operation and maintenance costs (except storage costs[1]) were multiplied by 0.3 in order to get estimates of the annual operation costs of the MAR scheme's extension. Details on the calculation of maintenance costs are provided in Appendix A.

Average values and the range of the annual operation, maintenance and management costs along with the

[1] Additional storage is not planned

capital costs are presented in Table 6.1.

Table 6. 1. Costs associated with MAR scheme's extension.

Cost group	Average value [PLN]	Range (min-max) [PLN]
Initial investment-capital costs	726,550	666,950-786,150
Investigation costs	68,450	58,400 - 78,500
Cost of wells	117,050	
Cost of piezometers	31,150	30,900 - 31,400
Cost of infiltration ditch	234,900	210,600 - 259,200
Cost of connecting new wells and ditch to the existing system	275,000	250,000-300,000
Annual operation and maintenance costs	676,418	
Raw water costs	96,885	
Cost of extraction and distribution	348,478	
Labour costs	60,452	
Electricity costs	108,528	
Amortization costs	35,579	
Post-treatment costs	12,997	
Regulatory testing cost	13,500	

Source: Data provided by AP - Tarnów Waterworks

Benefit analysis (direct benefits)

The local population of the city of Tarnów and the surrounding smaller towns that are supplied with water by Tarnów Waterworks (TW) are the main beneficiaries of the proposed extension of the MAR scheme. The main direct benefit is the increase in the available drinking water resources for the city and nearby towns. Besides that, the local population will also experience an environmental benefit, namely minimization of poor quality of groundwater inflow from the industrial zone.

The direct use benefit of the MAR scheme's extension is estimated as a product of the annual amount of the available water resources due to the extension of the MAR scheme multiplied with the price paid by the local population for drinking water supply (taking into account its gradual increase during the first three years of the project and stable price afterwards).

The existing MAR scheme covers approximately 22% of the potable water produced by Tarnów Waterworks - a major water supplier in the pilot area. The extension of the MAR scheme is expected to increase this share by 6%. Calculated values of direct benefits from the extension are presented in Table 6.2.

Table 6. 2. Calculation of direct benefits.

Indicator		Unit of measurement	Value
Average total drinking water demand of the city of Tarnów and surrounding smaller towns in 2019-2020		m^3	7,986,713
The annual amount of available water resources due to the extension of the MAR scheme		m^3	509,106
Price of drinking water supply		PLN per m^3	3.17
Annual growth rate for the price of water supply (in the first 3 years)		%	3-4.5
Revenue of TW from the MAR extension	1st year	thous PLN	1,686.5
	2nd year		1,737.1
	3rd year		1,789.2

Source: Data provided by Tarnów Waterworks

Net present value

Following the CBA literature, we use the net present value (NPV) as a profitability indicator assessing the economic feasibility of the MAR scheme. NPV is a sum of private and socio-environmental net cash flows (the difference between the present value of benefits and the present value of costs over a selected time horizon):

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

where

k: initial investment cost, t: time NCF_p: private net cash flow,

NCF_s: socio-environmental net cash flow, r_f: financial discount rate, r_s: social discount rate

In other words, NPV is the sum of the discounted value of the stream of benefits (in our case: both direct, indirect and non-use values of MAR schemes) 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, the project lifespan for our study is defined to be 30 years. Values of discounts rates were selected following the European Commission's benchmark, with 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%.

6.3. WTP survey

In order to estimate both use and non-use (socio-environmental) benefits, a survey was conducted to explore the maximum amount of money that the local population is willing to pay (WTP) to have a stable supply of drinking water, ensuring its quality (no contamination by chemicals) and for improvement of the ecological status of the aquifer.

Details on survey design and implementation

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

In designing the questionnaire for the drinking water MAR system, we followed the concept of “general specific”, i.e. we started with general questions on the state of the environment and narrow down the questions to address issues that are more specific. In particular, in the questionnaire, the first part contains questions on knowledge regarding problems related to groundwater quality and quantity in Tarnów area, main concerns and prevailing pressures on groundwater. Respondents were also asked to self-assess household impact on groundwater, whether they feel a responsibility to contribute to protection and preservation plan for groundwater, and whether they are aware of functioning chemical plant in the area.

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’s extension 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. Options of these maximum amounts were proposed in the questionnaire based on average drinking water prices. On one hand, if the respondent selects not to contribute to the proposed plan, he or she is asked to choose the reason for such decision. On the other hand, if the maximum amount of financial support is provided, the respondent is asked to distribute it to the distinct categories of benefits that the MAR scheme yields: use benefits (e.g. use of groundwater for drinking purposes by local community) and non-use benefits (e.g. use of water by future generations (bequest value), by groundwater-dependent ecosystems, scenic beauty).

The concluding part includes questions on the respondent’s profile, such as demographic and socio-economic questions. The questionnaire also includes a section that reveals respondent’s concerns regarding the safety of the drinking water supply from the MAR system. Appendix B contains a full version of the questionnaire.

Regarding the ways of conducting the survey, along with conventional ways of survey link’s distribution (in paper and online form via e-mail for self-filling), a social media ad (on Facebook) was used to boost the post with survey description and link, aimed at increasing awareness among the targeted population (citizens of Tarnów and surrounding areas). In Appendix C, a brief information on social media advertisement is provided.

Survey results

For the Polish case study, the total number of full responses obtained is 51 with a good balance in the demographic characteristics (Appendix D, D15). Three-fourths of respondents believe that there should be a protection and preservation plan for groundwater, while about half of them feel some responsibility to contribute to it (D7). While more than 90% of survey participants are aware of the chemical industry in the area, only slightly above half of them are concerned with endangered drinking water aquifer to a great or moderate extent (D8).

In regard to willingness to pay (WTP), about one-third of survey participants stated that they are not willing to pay for supporting the extension of the MAR scheme (D10), with a potential higher level of municipal/income taxes being the main reason for such a decision (D11). Following our expectations, the prevailing share of survey participants who indicated nonzero WTP are people, who are aware of problems with groundwater quantity, feel a responsibility to contribute to a groundwater protection plan, have higher education and are full or part-time employees. They distributed the amount of their financial support according to the following distinct categories of MAR scheme's benefits (D12): on average 40% to the use of groundwater by future generations; 23% to groundwater-dependent ecosystems; 21% to the use of groundwater by the members of their household and 16% to the use if groundwater by other members of the local community. These results clearly support the importance of the MAR scheme's non-use benefits.

In addition, a parametric estimation with explanatory variables was performed to investigate how different characteristics of the survey participants can explain whether a person is willing to pay to support the MAR scheme's extension. Using the Probit model approach (widely applied to model binary outcome variables, in our case WTP is introduced in the model as dummy dependent variable), we obtained average partial effects for participants' characteristics including the robust standard errors (Table 6.3). The majority of estimated effects are highly statistically significant and consistent with the expected parameter's sign. More specifically, the probability that respondents will be willing to pay non-zero amount increases when the respondent:

- believes that there should be a protection and preservation plan for groundwater;

- is of younger age (base group for age variable is 18-30 years);

- has close to average or above-average income (base group for income variable is below average level);

- has high education (base group for education variable is high school).

Another important finding for MAR scheme implementation is that the prevailing share of respondents (82%) have no concerns regarding the safety of the drinking water supply from the MAR system. Appendix D contains detailed summary tables of survey results.

Table 6. 3. Binary Probit model results.

Variable	Definition	Average partial effect (Robust standard error)
Gender	Male	-0.213*** (0.091)
Age	30-45	-0.338*** (0.049)
	45+	-0.453*** (0.091)
Income	Close to the average level	0.278** (0.113)
	Above the average level	0.315*** (0.096)

Education	Bachelor degree	-0.412*** (0.125)
	Master degree and higher	0.324** (0.132)
Protection plan	Should be in place	0.738*** (0.195)
Concern chemical contamination	Great or modarate concern)	0.189 (0.127)
Household impact	Household impacts groundwater quality	-0.491*** (0.13)
Number of observations	42	
Wald chi2	360.09	
Pseudo R2	0.499	

*** correspond to p-level<0.01

Benefit analysis

The mean and median WTP along with 95% confidence interval were estimated using Krinsky and Robb's Procedure (Jeanty, 2007). Mean and median WTP were obtained controlling for respondent's characteristics: demographics, income level, educational level and green commitment. According to the literature, the obtained mean value of WTP multiplied by the target population number serves as an annual estimate of benefits (Rupérez-Moreno et al., 2017).

However, since we have a noticeably skewed distribution of WTP (see Appendix D), the median is the preferred measure of central tendency, because the median is more resistant to outliers than the mean. We calculate the annual estimate of benefits as a product of the number of MAR system users (accounting for annual population growth rate for the pilot site) and weighted median annual WTP amount. The weights were calculated as the shares of respondents who specified non-zero and zero WTP. Tables 6.4a and 6.4b present the main indicators' values and calculation results for the first five years, respectively.

Table 6. 4a. Calculation of benefits based on WTP.

Indicator	Unit of measurement	Value	95% confidence interval
Number of MAR system users	people	40,000	
Annual population number growth rate	%	-0.23	
Mean monthly WTP	PLN	10.85	(8.53; 13.53)
Median monthly WTP	PLN	8.86	(5.65; 11.33)
Beneficiaries with zero WTP	%	35	

Table 6. 4b. Calculation of benefits based on WTP for the first five years.

Year	Number of MAR system users, people	The weighted median of annual WTP amount, PLN	Total annual WTP amount, thous PLN
1	40,000	69	2,758.0
2	39,908	69	2,751.6
3	39,816	69	2,745.3
4	39,725	69	2,739.0

5	39,633	69	2,732.7

Source: Data provided by Tarnów Waterworks, own calculations based on survey results

6.4. Results

Feasibility of MAR scheme

To assess the economic feasibility of the MAR scheme's extension, firstly we compared only direct costs and benefits associated with it. A financial discount rate of 4% was applied 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.6.1).

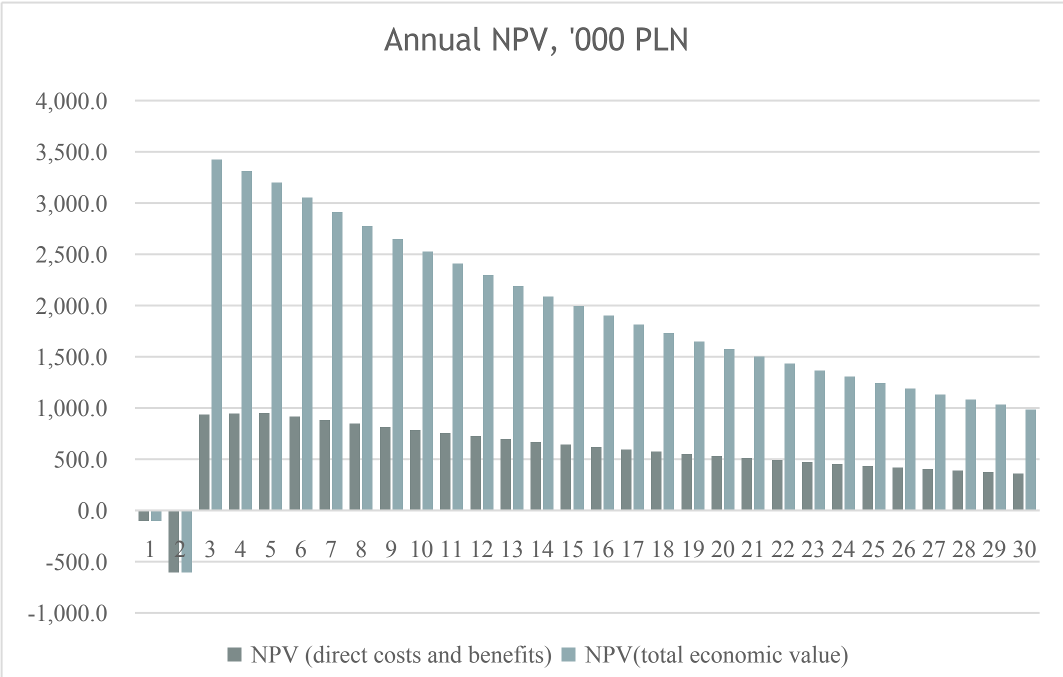


Fig. 6. 1. Annual net present value of MAR scheme's extension.

Obtained positive differences between direct costs and benefits suggest that the MAR scheme's extension is economically feasible with an expected NPV over 30 years of 16.98 million PLN. Regarding NPV calculated as the difference between costs and expected total economic value of MAR scheme's extension, its estimate is much higher, approaching around 55.02 million PLN.

Feasibility of MAR scheme under different scenarios

To incorporate uncertainty in our CBA, we developed three scenarios (conservative, neutral and optimistic) based on the following criteria:

- range of capital costs associated with MAR scheme's extension;

- range of WTP median values (based on estimated 95% confidence interval);

- variation of weights for the median value: 10% variation of the share of the targeted population with zero WTP.

Assumptions that define each scenario are presented in Table 6.5.

Table 6. 5. Developed scenarios.

Scenarios	Assumptions	
	Costs	Benefits
Conservative	The maximum value of capital costs	Including only direct benefits
Neutral	The average value of capital costs	Lower bound of the confidence interval of estimated WTP median value; 45% of the targeted population has zero WTP
Optimistic	The minimum value of capital costs	Estimated WTP median value; 35% of the targeted population has zero WTP (based on survey data)

Our aim is to check how sensitive NPV can be to the changes in parameters mentioned in Table 6.5. Under all scenarios, NPV always remains positive (Table 6.6), 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.

Table 6. 5. NPV under different scenarios.

Scenarios	NPV over 30 years, thous PLN	Change compared to neutral scenario,%
Conservative	16,927.7	-55
Neutral	37,508.9	
Optimistic	55,078.5	47

6.5. Assessment of socio-economic risks

Economic risks along with health, environmental, technical and management risks can incur by the implementation of MAR schemes. Primary economic risks of MAR are related to the financing of MAR projects and benefit's realization over time. One of the core discrepancies in the financing of water projects is that water users (primary stakeholders, who benefit from them) often have an insufficient amount of financial sources to support these projects (Maliva, 2014). Moreover, there is a time lag between construction costs and the realization of benefits. Burdens associated with the financial constraints of MAR schemes' implementation may lead the main beneficiaries to consider the investment in the MAR system infeasible in terms of costs and benefits. Thus, governmental support through subsidies is often considered to be justified in such cases, though subsidies may sometimes create incentives that induce water inefficient behaviors (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., 2017) 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 potential 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 a 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 that the revenues are lower than anticipated because of the not fully realized water demand. In addition, MAR systems can be sensitive to extreme climate events. When it comes to drinking water demand, the percent of MAR water in the total household water consumption during the dry season is strongly affected by the person’s subjective perception of his/her risk of contracting a disease from drinking MAR water (Hasan et al., 2019).

For the case of the Polish MAR scheme, Table 6.7 presents a matrix of possible socio-economic risks and the probability of occurrence for each risk as it was assessed by local experts (a hydrogeologist and a technologist from Tarnów Waterworks). The only risk related to lower benefits than anticipated due to overestimated WTP is considered to have medium probability since discrepancies between stated and actual WTP are quite probable. However, the realization of this risk can have minor consequences since the NPV calculated accounting only for direct benefits is already positive.

Among considered socio-economic risks, only changing standards for end-users is expected by experts to have major consequences while a moderate level of risk outcomes is forecasted for lack of financial support and environmental fees policy. Realization of other risks is expected to have minor consequences. There are no reasons to expect that demand for drinking water might be not fully realized, that is why this risk is not applicable for the Polish pilot site.

Table 6. 6. Matrix of socio-economic risks.

Socio-economic risk	Not applicable	Risk probability			Risk consequences		
		Low	Medium	High	Low	Medium	High
Lack of funding/financial support		+				+	
Unplanned additional costs (installation, maintenance etc)		+			+		
Changing standards for end-users		+					+
Insufficient communication and negative risk perception of the public		+			+		
Missing acceptance and trust of the public		+			+		
Not fully realized water demand	+						
Lower benefits than anticipated due to overestimated WTP			+		+		

Other: Environmental fees policy (including local) - economic and legal aspects		+				+	

6.6. Conclusions on CBA

Cost-Benefit Analysis (CBA) is an important part of the MAR scheme's feasibility assessment. MAR schemes can support both use and non-use benefits associated with the use of groundwater; thus, it is important to account for both use and non-use values in the economic feasibility analysis. To reveal the value of non-use benefits, stated preference techniques and in particular the contingent valuation method are widely used in MAR studies. The net present value NPV is calculated as the difference between the discounted total economic value of the MAR scheme (from both use and non-use values) and the costs associated with it. A positive NPV value can be considered from an economic perspective as a reliable sign of a financially sustainable MAR system. In addition, it is important to incorporate uncertainty in the CBA through the incorporation of sensitivity analysis that allows to check whether and how net benefits will change under different scenarios.

In this study, we conducted a CBA for the MAR scheme's extension at the Polish pilot site. This extension is expected to increase the water withdrawal of the well field with simultaneous control and improvement of groundwater quality. Our survey results suggest that the non-use benefits of the MAR scheme are particularly important for the local population. Calculated NPVs indicate that the MAR scheme's extension and operation are economically feasible under all considered scenarios.

This report outlines also possible socio-economic risks associated with the MAR scheme in the pilot study area together with the experts' assessment of their probability and consequences. Policymakers should beware and consider these risks, especially those with a high probability of realization and/or major risk consequences. Based on the assessment of local experts for our pilot study area, changing standards for the end-user is the only risk with major consequences expected in case of its realization.

References

Arshad, M., Guillaume, J., Ross, A., 2014. Assessing the Feasibility of Managed Aquifer Recharge for Irrigation under Uncertainty. Water, 6, pp. 2748-2769.

Bartram J., Corrales L., Davison A., Deere D., Drury D., Gordon B., Howard G., Rinehold A., Stevens M., (2009) Water safty plan manual: step-by-step risk management for drinking-water suppliers. World Health Organization, Geneva.

Boardman, A., Greenberg, D., Vining, A., Weimer, D., 2017. Cost-benefit analysis: concepts and practice, fourth edition. Cambridge University Press.

Bugla W. (2021). Ocena czasu przesączania przez strefę aeracji na podstawie wzorów obliczeniowych w rejonie ujęcia świerczków w Tarnowie (rejon północny). Engineering thesis. University of Silesia in Katowice. [unpublished, in Polish].

Cieślak W., Mach D., Czop M., Kwiatkowska N., 2021. Hydrogeological Documentation, specifying hydrogeological conditions in the area of the planned connection of the A4 motorway junction in Wierzchosławice with the Economic Activity Zone in Tarnów, inclusive of groundwater monitoring points in the area of infiltration groundwater intake of the Tarnów Waterworks "Kępa Bogumiłowicka", Tarnów County, Wierzchosławice and Tarnów Commune, Małopolskie Voivodeship (in Polish).

Corine Land Cover (2018). Corine-CLC (Online) Version 2020_20u1. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018.

Damigos, D., G. Tentes, M. Balzarini, F. Furlanis, and A. Vianello, 2017. Revealing the economic value of managed aquifer recharge: Evidence from a contingent valuation study in Italy, Water Resour. Res., 53, 6597–6611, doi:10.1002/2016WR020281.

Dashora, Y., Dillon, P., Maheshwari, B., Soni, P., Mittal, H. K., Dashora, R., Singh, P. K., Purohit, R. C., & Katara, P., 2019. Hydrologic and cost-benefit analysis at the local scale of streambed recharge structures in Rajasthan (India) and their value for securing irrigation water supplies. Hydrogeology Journal, 27(6), 1889–1909. https://doi.org/10.1007/s10040-019-01951-y

DEEPWATER-CE (2020a). Transnational Decision Support Toolbox For Designating Potential MAR Locations In Central Europe. D.T2.4.3 of the project DEEPWATER-CE. https://www.interreg-central.eu/Content.Node/2020-09-07-Handbook-Deliverable-D.T2.4.3-final.pdf (accessed July 2021).

DEEPWATER-CE (2020b). Common Methodological Guidance For Deepwater-CE MAR Pilot Feasibility Studies. D.T3.2.5 of the project DEEPWATER-CE. https://www.interreg-central.eu/Content.Node/DEEPWATER-CE/D.T3.2.5-COMMON-METHODOLOGICAL-GUIDANCE-FOR-DEEPWATER-CE-MAR.pdf (accessed July 2021).

DEEPWATER-CE (2021a). D.T3.4.1 - Report on the desk analysis of the pilot feasibility study for MAR deployment in porous aquifers located near industrial sites on contamination of aquifers.

DEEPWATER-CE (2021b). D.T3.4.2 - Report on the field work of the pilot feasibility study for MAR deployment in Tarnow area.

DEEPWATER-CE (2021c). D.T3.4.3 - Compiled check list for the application of risk management protocol during the field works for MAR in Tarnow shallow aquifers.

DEEPWATER-CE (2021d). D.T3.1.2 - Toolbox-based MAR pilot sites and aquifers selected (Poland).

Dillon, P.; Fernández Escalante, E.; Megdal, S.B.; Massmann, G. Managed Aquifer Recharge for Water Resilience. Water 2020, 12, 1846. https://doi.org/10.3390/w12071846

Gillefalk, M., Massmann, G., Nützmann G., Hilt S., 2018. Potential Impacts of Induced Bank Filtration on

Surface Water Quality: A Conceptual Framework for Future Research. Water. 10(9):1240. https://doi.org/10.3390/w10091240

Gorczyca, G., Gągólski, T. 2018: Baza danych GIS Mapy Hydrogeologicznej Polski 1:50000, pierwszy poziom wodonośny - występowanie i hydrodynamika, mapa zbiorcza arkusz Tarnów (977). Państwowy Instytut Geologiczny, Warszawa [in Polish].

Gorczyca, G., Koziara, T. 2018: Baza danych GIS Mapy Hydrogeologicznej Polski 1:50000,: pierwszy poziom wodonośny - występowanie i hydrodynamika, mapa zbiorcza arkusz Wojnicz (1000). Państwowy Instytut Geologiczny, Warszawa [in Polish].

Hasan, M.B., Driessen, P.P.J., Majumder, S., Zoomers, A., van Laerhoven, F., 2019. Factors affecting consumption of water from a newly introduced safe drinking water system: The case of managed aquifer recharge (MAR) systems in Bangladesh. Water (Switzerland) 11. https://doi.org/10.3390/w11122459

Herbich, P., Skrzypczyk, L., 2008. Wskazania metodyczne do opracowania warstw informacyjnych bazy danych GIS mapy hydrogeologicznej Polski 1:50 000 „Pierwszy poziom wodonośny - wrażliwość na zanieczyszczenie i jakość wód". Warsaw. Polish Geological Institute - Polish Research Institute (in Polish).

Jeanty, P. W., 2007. Constructing krinsky and robb confidence intervals for mean and median willingness to pay (WTP) using Stata. Sixth North American Stata Users' Group Meeting, Boston.

JCWPd, 2017 - Karta informacyjna JCWPd nr 150 [in Polish] https://www.pgi.gov.pl/dokumenty-pig-pib-all/psh/zadania-psh/jcwpd/jcwpd-140-159/4528-karta-informacyjna-jcwpd-nr-150/file.html

Journal of Laws (2015). Regulation of the Minister of Economy on allowing waste to be stored in landfills. Item 1277 of 16 July 2015 (in Polish).

Journal of Laws (2016). Regulation of the Minister of the Environment of November 18, 2016 on hydrogeological documentation and geological-engineering documentation. Item 2033 of 18 November (in Polish).

Journal of Laws (2016). Regulation of the Minister of Environment on the manner of conducting assessment of contamination of the earth surface. Item 1395 of 1 September 2016 (in Polish).

Journal of Laws of 2017, item 2294: Ordinance of the Minister of Health of 7 December 2017 on the quality of water intended for human consumption (in Polish).

Journal of Laws 2019, Item 1839: Regulation of the Council of Ministers of 10 September 2019 on projects that may significantly affect the environment (in Polish).

Journal of Laws (2020). Announcement of the Marshal of the Sejm of the Republic of Poland of 29 May 2020 on the announcement of the uniform text of the Act - Environmental Protection Law. Item 1219 of 29 May 2020 (in Polish).

Journal of Laws of 2021, item 247: Announcement of the Marshal of the Parliament of the Republic of Poland of 20 January 2021 on the announcement of the consolidated text of the Act on the provision of information about the environment and its protection, public participation in environmental protection and environmental impact assessments (in Polish).

Journal of Laws 2021, item 2233: Announcement by the Marshal of the Sejm of the Republic of Poland of 14 October 2021 on the publication of the consolidated text of the Act - Water Law (in Polish).

Journal of Laws (2021). Announcement of the Marshal of the Sejm of the Republic of Poland of 1 March 2021 on the publication of the consolidated text of the Act - Water Law. Item 624 of 1 March 2021 (in Polish).

Journal of Laws (2021). Announcement of the Marshal of the Sejm of the Republic of Poland of 2 July 2021 on the publication of the uniform text of the Act - Geological and Mining Law. Item 1420 of 2 July 2021 (in Polish.)

Jeanty, P. W., 2007. Constructing krinsky and robb confidence intervals for mean and median willingness to pay (WTP) using Stata. Sixth North American Stata Users' Group Meeting, Boston.

Kruk, L., Kapuściński, J., Leśniak, J., Górka, J., Reczek, D., Biedroński, G., Hotloś, Ł., Orlak, M., Tkaczuk, W., Bubrowsk,i T., Augustyn, K., Czechowska, B. 2017: Dokumentacja hydrogeologiczna ustalająca zasoby dyspozycyjne wód podziemnych obszarów bilansowych: zlewnia Dunajca i zlewnia Czarnej Orawy. Państwowy Instytut Geologiczny, Warszawa [in Polish].

Maliva, R.G., 2014. Economics of managed aquifer recharge. Water (Switzerland) 6, 1257–1279. https://doi.org/10.3390/w6051257

Marciniec, P., Zimnal, Z., Nescieruk, P. 2006: Szczegółowa mapa geologiczna Polski 1:50000, arkusz Wojnicz (1000). Państwowy Instytut Geologiczny, Warszawa [in Polish].

MIIIP, 2021: Małopolska Infrastuktura Informacj Przestrzennej. https://miip.geomalopolska.pl/ (16.11.2021) [in Polish].

Nadebaum, P., Chapman, M., Morden, R. and Rizak, S., 2004. A guide to hazard identification and risk assessment for drinking water supplies, CRC for Water Quality and Treatment Research Report Number 11.

Nandha M., Berry M., Jefferson B., Jeffrey P., 2015. Risk assessment frameworks for MAR schemes in the UK. Environmental Earth Sciences 73:7747–7757.

NRMMC–EPHC–NHMRC (2009). Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge; Natural Resource Management Ministerial Council; Environment Protection and Heritage Council; National Health and Medical Research Councouncil [WWW Document]. waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-mar-24.pdf

Paczyński, B. (Red.), 1995: Atlas hydrogeologiczny Polski. Państwowy Instytut Geologiczny, Warszawa [in Polish].

PN-EN 12457 Characterisation of waste Leaching Compliance test for leaching of granular waste materials and sludges Part 4: One stage batch leaching test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size reduction).

PN-EN 15975-2. Security of drinking water supply. Guidelines for risk and crisis management Risk management, 2013.

Purchla, J. 1991: Szczegółowa mapa geologiczna Polski 1:50000 arkusz Tarnów (977). Państwowy Instytut Geologiczny, Warszawa [in Polish].

Rodríguez-Escales P., Canelles A., Sanchez-Vila X., Folch A., Kurtzman D., Rossetto R., Fernández-Escalante E., Lobo-Ferreira J.-P., Sapiano M., San-Sebastián J., Schüth C. (2018). A risk assessment methodology to evaluate the risk failure of managed aquifer recharge in the Mediterranean Basin, Hydrol. Earth Syst. Sci., 22, 3213–3227, https://doi.org/10.5194/hess-22-3213-2018.

Ross, A. and Hasnain, S., 2018. Factors affecting the cost of managed aquifer recharge (MAR) schemes. Sustainable Water Resources Management, 4(2), pp.179-190.

Rupérez-Moreno, C., Pérez-Sánchez, J., Senent-Aparicio, J., Flores-Asenjo, P., Paz-Aparicio, C., 2017. Cost-Benefit Analysis of the Managed Aquifer Recharge System for Irrigation under Climate Change Conditions in Southern Spain. water 9, 343. https://doi.org/10.3390/w9050343

Rutkowski J. (2021). Analiza uziarnienia osadów dennych ze stawów infiltracyjnych ujęcia Świerczków w Tarnowie.Engineering thesis. University of Silesia in Katowice. (unpublished, in Polish).

Swierc J., Page D., Leeuwen J. Van (2005). Preliminary Hazard Analysis and Critical Control Points Plan (HACCP) -Salisbury Stormwater to Drinking Water Aquifer Storage Transfer and Recovery (ASTR) Project of Montana. Water.

Treichel, W., Haładus, A., Zdechlik, R. 2015: Simulation and optimization of groundwater exploitation for the water supply of Tarnów agglomeration (southern Poland). Bulletin of Geography, Physical Geography Series, 9 (1), pp. 21-29. https://doi.org/10.1515/bgeo-2015-0012.

Wojtal G., Kowalczyk A., Rzepecki T. (2009). Groundwater quality in the catchment area of the Świerczków infiltration groundwater intake in Tarnów. Biuletyn Państwowego Instytutu Geologicznego, 436, 547-554 [in Polish].

Wojtal, G. 2013: Formowanie się składu chemicznego wód podziemnych w warunkach antropopresji przemysłowej na przykładzie infiltracyjnego ujęcia wody Świerczków dla miasta Tarnowa. Uniwersytet Śląski, Wydział Nauk o Ziemi, Sosnowiec. [PhD thesis in Polish].

Woś, A. 2010: Klimat Polski w drugiej połowie XX wieku. Wydawnictwo Naukowe UAM, Poznań: p. 489 [in Polish].

websites:

https://www.interreg-central.eu/Content.Node/DEEPWATER-CE.html

https://ggis.un-igrac.org/maps/2171/embed

https://ggis.un-igrac.org/maps/2171/view

http://www.marsol.eu/6-0-Home.html

Appendix A. Costs of MAR system's extension

		Average value (range), PLN	*Number*
Initial investment - Capital costs		726,550 (666,950-786,150)	
Investigation costs		***68,450*** ***(58,400 - 78,500)***	
Geophysical surveys (ERT) to determine areas most suitable for MAR (1 profile)		2,700 (2,400 – 3,000)	1 profile
Conducting physicochemical analyses of water (per one sample)		425 (350 – 500)	10 samples
Modeling studies together with forecasting simulations		35,000 (30,000 – 40,000)	
Execution of projects, water use permit proceedings, hydrogeological documentation required by law		26,000 (22,000 – 30,000)	
Purchase of maps and data		500	
Cost of wells		***117,050***	
The average cost per one well (from putting the drilling rig on the point, through drilling a hole, installing a filter column, cleaning the area, pump tests etc)		23,210	5 wells
Cost of geodesic surveyance		1,000	
Piezometers		***31,150*** ***(30,900 - 31,400)***	
The cost of making one meter of borehole		300	89 meters
Execution and installation of protective casings per 1 piezometer		300	9 piezometer
Other works connected to the ALL PLANNED piezometers (protocols, documentation materials, land reclamation)		1,750 (1,500 – 2,000)	
Infiltration ditch [length of the ditch: 300 m; the width of the top of the ditch: 10 m; width of the bottom of the ditch: 7-8 m; ditch height: 3-3.5 m; the volume of excavations: 8100 m^3]		***234,900*** ***(210,600 - 259,200)***	
Option 1	Excavation [excavation and leveling of soil in the adjacent area]	145,800	
	Ground leveling with a bulldozer [excavation and leveling of soil in the adjacent area]	64,800	

Option 2	Excavation, loading and removal [excavation with transport the material up to 10 km]	259,200	
Connecting new wells and a ditch to the existing system [length of pipes needed for connection: 250-300 meters, cost of installation work: 1000 PLN/meter]		***275,000*** ***(250,000 - 300,000)***	

	Current cost [17 working wells and 3 infiltration ditches], PLN	Estimate of cost for an extension [5 wells and 1 ditch], PLN
Annual operation and maintenance costs	2,257,340	676,418
Annual raw water costs	322,950	96,885
Annual cost of extraction and distribution	1,161,594	348,478
Annual labor costs	201,508	60,452
Annual electricity costs	361,759	108,528
Annual amortization costs	118,595	35,579
Annual post-treatment cost (purchase costs of hypochlorite and chlorine)	43,322	12,997
Storage costs: one reservoir at Świerczków that could act as a water storage tank, the costs of its maintenance are related only to the real estate tax (without ammortization)	2,612	0
Regulatory testing costs	45,000	13,500

Appendix B. Questionnaire

Questionnaire for water users

Within DEEPWATER-CE project, we're conducting research on the extension of managed aquifer recharge scheme in your area and your answers will sufficiently help us in evaluating the proposed project. We really appreciate your input!

Thank you for taking the time to fill in this questionnaire; it should only take 10-15 minutes.

Your answers will be treated with complete confidentiality and will be entirely anonymous.

Background information

Managed aquifer recharge (MAR) is a water management approach that can be used to maximize natural storage and increase water supply system resilience during periods of low flows and high seasonal variability. During these periods, such as in the dry season, aquifers are intentionally recharged to recover water. A managed recharge implies that the recharge process is controlled and ensures health and environmental risks are minimized.

Groundwater is the water found underground in the cracks and spaces in soil, sand and rock. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers.

Section 1. Current local environmental conditions and existing problems

1. Do you have expertise and qualification in the field of groundwater management?

   a. Yes, it is my major specialization
   b. I have some experience but it is not my direct field of expertise
   c. No, I have no experise in this field

2. Do you know what type of water is the source of your tap water? (please tick one)

   a. Yes, groundwater
   b. Yes, surface water
   c. Yes, a mix of groundwater and surface water
   d. I do not know

3. Have you ever heard of problems related to groundwater quantity (from any type of media or relatives/friends) in the area? (please tick one)

   a. Yes, rather frequently
   b. Yes, a few times
   c. Never heard

4. Have you ever heard of problems related to groundwater quality (from any type of media or relatives/friends) in the area?

   a. Yes, rather frequently
   b. Yes, a few times
   c. Never heard

5. Please, select your main concern with regards to groundwater problems (please tick all that apply)

   a. over-pumping
   b. water scarcity during drought periods
   c. pollution from industrial wastewater
   d. pollution from pesticides and fertilizers
   e. other (please, specify)___________________________________

6. Do your household have an impact on groundwater quality and/or quantity? (please tick one)

   a. Yes, we impact groundwater as much as the other households
   b. Yes, but we impact groundwater more than the other households
   c. Yes, but we impact groundwater less than the other households
   d. No impact

7. Please, select prevailing pressures on groundwater among the following (please tick up to two)

   a. wasting of water
   b. municipal wastewater discharge
   c. industrial pollution
   d. inappropriate municipal waste management
   e. other (please, specify)___________________________________

8. Do you believe that there should be a protection and preservation plan for groundwater? (please tick one)

   a. Yes
   b. No
   c. Not sure

9. Do you feel some responsibility to contribute to it? (please tick one)

   a. Yes
   b. No
   c. Not sure

10. Are you aware of functioning chemical plants in your area and the danger that it might bear for local water resources? (please tick one)

   a. Yes
   b. No

11. To what extent are you concerned with endangered by chemical industry drinking water aquifers? (please tick one)

    a. Not at all
    b. To some extent
    c. To a moderate extent
    d. To a great extent

Section 2. Willingness to pay

A plan is proposed in your area that aims to extend the area of existing managed aquifer recharge scheme in order to increase the available water resources for your city/town. The main objective of the artificial aquifer recharge is to store excess water and thus to increase available reserves of groundwater for future use while improving water quality. In addition, it can have a significant environmental benefit by mitigating the negative effects of a functioning chemical plant that may lead to contamination of drinking water in your area. However, if this extension of MAR scheme was implemented, it would cost money. So citizens would be asked to financially contribute to putting this MAR's extension in place.

1. What is your preferred way of funding the proposed policy? (please tick one)

    a. through municipal taxes
    b. through water bills
    c. through higher income taxes
    d. other way (please, specify)____________________

2. If you were given the choice to make a monetary contribution, through your preferred way of donation, what is the MAXIMUM amount you would be willing to pay per month? (please tick one)

    a. 0 PLN
    b. 10 PLN
    c. 20 PLN
    d. 30 PLN
    e. 40 PLN
    f. 50 PLN
    g. 60 PLN
    h. 70 PLN
    i. more than 70 PLN (please specify the exact amount)___________

3. If your answer is zero in the previous question, please, choose the reason for your decision (please tick all that apply)

    a. I already pay enough municipal/income taxes
    b. I cannot afford it
    c. It is the government's responsibility
    d. The proposed plan is not feasible, good enough, convincing, etc.
    e. I don't care much about preserving and protecting groundwater

f. Other reason (please, specify)_________________________

4. If your answer is nonzero in the previous question, 3lease, distribute the amount of your financial support according to the following distinct categories of benefits that MAR scheme yields (please treat the amount of your financial support as 100%)

a. Use of groundwater by the members of your household	
b. Use of groundwater by other members of the local community	
c. Use of groundwater by future generations	
d. Use of groundwater by groundwater-dependent ecosystems	

Section 3. Safety of water from MAR

1. Do you have any concerns regarding the safety of drinking water supply from the MAR system? (please tick one)

   a. Yes
   b. No

2. If yes, to what extent are you concerned with the safety of drinking water supply from the MAR system? (please tick one)

   a. Not at all
   b. To some extent
   c. To a moderate extent
   d. To a great extent

3. Please specify the particular concerns you have:____________________________

Section 4. Demographic questions

1. Which gender do you identify with (please tick one)

   a. Male
   b. Female
   c. Prefer not to answer

2. What is your age? (please tick one)

   a. 18 - 30 years old
   b. 30 - 45 years old
   c. 45+
   d. Prefer not to answer

3. What is the highest degree or level of education you have completed? (please tick one)

   a. High School
   b. Bachelor's Degree
   c. Master's Degree
   d. Ph.D. or higher
   e. Prefer not to say

4. The average monthly gross income in Tarnów for 2019 was PLN 5200. Please specify your gross income compared to the average level (please tick one):

   a. Below the average level
   b. Close to the average level
   c. Above the average level
   d. Prefer not to say

5. What is your current employment status? (please tick one)

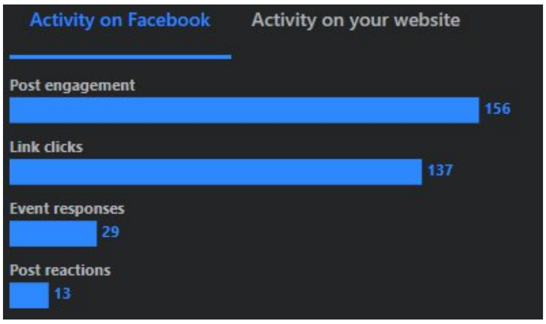
   a. Employed Full-Time
   b. Employed Part-Time
   c. Seeking opportunities
   d. Retired
   e. Prefer not to say

6. How many children do you have? (please tick one)

   a. None
   b. 1
   c. 2
   d. 3
   e. More than 3
   f. Prefer not to say

Thank you very much for taking the time to complete this questionnaire.

Appendix C. Social media advertisement



We had quite a good post engagement and number of link clicks but of course only part of them resulted in a fully completed questionnaire. We have a relatively good balance in demographic characteristics, which supports representativeness of obtained results.

Appendix D. WTP Survey: Summary tables

WTP survey summary: Polish pilot site *(51 full responses)*

- Do you have expertise and qualification in the field of groundwater management?

	Share of respondents
I have some experience but it is not my direct field of expertise	19.61%
No, I have no experise in this field	70.59%
Yes, it is my major specialization	5.88%
No answer	3.92%

- Do you know what type of water is the source of your tap water?

	Share of respondents
I do not know	35.29%
Yes, a mix of groundwater and surface water	31.37%
Yes, groundwater	9.80%
Yes, surface water	19.61%
No answer	3.92%

- Have you ever heard of problems related to groundwater quantity

	Never heard	Yes, a few times	Yes, rather frequently	Share of respondents
Never heard	33.33%	15.69%	5.88%	54.90%
Yes, a few times	0.00%	21.57%	5.88%	27.45%
Yes, rather frequently	0.00%	1.96%	15.69%	17.65%
Share of respondents	33.33%	39.22%	27.45%	100.00%

- Please, select your main concern with regards to groundwater problems

Share of respondents	Over-pumping	Water scarcity during drought periods	Pollution from industrial wastewater	Pollution from pesticides and fertilizers
No	90.20 %	31.37%	70.59%	56.86%
Yes	9.80%	68.63%	29.41%	43.14%

- Does your household have an impact on groundwater quality and/or quantity?

	Share of respondents
No	25.49%
Yes, but we impact groundwater less than the other households	21.57%
Yes, but we impact groundwater more than the other households	1.96%

Yes, we impact groundwater as much as the other households	47.06%
No answer	3.92%

- Please, select prevailing pressures on groundwater

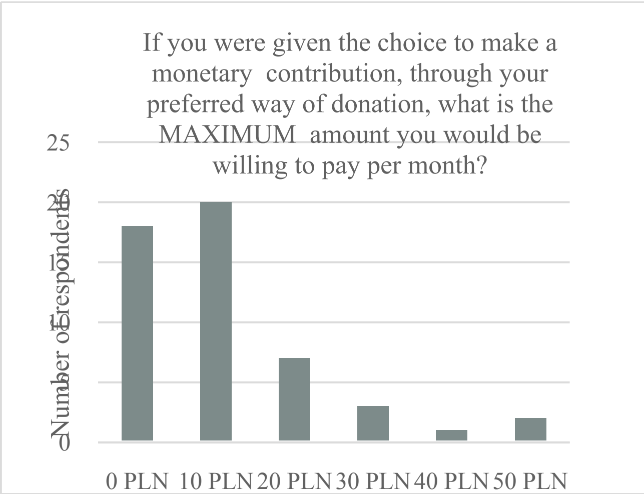
Share of respondents	wasting of water	municipal wastewater discharge	industrial pollution	inappropriate municipal waste management
No	29.41%	80.39%	54.90%	60.78%
Yes	70.59%	19.61%	45.10%	39.22%

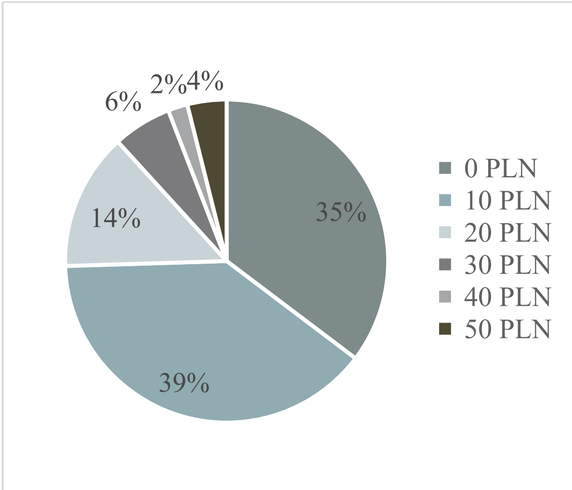
Do you believe that there should be a protection and preservation plan for groundwater?	*Do you feel some responsibility to contribute to it?*				
	No	*Not sure*	*Yes*	*No answer*	*Share of respondents*
No	0.00%	0.00%	0.00%	3.92%	3.92%
Not sure	0.00%	3.92%	0.00%	17.65%	21.57%
Yes	3.92%	15.69%	50.98%	3.92%	74.51%
Share of respondents	3.92%	19.61%	50.98%	25.49%	100.00%

Are you aware of functioning chemical plants in your area and the danger that it might bear for local water resources? *To what extent are you concerned with endangered by chemical industry drinking water aquifers?*	*Share of respondents*
No	7.84%
To a moderate extent	1.96%
To some extent	5.88%
Yes	92.16%
Not at all	7.84%
To a great extent	23.53%
To a moderate extent	31.37%
To some extent	29.41%
	100.00%

- What is your preferred way of funding the proposed policy?

	Share of respondents
Other	11.76%
through higher income taxes	11.76%
through municipal taxes	29.41%
through water bills	47.06%

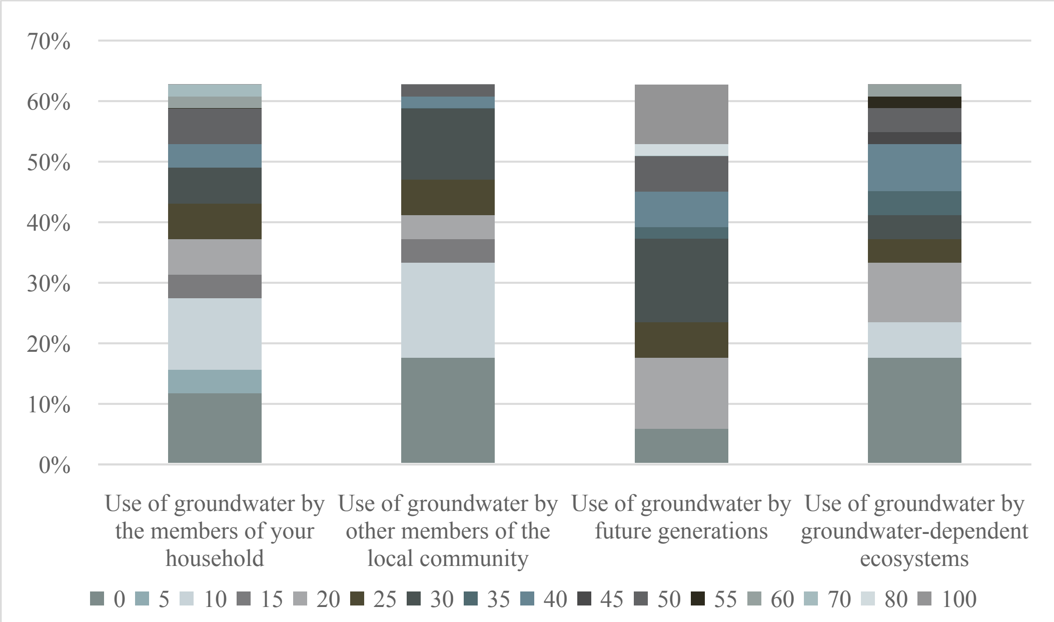




- If your answer is zero in the previous question, please, choose the reason for your decision

	I already pay enough municipal/income taxes	I cannot afford it	It is the government's responsibility	The proposed plan is not feasible, good enough, convincing, etc.	I don't care much about preserving and protecting groundwater
No	5.88%	27.45%	29.41%	31.37%	35.29%
Yes	29.41%	7.84%	5.88%	3.92%	

- If your answer is nonzero in the previous question, please, distribute the amount of your financial support according to the following distinct categories of benefits that MAR scheme yields (y axis – percent of respondents that assigned particular percent of monetary contribution)



- Do you have any concerns regarding the safety of drinking water supply from the MAR system?

	Share of respondents
No	82.35%
Yes	15.69%
No answer	1.96%

- To what extent are you concerned with the safety of drinking water supply from the MAR system?

	Share of respondents
Not at all	5.88%
To a great extent	3.92%
To a moderate extent	5.88%
To some extent	7.84%

- Respondents' profile

	Age					
Gender	18-30	30-45	45+	Prefer not to answer	No answer	*Share of respondents*
Female	5.88%	25.49 %	19.61 %	0.00%	0.00%	50.98%
Male	11.76 %	13.73 %	13.73 %	0.00%	0.00%	39.22%
Prefer not to answer	0.00%	0.00%	0.00%	3.92%	0.00%	3.92%
No answer	0.00%	0.00%	0.00%	0.00%	5.88%	5.88%
Share of	17.65	39.22	33.33	3.92%	5.88%	100.00%

respondents	%	%	%			

- Educational level

	Share of respondents
Bachelor's Degree	9.80%
High School	19.61%
Master's Degree	54.90%
Ph.D. or higher	7.84%
Prefer not to answer	1.96%
No answer	5.88%

- Income level

	Share of respondents
Above the average level	15.69%
Below the average level	43.14%
Close to the average level	25.49%
Prefer not to answer	9.80%
No answer	5.88%

- Employment status

	Share of respondents
Employed Full-Time	56.86%
Employed Part-Time	7.84%
Prefer not to answer	15.69%
Retired	9.80%
Seeking opportunities	3.92%
No answer	5.88%

- Number of children

	Share of respondents
0	33.33%
1	25.49%
2	21.57%
3	7.84%
None	1.96%
Prefer not to answer	5.88%
No answer	3.92%