DEEPWATER-CE

WORKPACKAGE T3, ACTIVITY T3.4

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

REPORT D.T3.4.1.

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Table of content

I. Introduction

Within the **DEEPWATER-CE** project a transnational decision support toolbox on designating potentially suitable MAR locations in Central Europe **(output O.T2.1, DEEPWATER-CE, 2020b)** was developed. Based on this toolbox, pilot sites with applicable MAR types can be identified **(deliverables D.T3.3-6.1-5)**. Further a common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies **(deliverable D.T3.2.5)** was proposed which can be used in combination with the transnational decision support toolbox to identify the potential of MAR application. The report on the desk analysis of the pilot feasibility study for MAR deployment in porous aquifers located near industrial sites on contamination of aquifers **(D.T3.4.1)** is giving an overview on existing data for the feasibility assessment of the DEEPWATER-CE pilot site in Poland. Based on the existing data the further steps for determining missing data for a comprehensive feasibility assessment is developed and documented in a pilot action design plan. Polish pilot site is located in southern Poland, on the west side of the city of Tarnów and in its vicinity. The study area was selected on the basis of the developed suitability maps for two MAR techniques, performed in accordance with the developed methodology **(output O.T2.1)**. The feasibility study will include infiltration ditches and induced river and lake bank filtration.

II. Data availability and sources of data

The study site is relatively well recognised in terms of hydrogeological conditions and geological formation. In order to obtain as much information as possible about the Polish pilot site, an extensive desk study was carried out, including a review of publications in the field of water management, hydrogeology and geology for the Tarnów area, various thematic maps were collected and a significant amount of basic data (Table 1) was obtained for analysis. The findings were used to prepare the required data set and design the necessary field, laboratory and modelling studies for the feasibility study of two types of MAR (induced river bank filtration and infiltration ditches).

Table 1. *Data availability and sources of data.*

Data type	The place where the data was obtained	The form in which the data was provided
Land use map	https://clc.gios.gov.pl/	Shapefile
Topographic map	https://www.geoportal.gov.pl/uslugi/usluga-przegladania-wms	WMS
Flood hazard and flood risk maps	https://isok.gov.pl/hydroportal.html	PDF
Geological maps	https://geolog.pgi.gov.pl/	Shapefile / Raster
Borehole logs and locations	http://geologia.pgi.gov.pl/	Shapefile
Hydrogeological map	https://geolog.pgi.gov.pl/	Shapefile / Raster
Meteorological data	https://dane.imgw.pl/datastore	Text file

III. Pilot site characterization based on existing data

3.1 Surface topography

The described area is located mainly within the mesoregion of the Nadwiślańska Lowland belonging to the Sandomierz Basin, only in its southern part there is a distinctive fragment of the Ciężkowice Foothills (Pogórze Ciężkowickie), belonging to the Central Beskids Foothills (Kondracki, 1998).

The Nadwiślańska Lowland is a fragment of the river valleys of the Dunajec and Biała Tarnowska rivers, which covers the flood and alluvial terraces of both rivers. The average width of the Dunajec valley in this section is about 1000 m, the Biała Tarnowska valley has an average width of about 300 m. In the area of the Swierczków wellfield, the ordinates of the river terraces are 190-200 m.a.s.l. The land surface is practically flat here, rising slightly in the southern part of the wellfield, where it reaches about 210 m.a.s.l. Larger denivelations are of anthropogenic origin and include flood banks, gravel pits, drainage ditches and landfills.

In the southern part of the described area in the region of Zbylitowska Góra, there is an upland of the Ciężkowice Foothills mesoregion. The foothills are made up of flysch deposits of the Silesian and Sub-Silesian Nappe with Ciężkowice sandstones. The highlands of the Ciężkowice Foothills rises here at the level of 230-260 m.a.s.l.

3.2 Climatic conditions

Tarnów is located in south-eastern Poland (50,03 N, 20,98 E, 209 m.a.s.l.) in the Lesser Poland Province, upon the river Dunajec, at the mouth of the Biała Tarnowska river and represents the Southern Lesser Poland climatic region according to A. Woś (2010) classification. The weather of the area is mostly shaped by 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 weather are weather fronts that mark the transition zone between two air masses and lead to weather change and precipitation. The warm front crosses the region during ca. 66% of days a year with the maximum in January (8.3%). The annual frequency of cold fronts is higher – 126% a year – and the peak of their occurrence falls in November and December (c.a. 12% in both months).

Based on long-term weather observations for Tarnów (1966-2019), the following are described trends in air temperature and related indices, calculated with the least square method and tested with a t-student test. Trends in precipitation and related indices were calculated with Sen’s slope and tested with Mann-Kendal non-parametric test which requires no conditions as to the statistical distribution of the data.

Table 2. *Average values and trends (change per decade) in mean air temperature (Tavg), the number of days with maximum air temperature ≥25°C (Tmx25), ≥30°C (Tmx25), ≥35°C (Tmx25), and in the number of days with mean air temperature <0°C (Tavg<0), Tarnów 1966-2019, p - statistical significance: * a ≤0.05, ** a ≤0.01, *** a ≤0.001.*

Month	Tavg [°C]	Tr	p	Tmx25 [days]	Tr	p	Tmx30 [days]	Tr	p	Tmx35 [days]	Tr	Tavg<0 [days]	Tr	p
Jan	-1.8	+0.4		0	-		0	-		0	-	17.1	-0.8	
Feb	-0.2	+0.2		0	-		0	-		0	-	13.3	-0.3	
Mar	3.7	+0.2		0	-		0	-		0	-	6.2	-0.4	
Apr	9.1	**+0.5**	***	0.9	+0.3		0.0	-		0	-	0.3	0	
May	14.1	**+0.3**	*	5.3	**+0.7**	*	0.3	**+0.1**	**	0	-	0	-	
Jun	17.1	**+0.6**	***	10.0	**+1.6**	***	1.6	**+0.7**	***	0	-	0	-	
Jul	18.8	**+0.6**	***	14.7	**+2.0**	***	3.5	**+1.4**	***	0.2	-	0	-	
Aug	18.3	**+0.6**	***	13.8	**+2.2**	***	3.4	**+0.3**	***	0.2	-	0	-	
Sep	13.9	+0.2		3.8	**+0.6**	*	0.2	**+0.1**	*	0	-	0	-	
Oct	9.3	+0.1		0.3	0		0	-		0	-	0.4	-0.1	
Nov	4.4	+0.3		0	-		0	-		0	-	5.5	-0.3	
Dec	0.1	+0.4		0	-		0	-		0	-	13.7	-0.9	
MAM	8.9	**+0.4**	***	6.2	**+1.0**	*	0.3	**+3.7**	***	0	-	6.5	-0.3	
JJA	18.1	**+0.6**	***	38.5	**+0.8**	***	8.4	**+0.2**	*	0.4	-	0	-	
SON	9.2	**+0.2**	*	4.1	**+0.6**	*	0.2	**+3.4**	***	0	-	5.9	-0.4	
DJF	-0.5	**+0.4**	*	0	-		0	**+0.1**	*	0	-	43.5	-2.7	
Annual	8.9	**+0.4**	***	48.8	**+7.4**	***	8.9	**+3.6**	***	0.4	-	56.5	-2.8	

The climate of Tarnów is of a continental type. The mean annual air temperature is 8.9°C (1966-2019) and it has been significantly rising since 1966 with the rate of 0.4°C per decade (Figure. 1). July and January are the warmest and the coldest months, respectively (Table 2). All trends in monthly air temperature were positive, however, the warming was significant between May and September with the maximum rate in summer months (Table 2). The general increase in mean air temperature is related to an increase in high air temperatures rather than to changes in air temperatures below the freezing point. Significant trends calculated for the number of summer and heat days that occur between April and October, were in summer months and in May and September. The extremely hot days are very rare in Poland, therefore trends in their series were not calculated. However, it is interesting that in the entire research period there were 21 such days noted in Tarnów, 19 of which occurred after 2000. No significant trend was found in the frequency of days with Tavg < 0°C.

Tarnów annually receives ca. 725 mm of precipitation (1966-2019). The annual course of precipitation in Tarnów is typically continental with a clear maximum in the summer months (July) and minimum in winter (February). Unlike air temperature, most trends in precipitation were insignificant and of various directions depending on the month and season. The only significant trends were those in August and December (Table. 3).

An increase in air temperature influences the long-term trend in potential evapotranspiration (PET) on an annual scale and in JJA (both seasonal and monthly series, Table 2). All these trends were positive and statistically significant at 0.001 level.

The long-term variability in annual precipitation totals presented in Figure 3 shows three phases varying in the short-term precipitation tendency. From the beginning of the research period to the end of the 1970s, annual precipitation was higher than the long-term average with no particular trend, since the beginning of the 1980s until the end of the 2010s there was an increase in annual totals and then precipitation showed a decreasing tendency.

The frequency of days with precipitation (≥0.1 mm) does not change vividly throughout a year. Such days are the most frequent in winter (December, January) and the least frequent between August and

October (12-13 days). Trends in the indices of precipitation frequency calculated for the entire research period were sporadically significant and negative – if significant. These significant decreases concerned the number of days with precipitation ≥0.1mm in August and December, the number of wet days in June, December and JJA and the number of days with precipitation ≥10mm in August and JJA are shown in Table 4.

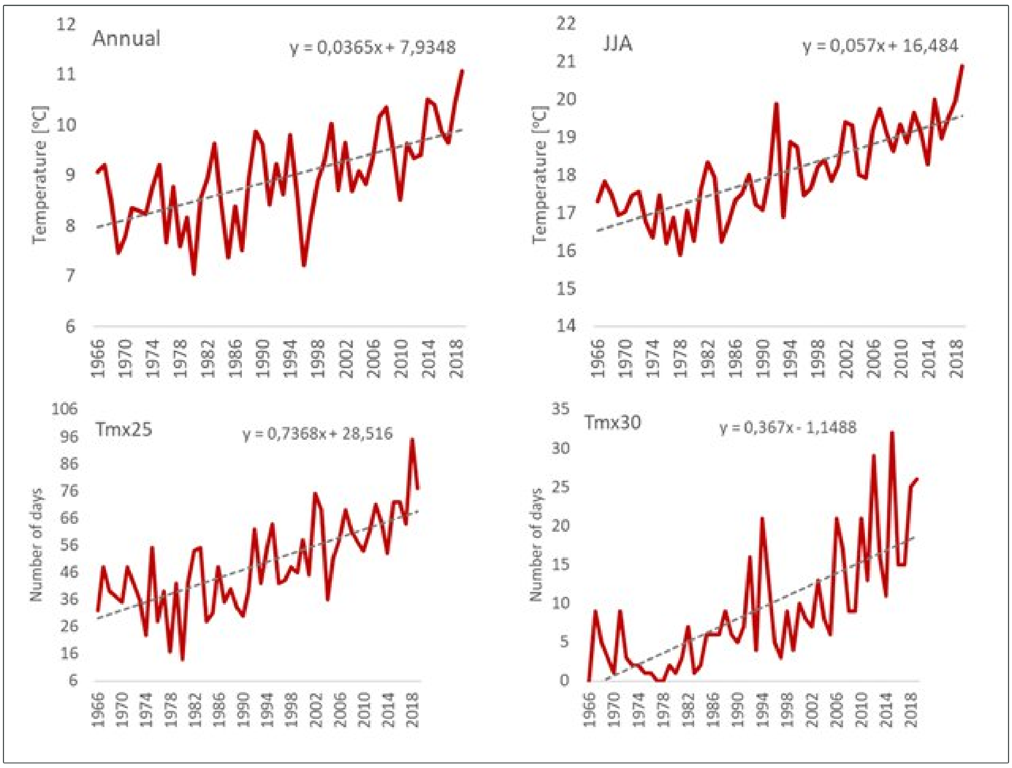


Fig. 1. *Long-term variability in annual and summer (JJA) air temperature and the numbers of summer (≥25°C) and heat (≥30°C) days in Tarnów, 1966-2018.*

Table 3. *Mean values and trends (change per decade) in the indices of precipitation frequency, P – precipitation totals, PET – potential, p – statistical significance: * a ≤0.05, ** a ≤0.01, *** a ≤0.001.*

	P [mm]	Tr	p	PET [mm]	Tr	p	CWB [mm]	Tr	p
Jan	36.2	+0.2		1.5	0		+34.7	0.1	
Feb	32.3	-0.5		3.6	0		+28.7	-0.8	
Mar	37.6	-0.2		16.7	+0.3		+20.9	-0.7	
Apr	53.5	-0.9		48.1	**+1.6**	*****	+5.3	-2.8	
May	86.7	+1.5		89.4	+0.6		-2.7	0.6	
Jun	102	-7.9		115.5	**+2.8**	*******	-13.6	**-9.9**	*****
Jul	108	-1.9		127.3	**+3.2**	*******	-19.3	**-5.8**	
Aug	79.8	**-10.5**	*****	111.9	**+3.1**	*******	-32.1	**-13.1**	******
Sep	64.6	+2.0		70.2	+0.2		-5.7	2.8	
Oct	47.7	+0.4		39.7	-0.4		+8.0	0.7	
Nov	39.9	-1.8		0.5	0		+39.4	-1.8	
Dec	37.2	**-3.4**	*****	3.1	**+0.1**		+34.1	-4.0	*
MAM	178	+2.7		154.3	+2.1		23.5	-0.3	
JJA	290	-16.4		354.6	**+8.7**	*******	**-65.0**	**-26.3**	*
SON	152	+3.8		110.4	-0.3		41.8	4.2	
DJF	104	-3.3		8.0	+0.6		95.6	-5.0	
Annual	725	-13.6		627.5	**+12.0**	*******	**97.7**	**-25.4**	*

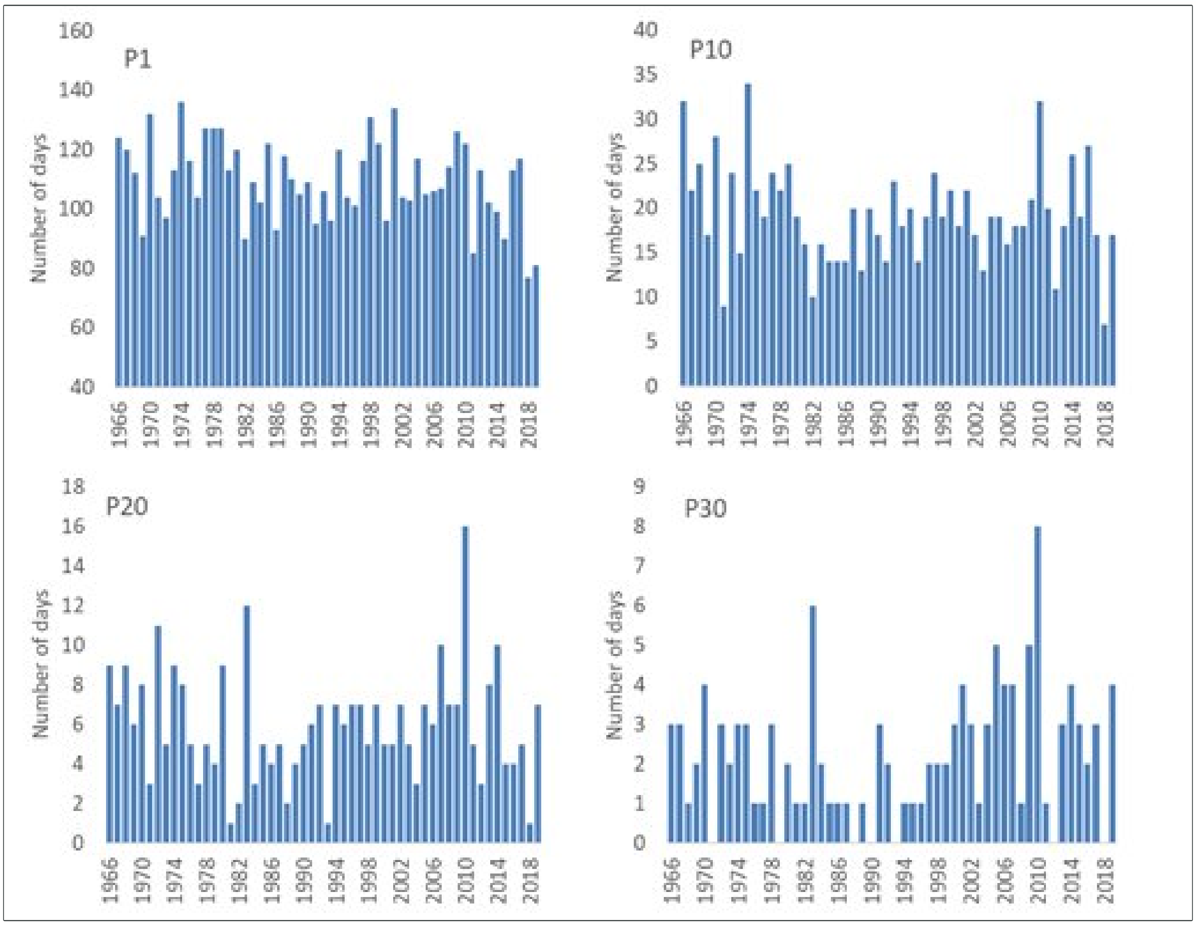


Fig. 2. *Long-term variability in the indices of precipitation frequency, Tarnów 1966-2019, P1, P10, P20 and P30 - number of days with precipitation ≥1.0 mm, ≥10 mm, ≥20 mm, ≥30 mm.*

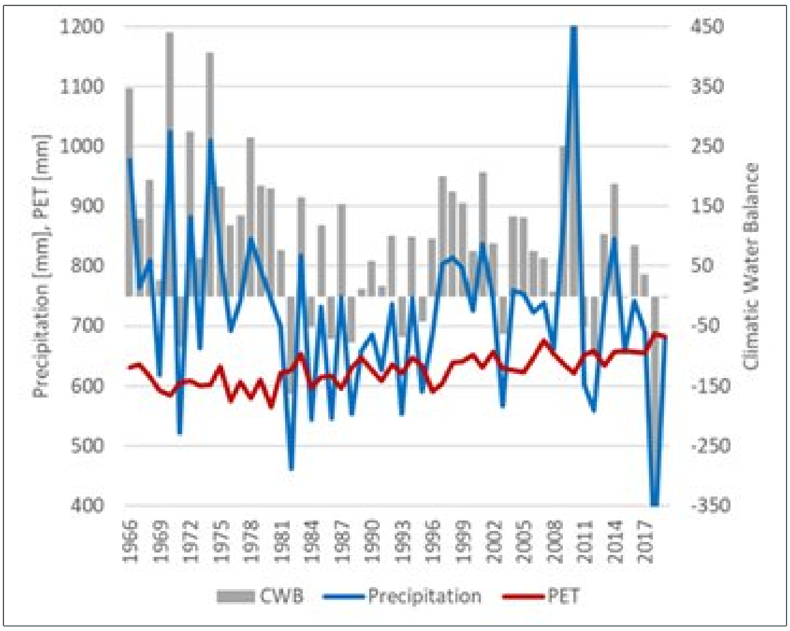


Fig. 3. *Long-term variability in Annual values of Climatic Water Balance (CWB), precipitation totals and potential evapotranspiration (PET) in Tarnów for 1966-2019.*

Table 4. *Average values and trends (change per decade) in the number of days with precipitation ≥0.1 mm, ≥1.0 mm (P1), ≥10 mm (P10), ≥20 mm (P20), ≥30 mm (P30) Tarnów 1966-2019 (trends in P20 and P30 were not calculated due to their low frequency)*, p - statistical significance: * α ≤0.05, ** α ≤0.01, *** α ≤0.001.

	P01 [mm]	Tr	p	P1 [mm]	Tr	p	P10 [mm]	Tr	p	P20 [mm]	P30 [mm]
Jan	17	0.5		9	0.3		0.4	0		0.1	0
Feb	14	0		7	0.0		0.5	0		0.1	0
Mar	15	-0.3		9	0.0		0.5	0		0.1	0
Apr	14	0		9	0.0		1.5	0		0.3	0.1
May	15	0		10	0.0		2.8	0		0.8	0.4
Jun	15	-0.5		11	**-0.8**	*	3.1	-0.2		1.2	0.6
Jul	15	0		11	0.0		3.3	0		1.2	0.6
Aug	12	-0.5		9	-0.4		2.6	**-0.3**	*	1.1	0.3
Sep	13	0		9	0.0		1.9	0		0.7	0.2
Oct	13	0		8	-0.4		1.4	0		0.3	0
Nov	14	**-0.7**	*	8	-0.4		1.0	0		0.1	0
Dec	17	**-1.1**	**	10	**-0.8**	*	0.4	0		0.0	0
MAM	43	0		28	0.0		4.7	0		1.2	0.5
JJA	43	-0.8		32	**-1.3**	*	9.0	**-1.0**	**	3.5	1.4
SON	39	-0.5		24	-0.7		4.2	0.3		1.1	0.3
DJF	48	-0.8		26	-0.5		1.2	0		0.1	0
Annual	173	-2.0		110	-2.6		19.2	-0.6		6.0	2.2

Although trends in the frequency of precipitation above the selected thresholds were not significant, their long-term variabilities illustrated in Figure 2 clearly show a decrease in the frequency of wet days and days with precipitation ≥10 mm since the end of 1990. The extreme precipitation above the daily total of 30 mm in the same period occurred more frequently (Figure. 3).

Summing up, the climate of Tarnów has experienced significant warming and an increase in evapotranspiration, which depends on air temperature. The most intense warming was recorded in summer. Precipitation indices did not reveal any long-term significant changes but short-term tendencies were obvious.

3.3 Land use and potential sources of surface and groundwater contamination | historical development

The city of Tarnów was established in the area of the knightly village of Tarnów Wielki, mentioned for the first time in 1309 (in *The Life of Blessed Kinga* by Jan Długosz). Obviously, more current events are more important for the subject of the report, such as the "industrial revolution" and the establishment of Grupa Azoty S.A. The decision to build the first factory was made in 1927 at the request of Ignacy Mościcki. The area of 670 ha, included in the villages of Świerczków and Dąbrówka Infułacka, purchased from Prince Roman Władysław Sanguszko for 210 000 American dollars, were used to build the factory with a housing estate. The official opening of the State Factory of Nitrogen Compounds took place in January 1930. The State Factory of Nitrogen Compounds was one of the largest investments of the 1920s in Poland during the Second Polish Republic, and one of the most modern factories in Europe. The factory ran its own farm with a vegetable garden of 6 hectares and experimental plots. After the war, the factory resumed operations in 1948 (https://www.it.tarnow.pl/). In 2012, "Zakłady Azotowe in Tarnów" signed a consolidation agreement with "Zakłady Azotowe in Puławy", the result of which was to create Grupa Azoty S.A (the company changed its name in April 2013).

Tarnów is an industrial centre with a dominant chemical industry (the aforementioned Grupa Azoty, Becker Farby Przemysłowe Sp. z o.o., Summit Packaging Polska Sp. z o.o.) and electromechanical industry (Zakłady Mechaniczne Tarnów, Ośrodek Badawczo-Rozwojowy Sprzętu Mechanicznego Sp. z o.o., Fabryka Silników Elektrycznych "Tamel", Lenze Tarnów Sp. z o.o., Fabryka Maszyn Tarnów). There are also other plants and enterprises, including those from the fuel and energy industry (GAZ-SYSTEM branch, Tauron-Dystrybucja branch, Tauron Dystrybucja Pomiary), food industry (Zakłady Mięsne "Mięstar" which is part of the Sokołów Group, Zakłady Mleczarskie "Mlektar", Zakłady Przemysłu Chłodniczego "Fritar"), concrete production (Bruk-Bet), clothing (Spółdzielnia "Tarnowska Odzież ", Tarnospin) and glass production (Huta Szkła Gospodarczego Tarnów, part of the Krosno S.A. Group). The Logistics Center of TC Dębica and Goodyear as well as the reloading and storage center for DHL wheeled transport operate in Tarnów.

108 117 people, 57 048 women and 51 129 men are registered in Tarnów (as of June 30, 2020; demografia.stat.gov.pl). Also, according to statistical data (Niemiec et al., 2020), at the end of 2019 Tarnów had 108,400 inhabitants (i.e. 3.2% of the population of the Małopolskie voivodship). The largest population in Tarnów was in 1996: 122 359 inhabitants (Statistics Poland). Since then, the number of inhabitants of the city has decreased (by approx. 12 thousand in the last 20 years). It is related to the negative population growth (−1.7 ‰ in the first half of 2016), migration and emigration. The balance of migration for permanent residence in the years 2014–2015 is −5.3 per 1000 inhabitants. The demographic forecast of the Central Statistical Office shows that in 2027 the number of inhabitants of the city will fall below 100 000, and in 2050 Tarnów will be inhabited by 72 500 people (https://gazetakrakowska.pl/). At the end of 2019, the registered unemployment rate was 4.2% (Niemiec et al., 2020).

The main land use type of the study area (47%) are anthropogenic areas - terrains related to "urban fabric" and the widely understood industry of the city of Tarnów. The second largest type is agriculture (39%). The remaining 14% are natural vegetation (e.g. forests) and water areas (Fig. 4).The land use types were derived from the CLC (CORINE Land Cover) 2018 database. Their detailed breakdown is presented in the Table 5 below.

Table 5. *Detailed distribution of land use in the analysed area (CLC 2018).*

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**

Presented below is the land use map of the groundwater model area, with an orthophoto of the region used as a background. In addition to the FEFLOW groundwater model boundaries, the map also shows the border of the "Świerczków" wellfield.

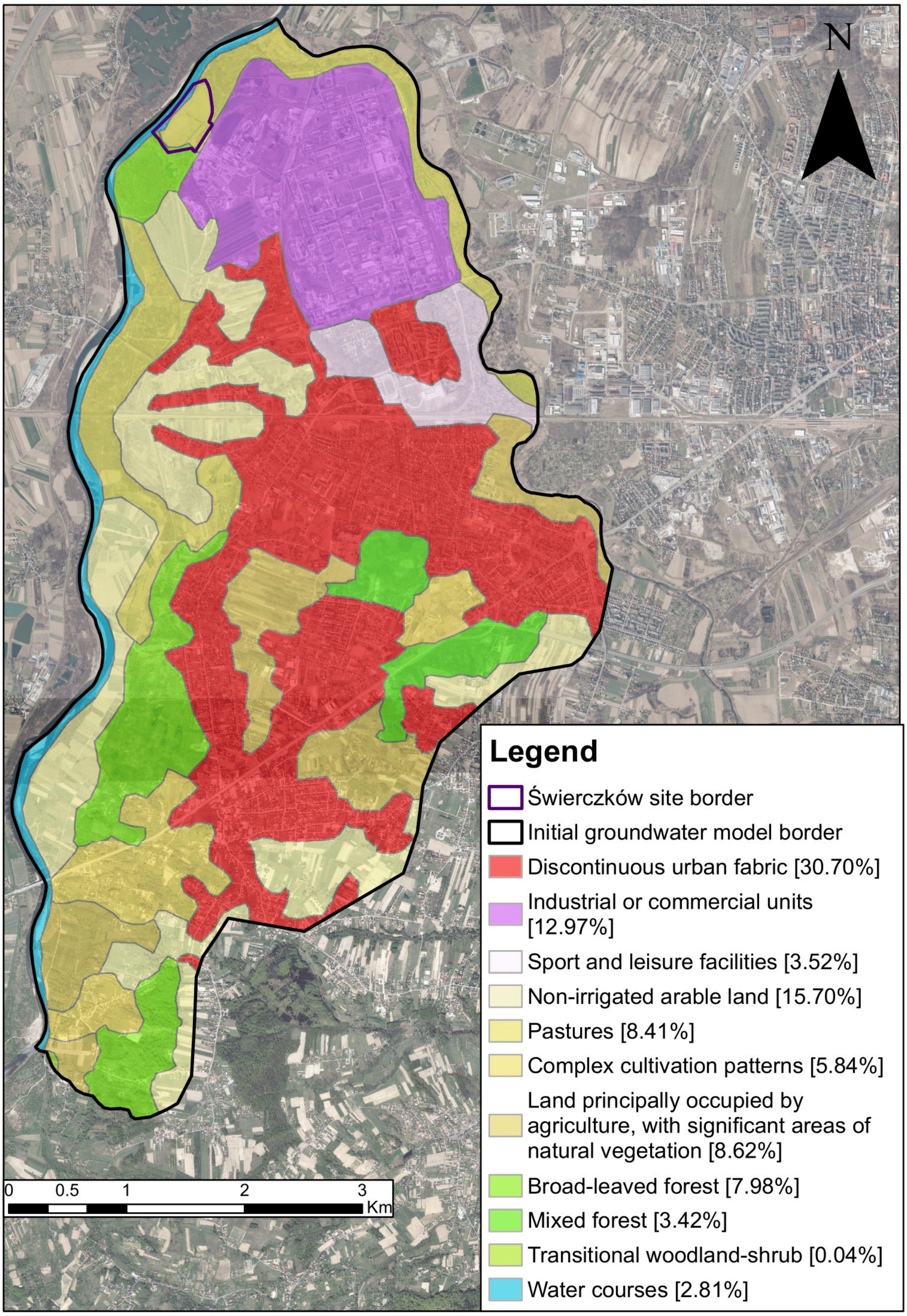


Fig. 4. *Land use map of the study area.*

The highest concentration of pollution sources occurs in the northern part of the study area (Fig. 5). The main source of groundwater pollution is the EU's number two manufacturer of nitrogen and compound fertilizers: Grupa Azoty S.A. The nitrogen plant is situated in close proximity to the Świerczków wellfield and its facilities include i.a.: the sector where nitrogen fertilizers are produced, a pig farm, industrial areas located west of Chemiczna Street, the ECII heat and power plant and coal storage facilities around the heat and power plant. Świerczków site is also surrounded by two reclaimed ash landfills (sectors A and B), as well as the toxic waste reservoir (Wojtal et al., 2009; Treichel et al., 2015).

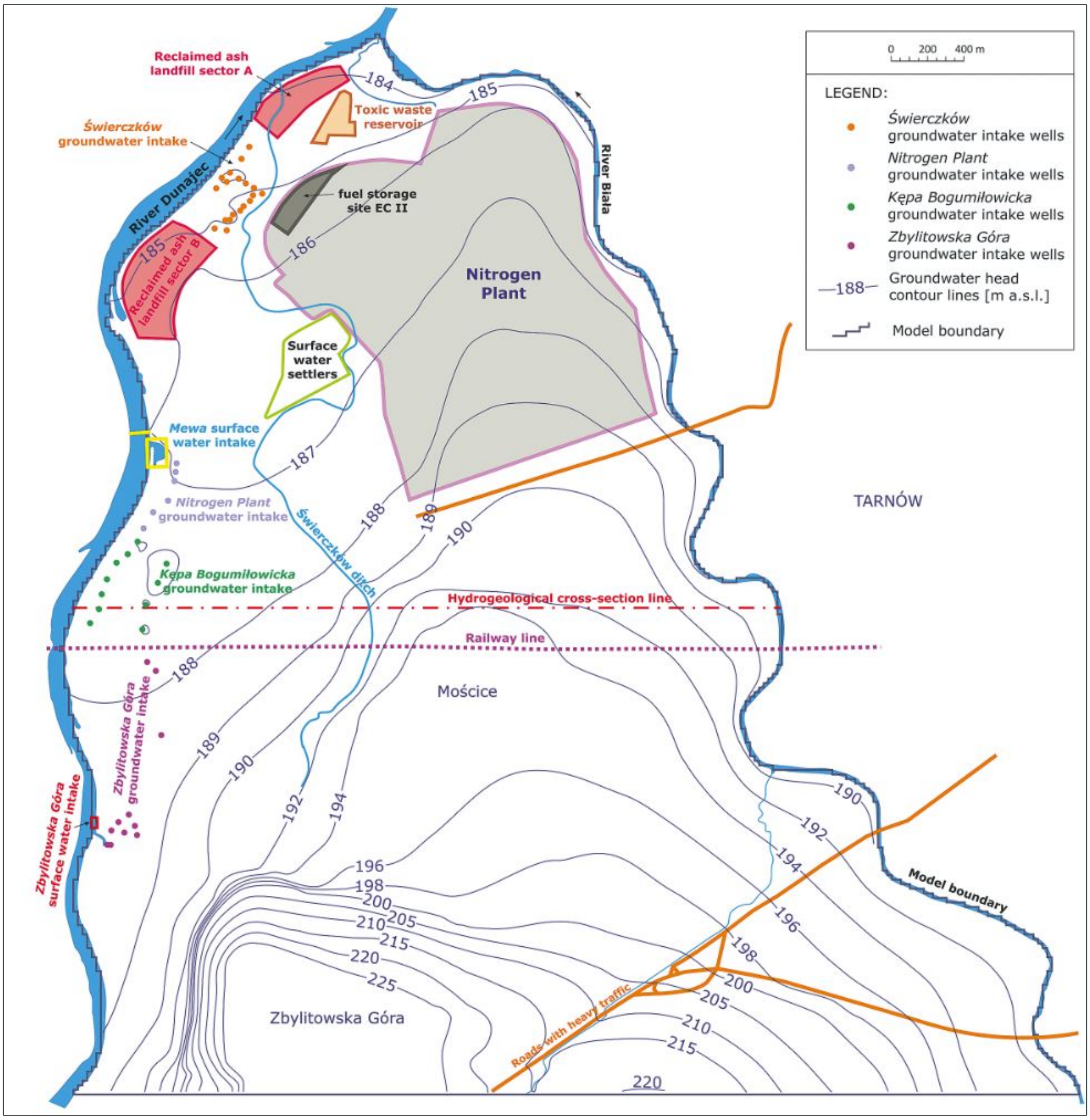


Fig. 5. *Potential pollution sources in the northern part of the study area (Treichel et al., 2015).*

Other important source of water pollution, especially surface water, but also groundwater, since the water table occurs at shallow depth are: roads, the busiest of which are no. 94 and 973 as well as railway lines no.115 and 91 pass through the northern part of the area. Another water pollution source is agriculture (39% of the area) which is directly related to the use of fertilizers that can degrade the quality of surface water and groundwater. Also, despite the fact that people's awareness is increasing, illegal landfills (mostly in forests) and illegal discharges of sewage into surface waters remain an important source of water pollution in anthropogenic areas, such as the analysed region. These illeagal acts leading to pollutions sources are difficult to quantify.

Fig. 6. *Topographic map of the study area.*

3.4 Hydrology

The study area lies in the Baltic Sea watershed, in the Vistula river basin, in the Upper Vistula water region within the Cracow Regional Water Management. It is located at the fork of the Dunajec and Biała Tarnowska rivers and lies within the range of 2 surface water bodies:

- the Dunajec river from the Czchów reservoir to the estuary, with the status of heavily modified water (Polish: SZCW) - (Polish: JCWP)- PLRW20001921499

- the Biała river from Rostówka to the estuary - with natural water status (Polish: NAT) - the water body code - PLRW200014214899.

Apart from the Dunajec and Biała Tarnowska rivers, there is the Świerczkowski Ditch running across the study area, which is a drainage ditch (Fig. 7) that periodically dries out. Until 2007, the ditch received the treated effluents from the local treatment plant at the Penitentiary in Świerczków. In the northern part of the area there is a local network of drainage ditches draining rainwater from the extreme northern part of the industrial area of the Grupa Azoty S.A. (Tarnów nitrogen plant) (Fig. 7). In addition to the aforementioned watercourses, there are surface water bodies of various sizes in the area. These are mainly artificial reservoirs, including:

- small water reservoirs south of the "Świerczków" wellfield area, which are the remains of former gravel mining activities,
- infiltration ditches in the "Świerczków" wellfield area,
- settling tanks (sedimentation tanks) of the GA S.A. surface intake,
- tanks for hazardous substances, the so called AN,
- GA S.A. wastewater treatment plant settling tanks (Fig. 7).

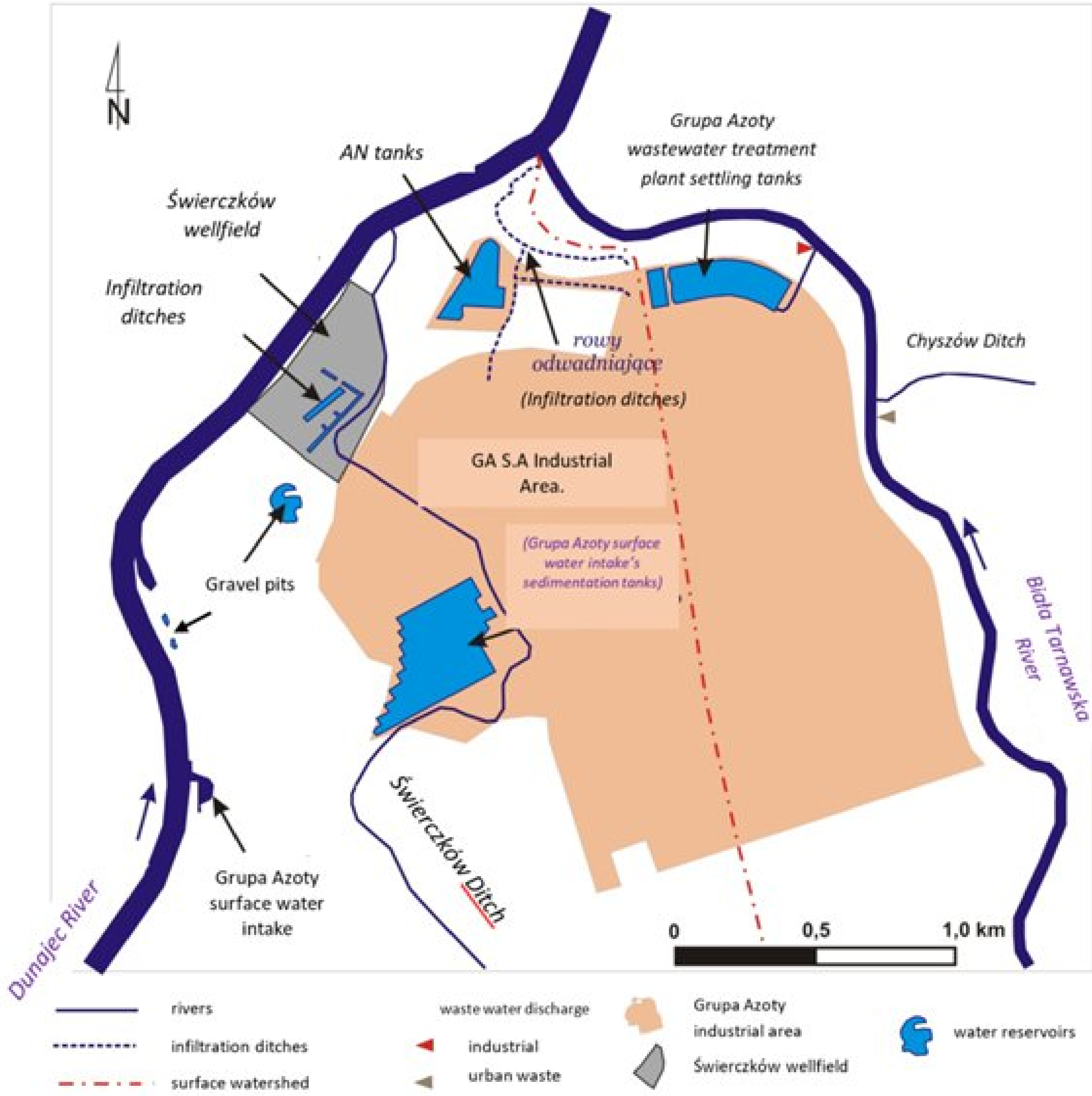


Fig. 7. *Hydrographic map of the study area (Wojtal, 2013).*

Hydrological profile of the Dunajec river

The source section of the Dunajec river (second-order catchment) is the Black Dunajec bordering the Black Sea catchment. At 199.2 km near Nowy Targ, the Czarny Dunajec joins the Bialy Dunajec and from this point the Dunajec river begins. The Czorsztyn - Niedzica reservoir, put into operation in July 1997, together with the reservoir in Sromowce Wyżne completed a few years earlier, have had a major impact on the water management conditions of the river by equalizing flow rates and retaining a significant portion of the dragged and floating material (Rybicki & Rybicki, 1999). At the 86,4 km from its estuary the Rożnowski Reservoir starts. A few kilometers below the dam in Rożnów there is the backwater of the Czchów reservoir, whose dam is located at 67 + 500 km.

The Czchów Reservoir was originally planned as a facility compensating the outflow from the Rożnów Reservoir. The Czchow reservoir has a significant impact on the flow characteristics of the lower Dunajec river, and thus also on the operation of surface and infiltration intakes located in close proximity to this river. Below the dam in Czchow, the Dunajec river flows across areas used mainly as agricultural land, to a lesser extent as recreational areas. There are also small industrial plants located in the area which has as a well-developed water supply network but much less developed sewage network.

In the section from the Czchów dam to the Zbylitowska Góra wellfield area, the Dunajec river does not receive significant inflows; the watercourses flowing into it in this section carry negligible amounts of water, which is confirmed by the small difference in the river's water flow rate between the rate at the outflow from the Czchów reservoir and the flow rate at the water gauge station in Zgłobice (Wojtal, 2013).

The lowest flow rate below the dam in Czchów was determined in the water management documentation for this facility as 17 m^3/s (danepubliczne.imgw.pl). In practice, the minimum flow rates in recent years have not been lower than 20 m^3/s. For about 60% of the days of the year, flows in the Dunajec river have been twice the guaranteed minimum flow rate (Rybicki & Rybicki, 1999).

Table 6 shows the typical flow rates of the Dunajec river at the Zgłobice water gauge station, located at km 38+560 of the river's course, from 1981-2017.

Table 6. *Typical flow rates of the Dunajec river in the section of the Zgłobice water gauge station from the hydrological period 1981-2017 (danepubliczne.imgw.pl).*

Flow rates	Flow rate [m^3/s]
Lowest (date)	8.80 (10-10-2002)
Medium low	18.7
Average of annual averages	77.4
Medium High	882
Highest (date)	2510 (07-10-1997)

In the last 5 years (2016-2020), the extreme flow rates in the analysed water gauge station were noted in 2017 and 2018. The lowest flow rate was 20.8 m^3/s and was recorded on 19/08/2017, while the highest rate was 1030 m^3/s and was recorded on 29/07/2018. The average flow rate for this period was 80.07 m^3/s. The extreme flow rates remained within the range given in the table for the multi-year period 1981-2017.

The calculated base flow rate for the five-year period 2016 -2020 ranged from 20.8 m^3/s (19/08/2017) to 124 m^3/s (21/05/2019) with a mean value of 40.44 m^3/s (danepubliczne.imgw.pl).

In the whole period of observations at the water gauge station Zgłobice, the flow rate in the Dunajec river varied within a very wide range from 3.3 m^3/s (in 1947) to 4000 m^3/s (in 1934).

According to the classification of ecological and chemical status/potential of surface waters, the Dunajec river from Czchów reservoir to the estuary (the heavily modified water code - PLRW20001921499) is currently classified as a good quality surface water body (including good and above good ecological status and good chemical status) (apgw.gov.pl).

<u>Hydrological profile of the Biała (Biała Tarnowska, Biała Dunajcowa) river</u>

The Biała river (third-order catchment), is the right-bank tributary of the Dunajec river (second-order catchment), a tributary of the Vistula river. The total length of the Biała river is 101.8 km. It flows into the Dunajec river at 30.3 km of its course. The river starts in the Beskid Niski at an altitude of about 900 m above sea level. Along its course, the river receives a number of right- and left-bank tributaries, such as the Kąśnianka, Zborowianka, Szwedka streams. At km 7.6 it receives the right-bank tributary Wątok before flowing into the Dunajec river, at 2+000 km, below it receives wastewater from the Tarnów treatment plant and below it receives waters of the Chyszowski Trench (at 1+945 km), at 1+180 km it receives industrial wastewater from GA S.A. (Fig. 7). At the mouth of the Dunajec river, the catchment area of the Biała river is 983.3 km^2.

The Biała basin in its upper and middle courses has an agricultural and recreational character, while in its lower course it is an industrial area.

Along its course, the Biała river receives wastewater from more than a dozen wastewater treatment plants that augment its flow rates. The waters of Biała river are also taken for supplying Ciężkowice and Tuchowo (intake in Lubaszowa).

In the analysed section of the Biała river there is a close connection of the river water with the Quaternary aquifer; depending on the water level in the river it can have a draining or infiltrating character.

The flow rates in the Biala river varies greatly. Based on the multi-year data (1971-2013) from the IMiGW Koszyce water gauge station located above the sewage outlet (i.e., above 2+000 km in the Biała Tarnowska section), the typical flow rate in this river are as follows (according to Cygan M, 2015):

- the highest observed flow rate - 836 m^3/s 04.06.2010
- average annual flow rate - 9,36 m^3/s 1971 – 2013
- minimal flow rate - 0,60 m^3/s 19.01.1984
- medium low flow rate - 1,38 m^3/s 1971 -2013
- medium high flow rate - 282 m^3/s 1971-2013

In the last 5 years (2016-2020) extreme flow rates at the analysed Koszyce water gauge station were observed in 2019 and 2020. The lowest flow rate was 0.92 m^3/s, recorded on 24.09.2020, while the highest flow rate was 270 m^3/s, recorded on 24.05.2019. The average flow rate for this period was 7.68 m^3/s. The extreme flow rates were within the range given above for the multi-year period 1971-2013.

The calculated base flow rate for the five-year period 2016-2020 ranged from 0.92 m^3/s (24.09.2020) to 13.8 m^3/s (24.05.2019) with a mean value of 3.68 m^3/s (danepubliczne.imgw.pl)

According to the classification of ecological and chemical status/potential of surface waters, the Biała river from Rostówka to the estuary (JCWP-PLRW200014214899) is currently classified as a surface water body of poor quality (including poor ecological status and good chemical status) (apgw.gov.pl).

The Świerczkowski Ditch

The Świerczkowski Ditch should be treated as a drainage ditch whose estuary to the Dunajec river is located about 0.5 km below the "Świerczków" wellfield area. It is a receiver of rainwater and infiltration water from areas located in the western part of the GA S.A. It begins in Zbylitowska Góra, then flows through Kępa Bogumiłowicka and further on crosses the Tarnów city, including the industrial areas of GA S.A. and industrial plants located in the vicinity of GA S.A. The total length of the ditch is approximately 5.2 km. There is a 1.5 km section of the ditch connected to a sewage network. In its lower course the Świerczkowski Ditch runs through the "Świerczków" wellfield area. During longer rainless periods, the ditch practically dries out. Until 2007, the ditch in question was a receiver of sewage from a treatment plant located on the premises of the Świerczków Penitentiary. As the plant did not meet environmental protection requirements, the sewage from the Penitentiary is currently discharged into the municipal sewage system (Wojtal, 2013).

3.4.1. Flood hazard and flood risk maps

Legal basis

Flood hazard maps (FHMs, Polish abbreviation: "MZP") and flood risk maps (FRMs, Polish abbreviation: "MRP") for the area of Poland are prepared on the basis of the following legal acts:

1. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Flood Directive);
2. Water Law Act (Journal of Laws of 2020, item 310, as amended);
3. Regulation of the Minister of Marine Economy and Inland Navigation of 4 October 2018 on the development of flood hazard maps and flood risk maps (Journal of Laws of 2018, item 2031).

The State Water Holding Polish Waters is responsible for the preparation of FHMs and FRMs projects. The minister responsible for water management authorizes FHMs and FRMs and submits them to the authorities specified in the Water Law. Flood hazard maps are prepared for the areas of potential significant flood risk (APSFR) indicated in the preliminary flood risk assessment (Polish abbreviation: "WORP").

WORP was developed as part of the project "IT System for the Protection of the Country against Extraordinary Hazards" (ISOK) financed by the European Regional Development Fund under the Innovative Economy Operational Program. The project was implemented by the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB) in consortium with the National Water Management Authority (KZGW), the Main Office of Geodesy and Cartography (GUGiK), the Government Centre for Security (RCB) and the Institute of Telecommunications.

Significant historical floods as well as floods that may occur in the future (the so-called probable floods) have been identified as part of the WORP. They constitute the basis for designating flood-prone areas. On December 22, 2013, the flood hazard maps and the flood risk maps were published on the "Hydroportal" (*https://wody.isok.gov.pl/imap_kzgw/?gpmap=gpPDF)*.

The flood hazard maps and flood risk maps are to be reviewed and, if necessary, updated every 6 years. The Water Law Act of 20 July 2017, which entered into force on 1 January 2018, upholds the validity of flood hazard maps and flood risk maps prepared during the 1st planning cycle and orders their review and update, if necessary, by 22 December 2019.

The Water Law Act (art. 169-170) specifies the general scope of FHMs and FRMs. However, the specific scope and requirements for the development of flood hazard maps and flood risk maps, as well as the scale, are determined by the Regulation.

The scope of flood hazard maps and flood risk maps

Flood hazard maps include areas with a specified probability of flooding such as:

- areas where the probability of flooding is low, which corresponds to 0.2% (once every 500 years), or extreme event scenario;
- areas where the probability of flooding is medium, which corresponds to 1% (once per 100 years);
- areas where the probability of flooding is high, which corresponds to 10% (once per 10 years);

– areas exposed to flooding in the event of:

- a flood embankment failure - estimated for the flow with the 1% probability of occurrence;
- a dam failure.

In addition, flood hazard maps shall include:

– water depths;

– the flow velocity and direction of water flow (for voivodship capitals and cities with the poviat status and other cities with a population exceeding 100 000.);

in the classes defining the level of risk for people and the way of impact on buildings, in accordance with the Regulation:

water depths:

- h ≤ 0.5 m – low hazard to people and buildings;
- 0.5 m < h ≤ 2 m – medium hazard to people (possibility of evacuation to upper floors of buildings), but high damage;
- 2 m < h ≤ 4 m – high hazard to people and very high damage;
- h > 4 m – very high hazard to people and very high or total damage;

flow velocity:

- v ≤ 0,5 m/s - low velocity; water has a small impact on buildings;
- 5 m/s < v ≤ 1 m/s – medium velocity; water has a moderate impact on buildings, poses a threat to people;
- 1 m/s < v ≤ 2 m/s – high velocity; water has a big impact on buildings, poses a serious threat to people;
- v > 2.0 m/s – very high velocity; water has a very big impact on buildings, may damage structures of static objects, poses a very serious threat to people.

In accordance with the regulation, cartographic versions of flood hazard maps are prepared separately for each scenario in two thematic sets:

– Flood hazard maps with water depths;

– Flood hazard maps with flow velocity (for the areas designated in the Regulation).

What deserves special attention here is the fact that FHMs do not show the historical floods extent, but present areas with a specified probability of flooding. To determine flood hazard areas, the maximum flow with a given probability of occurrence is used (calculated on the basis of maximum annual flows from the period of at least 30 years). The 1% probability of flooding means that statistically such a flood may occur once every 100 years. However, it should be noted that this is a statistical value - based on historical data, with the beginning of measurements in 1951 (Vistula basin) - and does not mean that flooding with the probability of 1% occurs at 100 years intervals.

Flood hazard areas are determined by using geographic information systems, on the basis of water surface elevation calculated with the hydraulic model. The digital terrain model (DTM) and the digital land cover model are used to determine flood hazard areas. DTM comes from airborne laser scanning (LIDAR), with the vertical accuracy of <20 cm and spatial resolution of 1 m. For the purposes of mapping, hydrological data that take into account the maximum flows that occurred during the flood in 2010 has been developed.

Flood risk maps are prepared for areas included in flood hazard maps. They show the potential adverse consequences of flooding for human health and life, the environment, cultural heritage and economic activity. Flood risk maps present objects important from the point of view of flood protection and information necessary to assess flood risk and potential consequences of flooding, in line with the objectives of the Floods Directive.

For this purpose, flood risk maps include:

- Indicative number of inhabitants potentially affected;
- Residential buildings and objects of social importance in the flood hazard area. For each building there is an estimation of the average depth of flooding, separately for each flood scenario and classified within two ranges: water depth <2m and >2m;
- Types of economic activities in flood hazard areas are defined by land use classes;
- Cultural heritage areas and buildings;
- Installations that, in the event of floods, may cause significant pollution to some parts of the environment or the environment as a whole (IED);
- Protected areas (water intakes, protection zones for water intakes, bathing areas, nature protection areas);
- Other potential sources of water pollution in the case of flooding including wastewater treatment plants, industrial factories, wastewater pumping stations, landfills, cemeteries;
- The value of potential flood losses for land use classes (i.e. residential areas, industrial areas, communication areas, forests, recreation and leisure areas, arable lands, water).

In accordance with the Regulation, cartographic versions of flood risk maps are prepared separately for each flood scenario in two thematic sets:

- Flood risk map – potential adverse consequences for human health and life and the values of potential flood damage,
- Flood risk map – potential adverse consequences for the environment, cultural heritage and economic activity.

For the purposes of this document, the authors have prepared four selected maps (Fig. 8 - Fig. 11), showing the region of the planned groundwater model FEFLOW (vicinity of Tarnów):

- Flood hazard map with water depths: areas where the probability of flooding is medium, which corresponds to 1% (once per 100 years);
- Flood hazard map with water depths: areas where the probability of flooding is high, which corresponds to 10% (once per 10 years).
- Flood risk map: the potential adverse consequences for human health and life as well as values of potential flood losses - areas where the probability of flooding is medium, which corresponds to 1% (once per 100 years);

- Flood risk map: the potential adverse consequences for human health and life as well as values of potential flood losses - areas where the probability of flooding is high, which corresponds to 10% (once per 10 years);

The maps are created in the scale of 1:40 000.

The use of flood risk maps and flood hazard maps

Flood hazard maps and flood risk maps constitute the basis for the development of flood risk management plans, including a sets of technical and non-technical measures, which aim to reduce the adverse consequences of flooding. As one can see on the presented maps, PP4's pilot site (the Świerczków wellfield) is located in the area of high flooding probability.

Knowing the flood hazard and flood risk data is extremely important as it contributes to the proper spatial planning and development and to the reduction of the adverse consequences of flooding. Flood hazard areas presented on FHMs are taken into account in spatial planning documents. As a result, residents and local authorities are informed and make responsible decisions concerning the location of investments.

The scope of data contained in the maps is also an element supporting the introduction of norms defining methods of insuring people and fixed assets in flood risk areas.

Maps can be a starting point for further analyses needed to implement different administrative tasks, including crisis management in case of flooding. These maps will also be an effective tool for obtaining data, setting priorities and making technical, financial and political decisions on flood risk management.

The above mentioned information was obtained from the official government website: https://powodz.gov.pl/en.

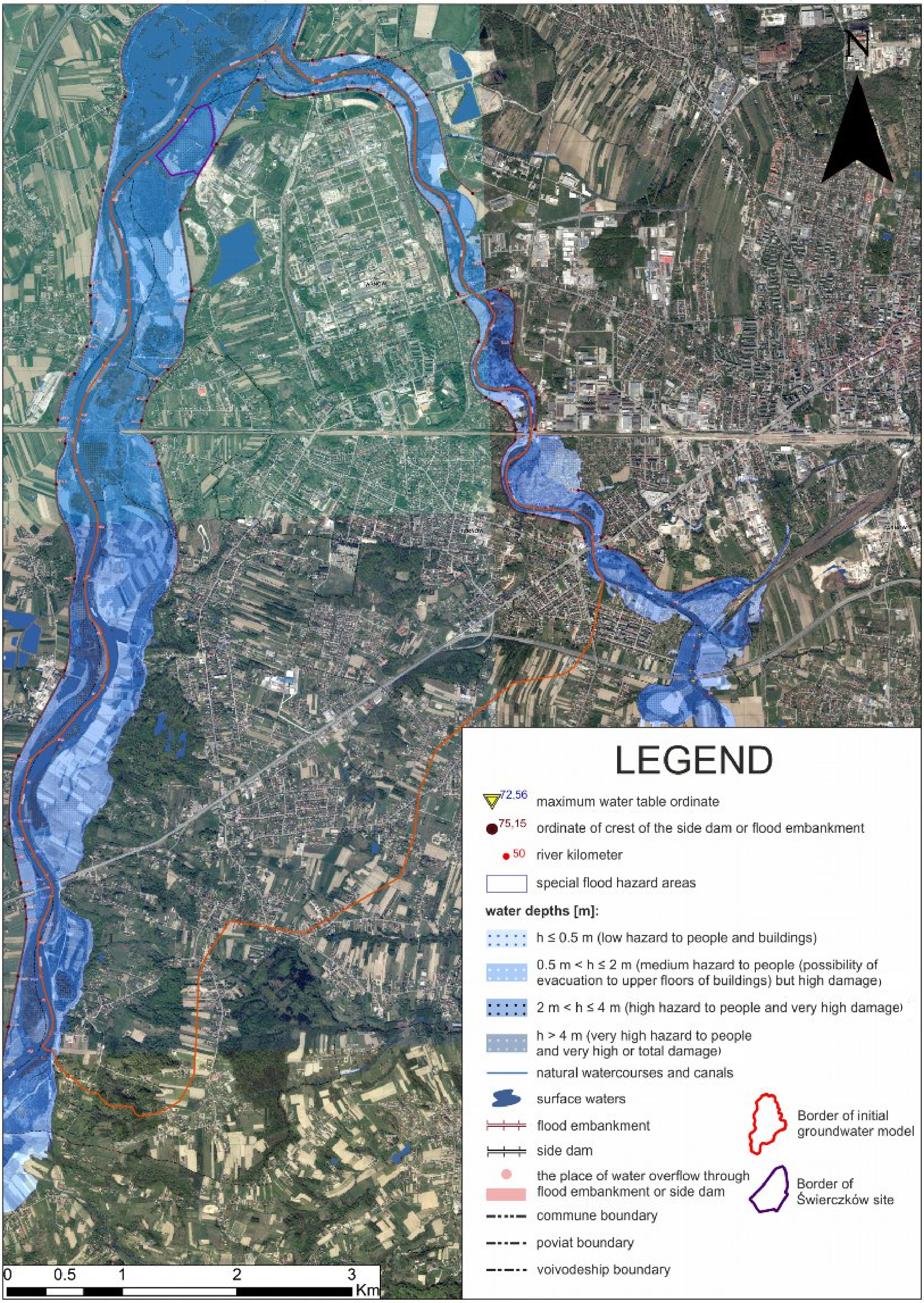


Fig. 8. *Flood hazard map with water depths: areas where the probability of flooding is medium, which corresponds to 1% (once per 100 years).*

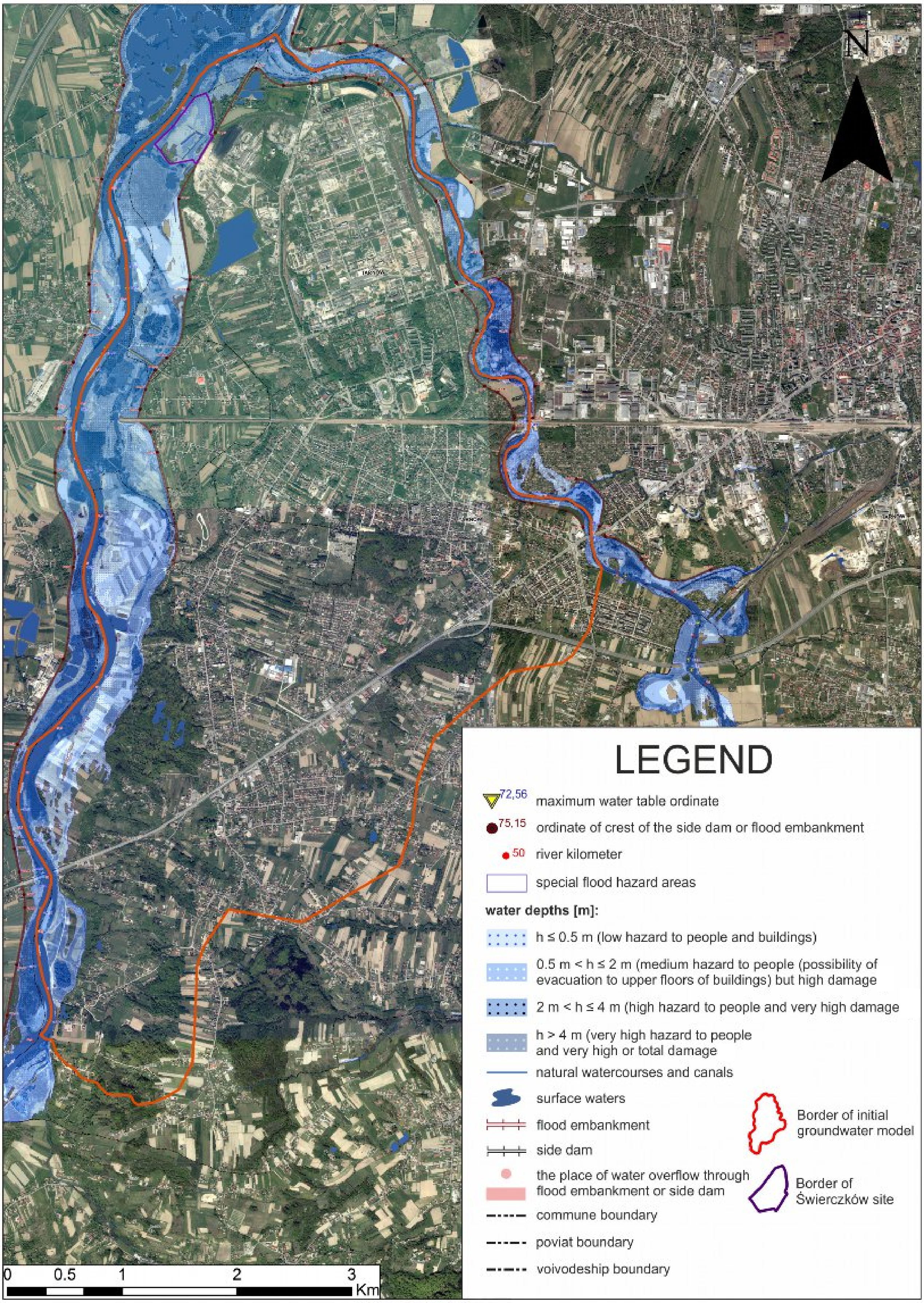


Fig. 9. *Flood hazard map with water depths: areas where the probability of flooding is high, which corresponds to 10% (once per 10 years).*

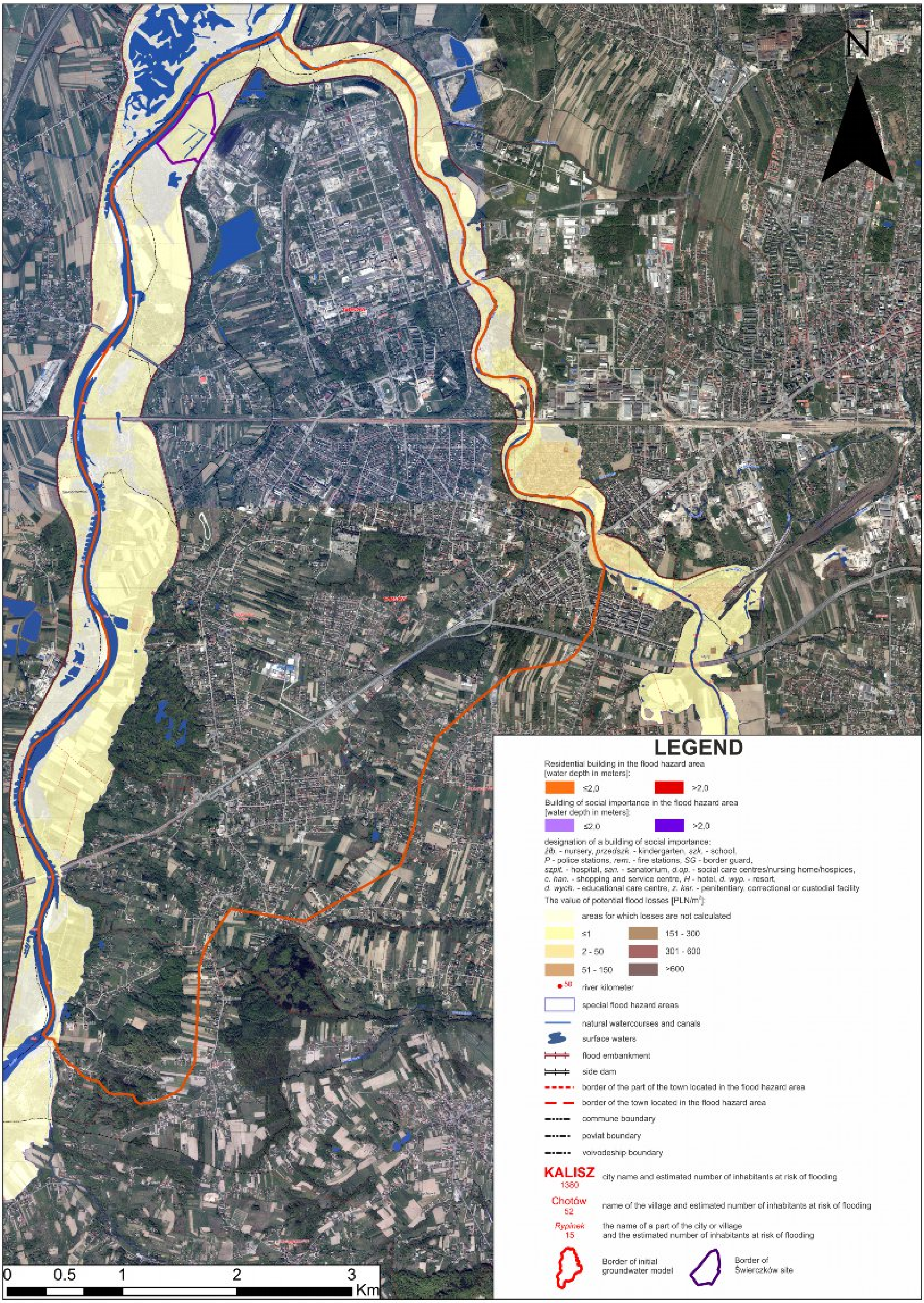


Fig. 10. *Flood risk map: the potential adverse consequences for human health and life as well as values of potential flood losses - areas where the probability of flooding is medium, which corresponds to 1% (once per 100 years).*

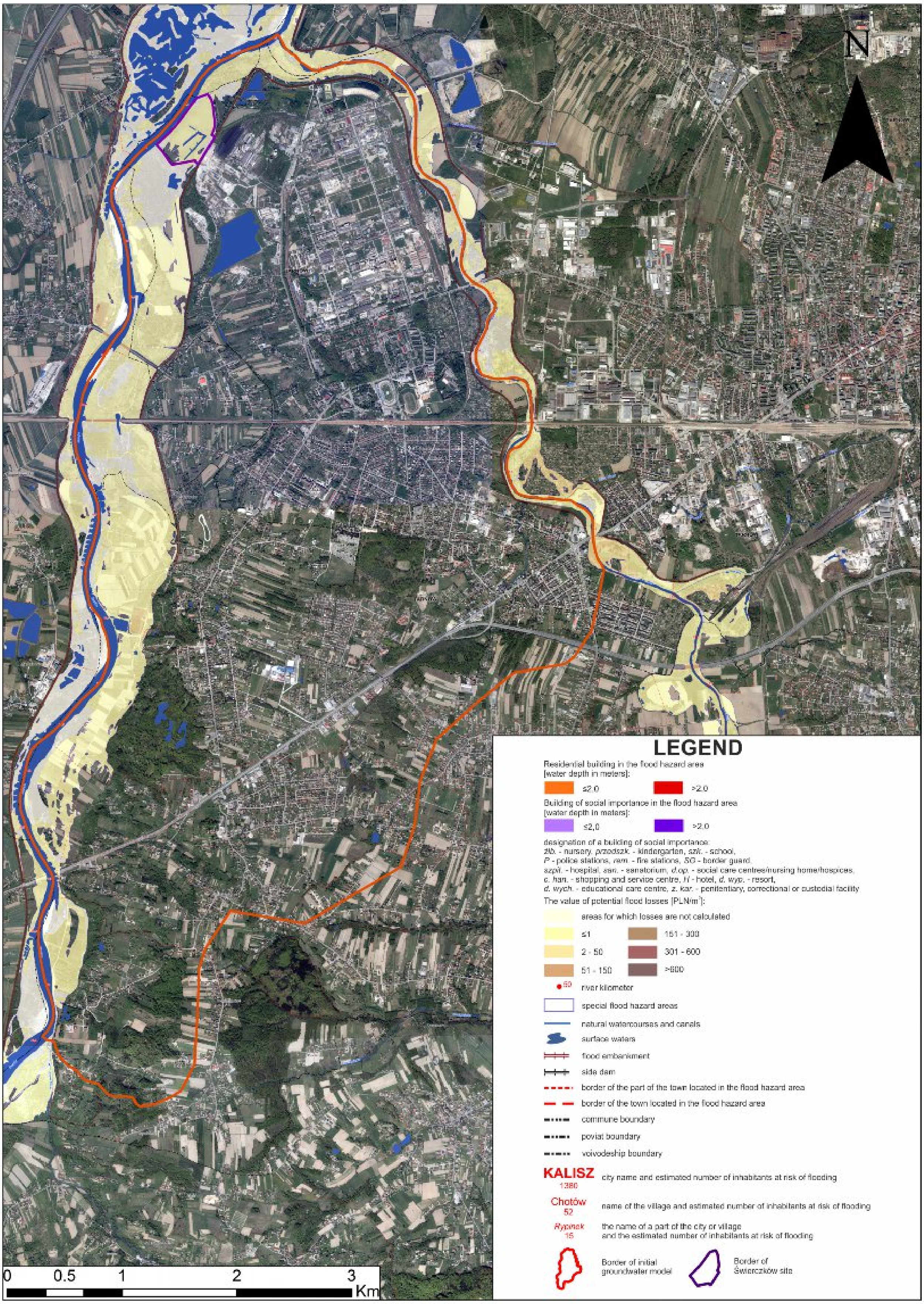


Fig. 11. *Flood risk map: the potential adverse consequences for human health and life as well as values of potential flood losses - areas where the probability of flooding is high, which corresponds to 10% (once per 10 years).*

3.4.2. River basin management plans

According to Art. 113 of the Water Law Act (Journal of Laws of 2015, item 469, as amended), one of the planning documents for water management in Poland are the river Basin Management Plans (RBMPs; Polish abbreviation: "PGW"; www.apgw.gov.pl/en/). In fact, RBMP is the main planning document according to the Water Framework Directive (WFD). These documents constitute the basis for desicionmaking that shape the condition of water resources and the principles of their management in the future. In Poland, RBMPs are prepared by the president of the National Water Management Authority in agreement with the minister responsible for water management and the minister responsible for the environment. RBMPs were developed for the first time in line with the requirements of the WFD in 2009 and adopted by a resolution of the Council of Ministers on February 22, 2011.

These documents are reviewed and updated periodically every 6 years. Therefore, in 2014, the work began on updating the RBMPs. Draft documents were subjected to the strategic environmental impact assessment procedure, in accordance with the Act of 3 October 2008 on the provision of information about the environment and its protection, public participation in environmental protection and environmental impact assessments (Journal of Laws of 2016, 353, as amended). They were also a subject to six-monthly public consultations (from November 2014 to June 2015).

RBMP updates (APGW) were adopted by the Council of Ministers in the form of regulations on October 18, 2016 and, similarly to the 1st planning cycle, were developed for 10 (the same) river basin districts. APGW are valid until the adoption of the 2nd APGW, i.e. until December 2022 (www.wody.gov.pl).

The RBMPs include:

1. General description of the characteristics of the river basin district, including in particular:

• a list of surface water bodies, along with their types and established reference conditions,

• a list of groundwater bodies (more specific information at the beginning of chapter 3.6);

2. Lists of protected areas with a graphic representation;

3. Map of the monitoring network, along with the presentation of monitoring programs;

4. Setting environmental objectives for water bodies and protected areas;

5. Summary of the results of the economic analysis related to the use of water;

6. Summary of the activities included in the country's water and environmental program, including the methods of achieving the environmental goals set;

7. List of other specific programs and management plans for the river basin district, concerning the catchment area, economic sectors, problems or water types, with an overview of the content of these programs and plans;

8. Summary of the measures used for public information and consultation, description of the results and the changes made to the plan based on this;

9. A list of authorities competent in matters of water management for the river basin district; information on the methods and procedures of obtaining information and source documentation used to prepare the plan, and information on the expected results of the plan implementation.

The binding document for the study area is the **river Basin Management Plan for the Vistula river** (isap.sejm.gov.pl).

3.5 Geology

The investigated region lies on the Carpathian Foredeep Basin, which is a deep mountain basin between the massifs of the Carpathians and the Świętokrzyskie Mountains. The basin is filled with a thick series of Miocene sediments lying inconsistently on the Precambrian, Palaeozoic and Mesozoic deposits, covered with the Quaternary sediments. When it comes to the Dunajec catchment, Miocene sedimentation developed in several stages, in two sedimentary basins: internal (in the south, between Nowy Sącz and Tarnów) and external (in the north, the area of the present Carpathian Foredeep Basin). In the first stage, sedimentation of silt and clay deposits with interbeds of sandstone and conglomerates developed only in the inner basin. In the next step, the sea extended, initiating sedimentation in the outer basin. In the north, shallow-water deposits formed, and in the south - deeper facies. In the next stage, sedimentation took place only in the external basin, which was associated with an increased inflow of terrigenous material. The clay-sandy sediments formed at that time. From the point of view of the planned works and modelling activities, the Quaternary formations present in the study area are of key importance. The occurrence, form and thickness of the Quaternary formations are mainly related to the glacial, river and aeolian activities. Their thickness depends mainly on the morphology of the terrain and the relief of the Miocene's top. The oldest formations are formed by glacial deposits of the South Polish Glaciations - tills on the plains as well as fluvioglacial sands and gravels in the valleys. In the great interglacial period, the backfill area formed during the Middle Polish Glaciations was cut with valleys to a depth of 10-20 m below the present river beds. Numerous gravel pits date from this glaciation period (Wojtal et al., 2009; Kruk et al., 2017).

Figure 12 presented below consists of two types of geological maps. Half of the figure is a fragment of the 1:50 000 Detailed Geological Map of Poland (from sheets no. 977 and 1000). The upper right part of the figure is occupied by a section of the Geological Map of Poland on a scale of 1: 500 000.The presented figure consists of two fragments of geological maps: in scales of 1:40 000 (DGMP) and 1:100 000 (GMP).

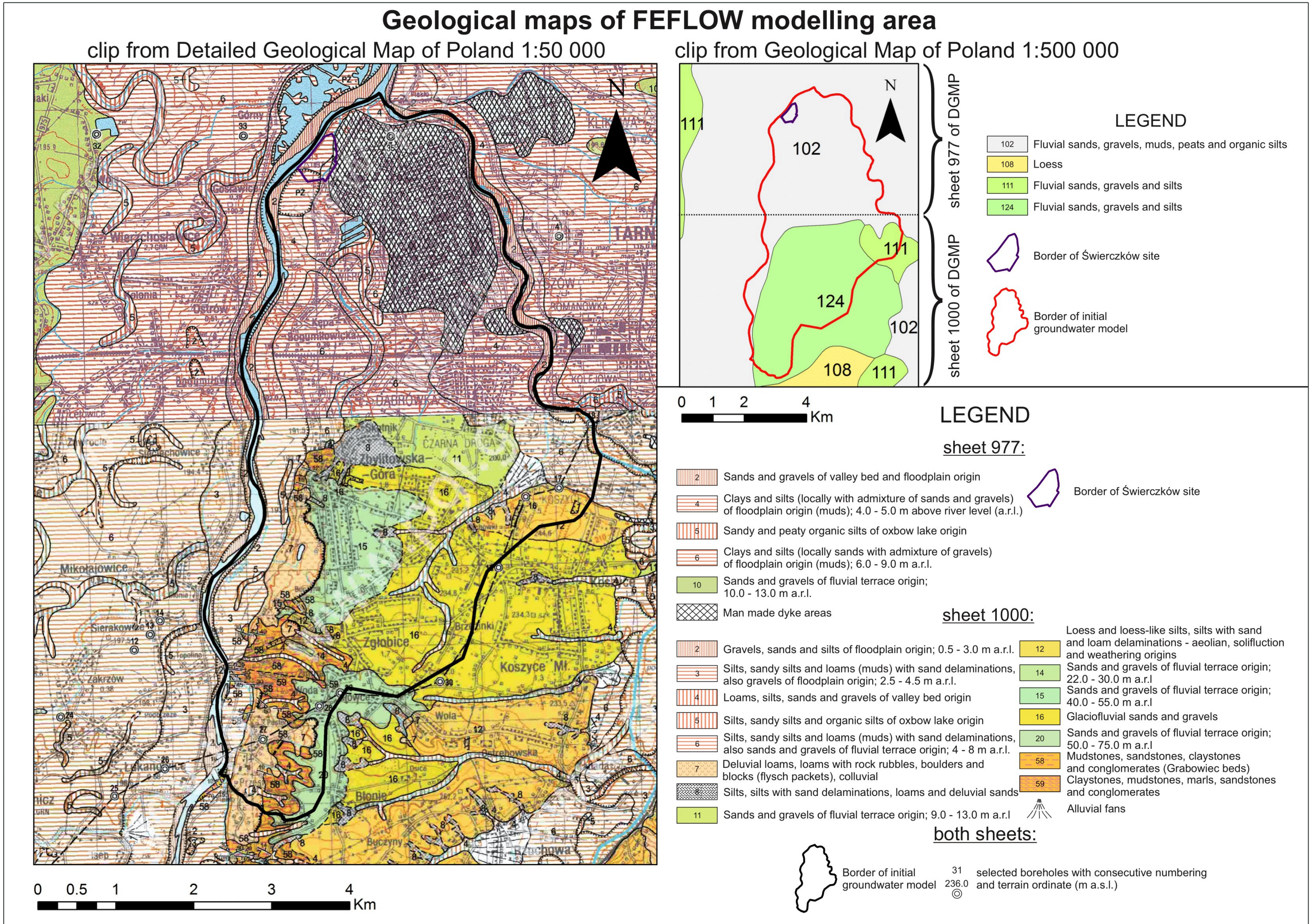
After analysing a fragment of the smaller map, one can conclude that the modelling area is dominated by loose sediments, like sands and gravels. An analysis of the bigger, more detailed map, leads to the conclusion that in the northern part of the region cohesive soils dominate in the subsurface zone. This information is very important in terms of groundwater flow modelling, because in the areas of silt or loam dominance near the surface the effective infiltration is significantly lower compared to areas dominated by sand or gravel.

In general, the top 10-20 m (for northern and southern part, respectively) below ground level are the Quaternary deposits. They consist of loams (muds), silts and organic silts or clays in the upper part of the profile (particularly in the northern part), and alluvial deposits in form of sands and gravels with a substantial fraction of pebbles in the lower part of the profile. Quaternary deposits lie on a clay Miocene bed. The analysis of 310 borehole logs (mostly from the Polish Geological Institute) shows that the further south, the bigger depth to the Miocene deposits in the study area is.

It is also worth noting that in the southern part of the modelling area Middle Miocene sediments outcrop, mostly as mudstones, sandstones, claystones, marls and conglomerates.

The youngest sediments are represented by so called "Anthropocene": embankments, landfills and anthropogenically transformed land.

Fig. 12. *Geological maps of FEFLOW modelling area.*



3.6 Hydrogeology

The area of pilot study can be considered in terms of several hydrogeological divisions in force in Poland. According to the division into 172 groundwater bodies (Polish abbreviation: “JCWPd”; https://www.pgi.gov.pl/psh/zadania-psh/8913-zadania-psh-jcwpd.html), the area is covered by one unit no. 150, and according to the division into the Major Groundwater Aquifers (MGA, Polish abbreviation: “GZWP”;https://www.pgi.gov.pl/en/phs/tasks/8878-gzwp-major-groundwater-reservoirs.html),no distinguished aquifer occurs in the analysed area. The closest aquifers are MGA no. 434 (The Biała Tarnowska river Valley) and no. 435 (Dunajec river Valley Zakliczyn), which are located about 4 km south of the study area. The mentioned ones are porous aquifers associated with Holocene sandy and sandy-gravel formations of the present and buried river valleys. The aquifers were designated according to the individual criteria, due to the deficit of groundwater in relation to the demand.

The division into the Main Useful Aquifers (Polish abbreviation: “GUPW”) from the Hydrogeological Map of Poland in scale 1: 50 000 (sheets 977 and 1000) distinguishes one unit covering the area: 1aQIII (”a” means that the Quaternary aquifer is unconfined, “III” is the range of specific disposable groundwater resources: 200-300 $m^3/24h/km^2$). The last division comes from the 1:50 000 Hydrogeological Map of Poland: First Aquifer – Extent and Hydrodynamics (sheets 977 and 1000). According to this division, the research area is located within three hydrogeological units (numbers 1, 3 and 5), the most important of which is unit 1. The unit is associated with the formations filling the valleys of the Dunajec and Biała Tarnowska rivers, covering around 60% of the modelling area: [1 p,ż, ma-p/dz/zsG/Q]. This abbreviation means: the dominant material in the unit number 1 is sand and gravel, the subordinate sediments are muds with underlying sand / hydrodynamic-geomorphological type of the aquifer is a floodplain / the aquifer is unconfined and is also the main useful aquifer / geological formations are of the Quaternary age. This described deposits relatively often contain pebbles.

The Quaternary aquifer lies on an impermeable clay Miocene bed, and is most often covered with silts and loams. Locally, in the upper part of the aquifer, there is a significant thickness of clay deposits. The depth to the first aquifer generally fluctuates within 2 - 5 m (on the southern upland the depth increases to over 35 m) and its thickness is generally 5 - 9 m, the aquifer is mostly unconfined (Treichel et al., 2015). Depth to the water table is dependent on the water level in the Dunajec and Biała Tarnowska rivers, the amount of water abstraction, and also on the intensity of the aquifer recharge from precipitation and infiltration ditches (in the Świerczków site). The recharge of the aquifer takes place in its entire area by direct infiltration of rainwater and in the periods of high surface water levels also by infiltration from the rivers. The aquifer conductivity varies from a few dozen to more than 100 m/d. The highest permeability of the aquifer occurs in the valley of the Dunajec, reaching up to several hundred m/d (Wojtal et al., 2009; Wojtal, 2013).

The map below shows hydrogeological conditions of the study area (Fig. 13). The main information is the depth to the top aquifer. The map also provides the information about groundwater dynamics - the local groundwater flow direction and the elevation of groundwater table. The groundwater level varies from 185 (Dunajec riverbed) to 260 (southern side of the region) m a.s.l. The hydrodynamic system is typical for an interfluve area. In this case the groundwater flow is in the W and NW direction towards the Dunajec, and E and NE direction towards Biała Tarnowska. The aquifer under natural conditions (before the abstraction of groundwater by wells) was drained by the two rivers. During the flood periods, the rivers change from gaining to losing. It should be emphasised that the flow rate in the Dunajec river is regulated by water discharge on the dam in Czchów (the wellfield is located about 5 hours from the dam), while the Biała Tarnowska is not regulated, therefore the periodic floods in this river are more violent (Wojtal, 2013).

Groundwater dynamics in the studied area is dependent on such factors as: topography, geological structure, intensity of recharge and drainage of the Quaternary aquifer. The location of the area in the inter-river basin of the Dunajec and Biała Tarnowska rivers is also associated with periodic fluctuations in the groundwater table caused by changing water levels in the rivers. The groundwater divide runs approximately from the south to the north, dividing the study area into two areas: the western one, from which groundwater flows towards the Dunajec, and the eastern one, from which groundwater flows towards Biała Tarnowska. Groundwater flowing westwards supply the wells of the Świerczków wellfield.

The authors have also marked part of the existing wells and piezometers on the map, for which additional data is available (mostly from Grupa Azoty S.A.).

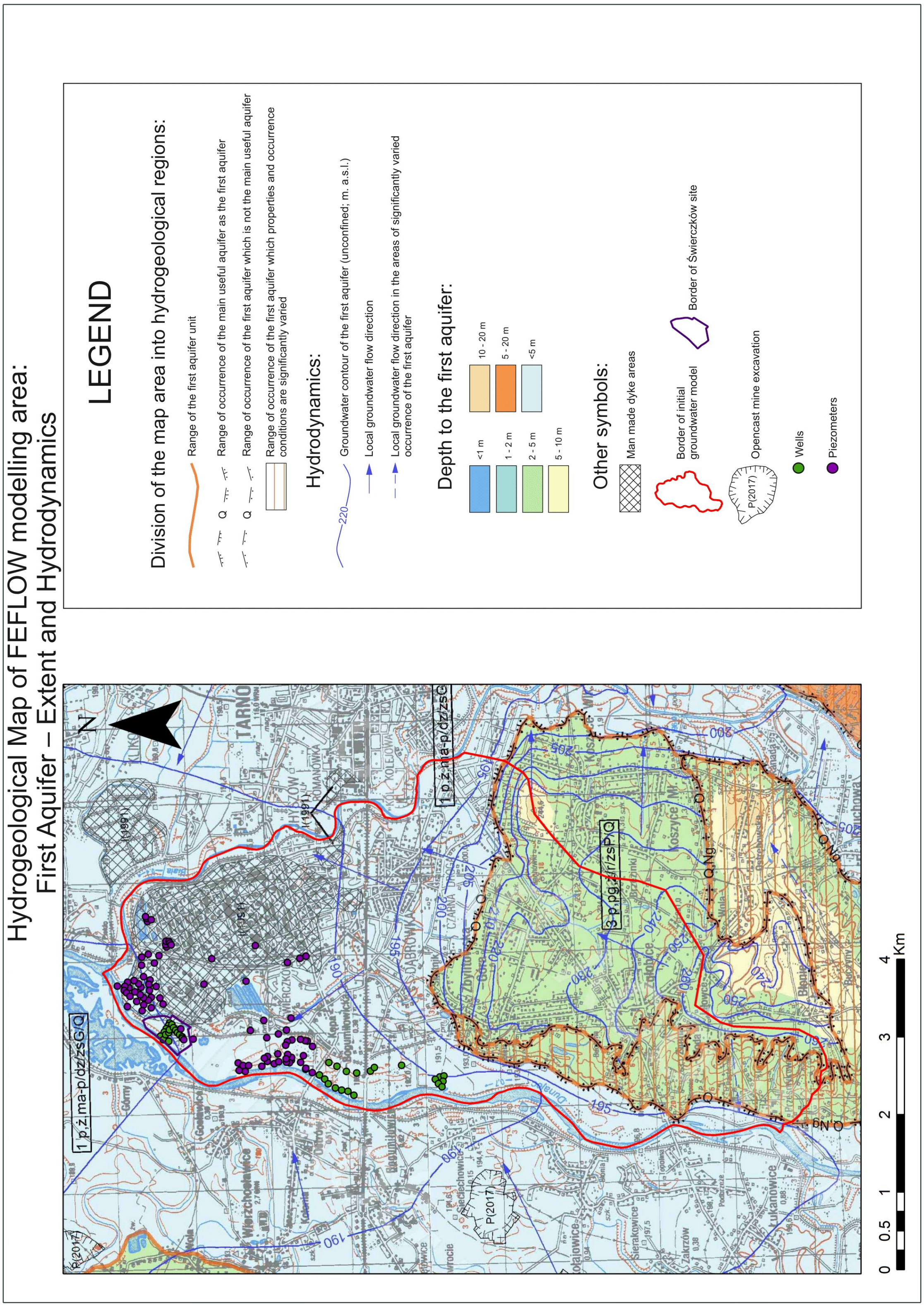


Fig. 13. Hydrogeological map of the study area.

3.7 Aspects of existing infrastructure

The Świerczków wellfield was established in 1910 as the main source of water for the city of Tarnów. Initially it consisted of 9 drilled wells. The facility was expanded several times by increasing the number of wells, some wells were, in turn, taken out of service. Even in the early years of its operation, the wells located on the landside slope of the floodbank were successively discontinued. In the 1950s a few (around 4) dug wells were created in order to increase the wellfield's discharge and a system of enriching the water bearing layer through a system of infiltration ditches was implemented. Irrigation water was pumped directly from the Dunajec river until the end of 1970s. The pumping station was located on the bank of the Dunajec river, within the wellfield area. In the 1970s, after locating ash dumps within the wellfield area and constructing a sheet pile wall in the southern part of the wellfield, the irrigation was taken over by Zakłady Azotowe, currently Grupa Azoty S.A (GA S.A.). Prior to its application, the irrigation water drawn from the Dunajec river is passed through sedimentation basins, which significantly reduces the amount of suspended solids, which in turn reduces the siltation of the infiltration ditches. This system of irrigation is currently operating. The amount of water pumped for the irrigation of the wellfield 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 from around 40% to over 60% of the wellfield's current discharge. The infiltration ditches are cleaned approximately every 3 years. Originally, the water drawn from the wellfield was subject to de-ironing, and since 1967 de-ironing has been abandoned due to a decrease in iron concentration. Currently the wellfield consists of 17 wells. Until October 2011 it contained 19 wells, numbered W-1, W-2, W-3, W-4, W-5, W-6, W-7, W-8, W-1A, W-1B, W-2A, W-3A, W-4A, W-19, W-20, W-21, W-22, W-23, W-24. The following wells are or were drilled wells: W-1, W-2, W-3, W-4, W-5, W-6, W-7, W-8, W-19 while the others: W-1A, W-1B, W-20, W-21, W-22, W-23, W-24, were dug. Wells: W-2A, W-3A, W-4A were dug to a certain depth and then deepened by drilling. In October 2011, 9 wells were discontinued, some of which were permanently taken out of service due to poor water quality. These were wells numbered W-1a, W-1b, W-19, W-23 and W-24, some wells were discontinued due to their very limited discharge, probably caused by chemical siltation – these were wells: W-4, W-6, W-7, W-8. The discontinued wells were replaced in 2012 by 7 wells: W-4bis, W-6bis, W-7bis, W-8bis, W-19bis, W-23bis, W-24bis.

The water abstraction from the "Świerczków" wellfield in 2020 varied from 152,854 m^3/month to 223,538 m^3/month. The average water abstraction from the wellfield 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.

The depth of the wells is similar, about 10 m bgl. The wells capture water from the Quaternary aquifer. The manhole entries to the "old" wells are elevated approx. 4.5 over the ground in order to prevent flood water from entering the wells. The wells drilled in 2012 were secured by a sealed casing embedded in a silt ring. From its very beginning, the wellfield has been operating in the siphon system. Currently, 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 floodbank, where the water is fed by low pressure pumps to a reservoir located at the pumping station of the "Świerczków" wellfield. Before entering the tank the water is treated with chlorine dioxide. The water from the reservoir is then pumped by high-pressure pumps into the municipal network.

The Tarnów Świerczków wellfield's resources have been determined and the hydrogeological documentation of the wellfield was approved by the Małopolska Voivode on March 23, 2005, ref. no.: ŚR.XIV.EM.7441-1-05. In connection with the geological works carried out at the wellfield in 2012, an addendum to the hydrogeological documentation of the wellfield was made and approved by the decision of January 15, 2013, ref. no.: SR-IX-1.7431.7.2012.ZP. Total resources of all the wells of the "Świerczków" wellfield currently amount to 538.67 m3/h (11 000 m3/d).

The Świerczków wellfield has a water permit, i.e. the decision of the President of Tarnów dated 13 June 2013, ref. no.: SO-OŚ.6341.15.2013.SS granting Tarnowskie Wodociągi Sp. z o.o. a water permit for groundwater extraction using the well of the Tarnów - Świerczków water wellfield, this decision was amended by the decisions: of 19 December 2013, ref. no.: SO-OŚ.6341.48.2013.SS and of 5 December 2017, ref. no.: WOŚ.6341.59.2017.SS. The permit expires on 13.06.2033.

According to the permit, the wellfield can extract water in the following quantity:

- maximum hourly quantity: 380 m^3/h;
- average daily quantity: 8,500 m^3/d;
- maximum yearly quantity: 3,100,000 m^3/y.

A direct protection zone was established for the wellfield by the decision of the President of the City of Tarnów dated 25 August 2016, ref. no.: WOŚ.6320.1.2016.SS.

3.8 Regulatory limitations

According to the Water Law Act, any intentional artificial groundwater recharge is understood as a special use of water. 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 2017, item 1566); 2) Geological and Mining Law Act (Journal of Laws 2011 No. 163, item 981); 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 2008 No. 199, item 1227); 5) Announcement of the Prime Minister on the publication of a uniform text of the Regulation of the Council of Ministers on projects that may have a significant impact on the environment (Journal of Laws 2016, item 71).

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 pemit 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.

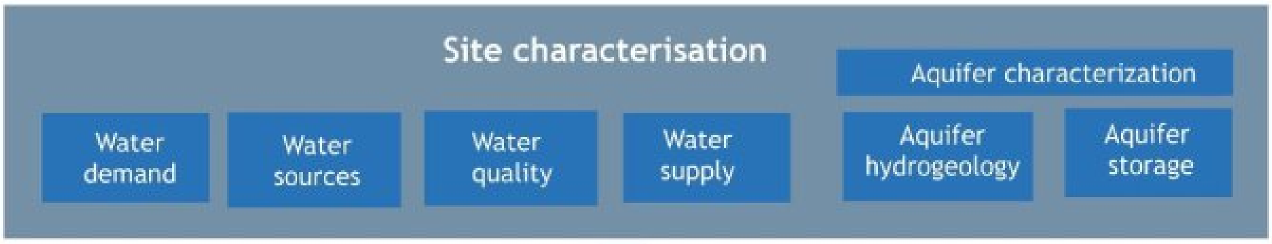
IV. Pilot action design plan

4.1 Aims

The objective of the DEEPWATER-CE project is to demonstrate the benefits that can result from the use of MAR in Central Europe. In the Polish pilot site, a feasibility study will be carried out for 2 types of MAR: induced river bank filtration and infiltration ditches. Based on the developed methodology (D.T2.4.3) it seems that these two methods could be potentially very useful in the selected pilot site to increase groundwater resources and to limit the deterioration of groundwater quality due to the presence of large chemical industry zones.

The widest range of studies was planned for the Świerczków wellfield, which is located on the right bank of the Dunajec river. In order to determine the groundwater flow conditions by means of modelling studies and to properly assess the evolution of water quality, the final pilot site was enlarged to about 30 km^2. The study was planned for the enlarged area.

According to the prepared report (D.T3.2.5), a correct implementation of the feasibility study requires a suitable approach in the characterization of the pilot site according to the developed concept.



Nowadays, the average **water demand** in Tarnów is quite stable. However, the climatic data for the Tarnów region clearly shows that the climate is warming up. The average annual temperature is increasing as well as the number of days with extremely high temperatures per year, which, in the long perspective, will lead to an increase in water demand. Taking into account that the aquifer in Tarnów region is of small thickness, the negative climatic changes may lead to the depletion of water resources, that could be replenished using MAR. The proposed modelling studies will help to determine how climate change may affect, for example, the quantitative changes in groundwater recharge.

The **water source** for the selected 2 MAR techniques is, in the case of induced river bank filtration and infiltration ditches, the water from the Dunajec river. Low and high flow rates on the river can be artificially modified in the upstream dam reservoirs. The influence of high and low water levels in Dunajec on the efficiency of MAR system operation will be analysed based on prognostic simulations from modelling investigations.

The collected historical data show a large ratio of artificially recharged water in relation to water abstracted from wells. However, this ratio varies across the pilot site and individual wells are characterised by a smaller or larger ratio of recharged water and groundwater. Furthermore, the historical data shows that groundwater flowing naturally from the south towards the Świerczków wellfield is of poor quality due to the negative impact of numerous pollution sources located in the vicinity of the wellfield. The negative impact of contaminated groundwater is mitigated by the infiltration of surface water from ditches into the aquifer. For complete characterization of the study area (from the point of view of **water quality**), information on temporal and spatial variability of chemical composition of groundwater and surface water is needed. It is also necessary to determine the proportion of surface water and groundwater within water pumped by the wells. Recognition of chemical and mineralogical properties of aquifer sediments will allow application of geochemical modelling, which is useful for the identification of chemical processes influencing groundwater chemistry.

The water supplied from the study area is intended to function as drinking **water supply** for the population. Therefore, its quality must meet the criteria specified in the regulation for drinking water. Nevertheless, the quality of water is also important as is the quantity of the supplied water. In order to provide an adequate quantity of water it is necessary to use the MAR system and optimize the existing solutions, because the natural groundwater resources in the study area are insufficient. In addition, recharge increased by MAR enhances the economic viability of the water supply at the pilot site.

Both MAR methods for which a feasibility study will be conducted require a good understanding of hydrogeological conditions and geological structure, therefore, based on the description in the chapter 3 of this report, the scope of studies necessary to conduct a comprehensive **aquifer characterization** is summarised and described in subchapters 4.1.1-4.1.3.

MAR pilot feasibility studies will then be conducted based on the 3 guidelines: 1) Guidelines for water demand and supply (report D.T3.2.1), 2) Guidelines for technical solutions (report D.T3.2.2) and 3) Guidelines for Cost-Benefit-Analysis (CBA) and regulatory framework (D.T3.2.3)

4.1.1 Planned geological and hydrogeological studies

Based on the information obtained from the archival data, the following detailed studies are planned to be conducted for the MAR feasibility study to supplement the identification and knowledge of hydrogeological conditions and geological structure in the pilot area.

- Geophysical survey to determine the thickness and the variability of the bottom of the aquifer in the area where the MAR feasibility study will be conducted.
- Carrying out shallow hand geological drilling to obtain information on vertical seepage times and to estimate the possibility of direct groundwater recharge from precipitation.
- Construction of a network of 9 piezometers to determine aquifer parameters and monitor groundwater table variations for model calibration.
- Observation of variability of groundwater table, surface water table in river and water table in infiltration ditches in the study area for the purpose of calibration of numerical models and development of a strategy for optimization of wellfield. Continuous measurements will be made by means of 5 data loggers. Moreover, once a month the measurements of groundwater table level in wells of the Świerczków wellfield will be made. In spring, measurements of groundwater table will be also made in all available wells within the boundaries of the groundwater model in the Tarnów region.

4.1.2 Planned chemical and isotopic analyses of groundwater, surface water and sediments

In general, all planned chemical and isotopic analyses can be divided into three groups:

- monthly measurements,
- seasonal measurements,
- single measurements.

<u>**Monthly measurements**</u> will be conducted for one year and are aimed at investigating temporal changes in selected parameters of water. The water samples include:

- groundwater from 9 wells and 1-5 piezometers (depending on their availability),
- surface water from the Dunajec river and 2 ditches,
- precipitation.

The group includes the following parameters:

- temperature,
- pH,
- redox potential,
- conductivity,
- concentration of dissolved oxygen,
- concentration of nitrate-nitrogen,
- concentration of nitrite-nitrogen,
- concentration of ammonia-nitrogen.

All these parameters will be measured in the field using portable equipment. Concentration of inorganic nitrogen forms will be measured using portable spectrophotometer HACH DR1900.

Apart from in-situ measurements, the water samples will be collected in order to perform isotopic analyses:

- $^{15}N/^{14}N$ and $^{18}O/^{16}O$ ratios in nitrate (13-17 water samples depending on the availability of the sampling points),
- $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios in water (10 water samples).

Stable isotopes of water will be analysed using isotope-ratio infrared spectroscopy (IRIS) and the isotopes of N and O in nitrate will be analysed using isotope-ratio mass spectrometry (IRMS).

Based on the results of monthly measurements, the following issues will be addressed:

- What are the sources of nitrogen in the abstracted groundwater?
- What is the fate of inorganic nitrogen forms under the MAR impact on groundwater?
- What are the temporal changes in groundwater chemistry across the wellfield area?
- What is the ratio of surface water artificially recharged from ditches in the total volume of groundwater abstracted by the wells?

<u>**Seasonal measurements**</u> of water will be carried on 4 times in different season of the year (autumn, winter, spring and summer). The water samples include:

- groundwater from 12 wells and 1-5 piezometers (depending on their availability), 2 wells from the neighbouring Kępa Bogumiłowicka wellfield for comparison with the Świerczków wellfield,
- surface water from the Dunajec river and 2 infiltration ditches,
- precipitation.

The scope of analyses is broader and, in addition to the monthly measurements, the group includes:

- major cations and anions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}),

- concentration of dissolved Fe^{2+} and Mn^{2+},
- total organic carbon,
- PAH: polycyclic aromatic hydrocarbons (16 compounds),
- surfactants (anionic and non-ionic compounds),
- PPCP: pharmaceuticals and personal care products (102 compounds).

Mg^{2+}, Ca^{2+}, K^{+} and Na^{+} will be detected using ICP-OES method (Inductively Coupled Plasma - Optical Emission Spectrometers), Cl^{-} will be analysed by titration (Mohr's Method), HCO_3^{-} will be measured by titration with HCl, SO_4^{2-} will be analysed with gravimetric method using barium chloride, and total organic carbon will be detected using high-temperature combustion method with IR detection.

Polycyclic aromatic hydrocarbons will be measured using high performance liquid chromatography with tandem fluorescence and spectrophotometric detection (HPLC-FLD/UV). Anionic surfactants will be analysed using LCK Cuvette Test HACH Lange no. LCK 332, and non-ionic surfactants will be detected with spectrophotometric method PN-72/C-04550/03. PPCP will be analysed using liquid chromatography - tandem mass spectrometry method (LC-MS/MS).

Based on the results of seasonal measurements, the following issues will be addressed:

- What is the impact of MAR on groundwater chemistry?
- Are there any significant seasonal changes in groundwater chemistry across the wellfield area?
- What is the fate of PPCP, PAH and surfactants during infiltration from the ditches into the aquifer?
- Which compounds present in the abstracted groundwater come from the managed aquifer recharge, and which come from the natural groundwater?
- What is the effectiveness of PPCP attenuation during infiltration of surface water into the aquifer?

Single measurements include sampling and analyses of surface water, groundwater and sediments. The aim of this group of measurements is to acquire new knowledge about the pilot site. The measurements comprise analyses and tests that have never been performed before, or were performed so long ago that is necessary to conduct them again in order to obtain current information on the geochemical state of the environment.

The measurements include:

- concentration of microplastic in 7 water samples,
- chemical and mineralogical analyses of sediments collected from the bottom of the ditches and from the aquifer during drilling of the new piezometers,
- content of organic compounds in 10 water samples and 10 sediment samples.

Microplastic will be measured in 7 water samples collected from the Dunajec river, one infiltration ditch, piezometer, 3 abstraction wells and from a water inlet for infiltration ditches. In total 8 compounds will be analysed: Polyethylene, Polypropylene, Polystyrene, Polyvinyl chloride (PVC), Polyethylene terephtalate (PET), Polyamide 6 (PA6), Polymethyl metacrylate (PMMA) and Polycarbonate (PC). The detection will be conducted using pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS). The aim of the analysis is to answer the question about the presence of microplastic in the source water for MAR, and to investigate the fate of the 8 tested compounds during the infiltration to the aquifer.

In order to study the migration of organic pollutants dissolved in groundwater and surface water, 10 water samples will be collected from wells, piezometers, ditches and the Dunajec river. Another 10 samples of sediments will be collected during drilling of the new piezometers. The collected samples will be prepared for the identification of organic compounds dissolved in water by gas chromatography coupled with mass spectrometry (GC-MS). The SPE (Solid-phase extraction) method will be used to extract organic matter from the liquid samples. It is an extraction technique whereby compounds dissolved or suspended in a liquid mixture are separated from other compounds in the mixture according to their physical and chemical properties. The total extracts obtained with the SPE will be derivatised with the N, O-bis (trimethylsilyl)trifluoroacetamide (BSTFA) reagent with 3 hours heating at 70°C. Derivatised extracts will be analysed on a gas chromatograph coupled with a mass spectrometer (GC-MS). Biomarkers will be identified based on their mass spectra, characteristic retention times, NIST libraries, and literature data. The identification of organic compounds dissolved in the tested water samples will be presented in the form of an electronic report.

In order to study the chemical and mineralogical composition of the soils in the area of the Świerczków wellfield 15 samples of soil and 5 samples of fly ash will be collected. The samples will be taken from the following places:

- surface layer of the soil (0-25 cm below the ground) – the pilot site will be divided into 6 polygons (6 samples);
- soil samples from the bottom of the infiltration ditches (9 samples including 1 sample from the dried ditch),
- samples of fly ash wastes deposited behind the sheet piling separating the wellfield area; 2 boreholes are planned to be drilled in order to take samples from two vertical profiles of wastes (5 samples).

The collected samples will be subjected to leaching tests in accordance with the PN-EN 12457 standard. The following compounds will be determined: Ag, Al, As, Au,, Hg, Ho, In, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, P, Pb, Pd, Pr, Pt, Rb, Re, Rh, Ru, S, Sb, Sc, Se, Si, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn, Zr, HCO3, SO4, NO3, NO2, NH4. Performing leachability tests will enable the determination of substances which could be leached from the surface layer of soil to groundwater.

The chemical composition of the collected samples will also be examined using XRD method. The following elements will be determined: Mg, Ca, Na, K, Ti, P, Mn, Cr, Ba, Ni, Sc, LOI, Be, Co, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, U, V, W, Zr, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, TOT/C, TOT/S, Mo, Cu, Pb, Zn, As, Cd, Sb, Bi, Ag, Au, Hg, Tl, Se. The samples will also be analysed for mineralogical composition.

4.1.3 Planned numerical modelling

Based on the results of the detailed geological and hydrogeological investigations two different hydrodynamic numerical models will be constructed in the pilot area. The first one, the SWAT catchment model, will help to obtain information about the components of water balance in sub-catchments for the Tarnów region. Moreover, based on this model, numerical simulations will be performed to show how climate change will modify specific elements of water balance, such as groundwater recharge. The results of the model will allow to determine water availability for population and industry.

The second model is a groundwater flow model which will be developed to simulate the groundwater flow conditions in the pilot area and in order to describe the groundwater budget elements. FEFLOW model will be used for groundwater flow simulation to determine the effectiveness of already existing MAR facilities. In addition, it will also be used to simulate the impact of new MAR facilities on groundwater resource increase.

In addition to the numerical modelling, geochemical modelling will be performed. Geochemical modelling is an effective tool in identifying chemical processes forming the chemical composition of groundwater. Based on the data on groundwater chemistry and mineralogical composition of the sediments building the aquifer, an attempt will be made to build geochemical models using PhreeqC software. Based on the model results it will be possible to infer the chemical processes occurring during infiltration of surface water into the aquifer.

V. Summary and conclusions

The DEEPWATER-CE project demonstrates the benefits of Managed Aquifer Recharge (MAR; D.T1.2.1) and analyses in detail 6 types of MAR schemes, for which a toolbox (D.T2.4.3) has been developed to assist in the selection of potential suitable locations for MAR in Central Europe.

In the Polish pilot area a detailed feasibility study will be conducted for 2 techniques: infiltration ditches and induced river and lake bank filtration. The feasibility study will be described in subsequent reports (D.T3.4.1 - 4.5) and will include a range of field, laboratory and modelling work. In addition, a risk and cost/benefit analysis will be conducted and the strengths and weaknesses of the proposed two MAR solutions for the Tarnów area will be highlighted.

This very report (D.T3.4.1) focused on the desk analysis of the research area (which is planned FEFLOW modeling area at the same time) located in the vicinity of the city of Tarnów, near a highly industrialized area, with a nitrogen plant belonging to Grupa Azoty S.A. at the forefront. In four chapters, the authors meticulously described the various elements that allow the characterization of the pilot site, such as geological and hydrogeological conditions, hydrology or terrain morphology. In addition, the second part of the report also focuses i.a. on the description of the existing infrastructure in the place of the potential expansion of already existing MAR area (wellfield belonging to Tarnow Waterworks - Świerczków), as well as on the legal aspects regulating MAR issues in Poland. The last chapter, in turn, presents the planned work in the area of research, which is intended to expand the knowledge obtained during the analysis of archival materials for the purposes of this report.

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