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Groundwater impact assessment of Lake Czorsztyn after 25 years of its operation

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Abstract: Artificial water reservoirs pose impact on the natural environment. Impact of the artificial Czorsztyn Lake on groundwater and land management is assessed. The study is based on long-term observations of chemistry, groundwater levels and spring discharges during reservoir construction, filling, and 25-year-long exploitation. Land management changes caused by reservoir construction were recognized using remote sensing. Reservoir construction resulted in land management change in the study area. Built-up and forest areas gained prevalence over farmland areas. Two types of groundwater dominate: HCO_3–Ca and HCO_3–Ca–Mg, both before reservoir filling (68% analyses) and afterwards (95% analyses), and in control analyses from September 2020 (100% analyses). Gradual decrease in the occurrence of water types with the sulphate ion exceeding 20% mvals is documented, which points to water quality improvement trends. Moreover, changes of water saturation index values with regard to aquifer-forming mineral phases during reservoir construction and early exploitation phase indicate hydrochemical modifications. Decrease of groundwater level was related with transformation of the Dunajec river valley during reservoir construction and, accordingly, decrease of regional drainage base level. Groundwater level increased after reservoir filling, which points to coupled impact of the reservoir and increased precipitation recharge. Construction of the Czorsztyn Lake resulted in gradual land management transformation from farmlands into tourist-recreational areas. This change and river valley flooding by surface waters did not cause significant modifications in groundwater quantity and quality. Organization of water-sewage management related with reservoir construction resulted in noticeably improved quality trends.

Introduction

Construction of a water reservoir is always a substantial interference in the natural environment of a river valley. It interferes with local hydrological, hydrogeological and microclimate systems, and often alters local fauna and flora populations (Baxter 1977, Graf 1999, Al-adili et al. 2014). At present, the influence of water dams and accompanying retention basins on the natural environment is studied and discussed in a wide spectrum of ecological and socioeconomic criteria (Ho et al. 2017), or in accordance with community law requirements.

There are relatively scarce reports devoted to the influence of water dams on groundwater; they mainly focus on the influence of water damming in retention basins on groundwater hydrodynamics (Francis et al. 2010, Al-adili et al. 2014, Zhang et al. 2014, Przybyłek 2016, Çelik 2018).

Using the results of archival studies in the Dunajec catchment basin related to groundwater dynamics and chemical composition before damming of the Dunajec waters by the Czorsztyn dam (Fig. 1), during the filling of Lake Czorsztyn and at present, an attempt was made to recognize the trends of groundwater impact of the artificial reservoir during the last 25 years. Due to the specific area and complex character of factors shaping the groundwater chemical composition, it became indispensable to recognize and take into account local conditions based on measurements conducted with a finer resolution than annual data.

In the study area, we had access to detailed groundwater analyses and spring discharges measured since the 1960s in 24 h and weekly cycles. We used long-term series of data on the chemical composition, groundwater levels, and spring discharges from numerous observation points, conducted by Professor Danuta Małecka's team from the Institute of Hydrogeology and Engineering Geology at the Faculty of Geology, University of Warsaw, which included also the authors of this report (Małecka et al. 1996).

The concept of the Czorsztyn dam construction reaches back to the early 1900s. Being widely discussed in scientific and popular science reports, the idea has raised numerous controversies. Contrasting opinions on the usefulness of the investment and design variants were often presented. In 1964, the design which included the construction of the main reservoir with a dam in Niedzica and a compensating reservoir in Sromowce Wyżne was considered as the most proecological one. It assured the maintenance of an undisturbed flow in the Dunajec river and the functioning of a flow through the Pieniny gorge. The design was supposed to provide a correct balance between particular functions of the reservoir, with a priority posed on water management and flood control measures. A significant reconstruction of the road infrastructure in direct vicinity of the future reservoir became an indispensable element of the project. It included the shifting of a significant part of regional road no. 969 and the construction of a new road to the raft landing in Kąty and the border crossing with the then Czechoslovakia (presently Slovakia), which cut through and divided the area of the Pieniny National Park into two parts. Dam construction began in 1975. Blockades and protests of ecological activists caused many interruptions in the construction process. The problem of polluting water by sewage drained into the streams recharging the designed retention basin was commonly brought up. In consequence, a sewage system was constructed, including 14 large and several tens of smaller water treatment plants in the reservoir catchment. In 1994, the compensating reservoir in Sromowce Wyżne was completed; its area (at maximal filling) is 95 ha, total volume is 6.7 mln. m^3, and maximal damming level is 11 m. The filling of the main Lake Czorsztyn began a year later; the reservoir started to operate in 1997. Its maximal area is 1120 ha, the total volume is 234.5 mln. m^3, and the maximal damming level – 56 m. The accomplishment of the project and the beginning of reservoir exploitation coincided with the large flood in July 1997. The decrease of the flood hazard on several lower lying settlements due to dam construction clearly weakened the arguments of the project opponents (Łaniewski 1997).

The Czorsztyn Basin is a dimictic reservoir. Complete water mixing takes place during spring and autumn, whereas complete water exchange in the reservoir takes place averagely 3 times a year (Wilk-Woźniak et al. 2010). The main rivers flowing into the Czorsztyn Basin are the Dunajec, the Białka and the Niedziczanka, with the contribution of the Dunajec waters in 2010–2016 averagely reaching 59.64%, the Białka – 32.31%, and the Niedziczanka – 8.05%. Results of monitoring surveys performed by the Regional Environmental Inspectorate in Cracow indicate that with regard to nitrogen and phosphorus forms, as well as water pollution indicators such as biological and chemical oxygen demand, water flowing out of the reservoir represents a better chemical state than the Dunajec water above the reservoir (Tab. 1). Higher contents of phosphates and nitrates in the Dunajec River compared to the Czorsztyn Basin have already been indicated by Wilk-Woźniak et al. (2010). In the present stage of research it can be concluded that the improvement of water quality is the result of:

- mixing of the Dunajec water with the Białka and the Niedziczanka water, which is characterized by lower pollution loads, in the reservoir;
- groundwater drainage, largely assigned to class I – very high quality water (Humnicki 2007);
- biological and chemical processes taking place in the reservoir basin.

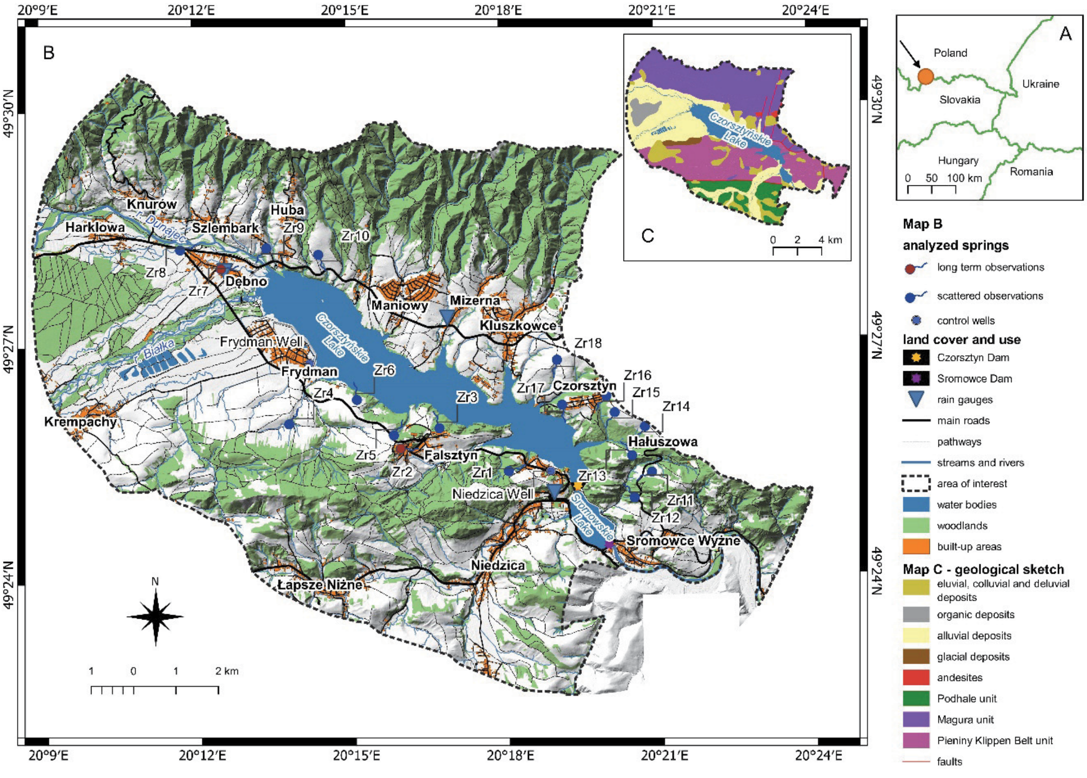


Fig. 1. Location of the study area with regard to geology, morphology and land management, with location of the hydrogeological control points

Geological setting and hydrogeological conditions

Lake Czorsztyn is located in the eastern part of the Orawa-Nowy Targ Basin, which represents a typical intramontane basin filled with Neogene and Quaternary deposits. From the south, the margin of this form comprises rocks of the Pieniny Klippen Belt, which form the southern and eastern reservoir banks. The northern bank of the reservoir is built of strongly deformed Paleogene flysch rocks of the Magura Nappe of the Outer Carpathians (Fig. 1).

The Pieniny Klippen Belt (PKB) represents one of the most complex structural units in Europe. In general, the PKB includes a series of klippe units composed mainly of Jurassic strata, dominated by relatively hard and stiff carbonate and carbonate-siliceous rocks, and a klippe cover, dominated by soft marly and flysch deposits od Cretaceous and Paleogene age (Birkenmajer 1979, 2017). Groundwater forms a discontinuous and variable aquifer, occurring within a strongly weathered and fractured sub-surface zone, composed of rocks representing different lithologies and characterized by different hydrogeological parameters (Chowaniec and Witek, 1997, Humnicki 2007, 2009).

Groundwater conditions are variable in the zone of the reservoir eddy (Dębno–Frydman). The thickness of the Quaternary aquifer reaches 30 m. Values of the filtration coefficients of Quaternary sandy-gravel deposits are from 2.0×10^{-5} to 7.5×10^{-4} m/s near Dębno, and from 9.1×10^{-6} to 8.0×10^{-4} m/s near Frydman (Małecka et al. 1996).

Values of the filtration coefficient determined on the basis of test pumping of wells draining the PKB fracture waters are from 4×10^{-6} to 2.4×10^{-5} m/s and the waters of the Magura Unit near the Pieniny Mts – from 3×10^{-7} to 3.8×10^{-4} m/s (Małecka et al. 1996). The most favorable conditions of groundwater occurrence are in the alluvia of the Dunajec and the Białka rivers, characterized also by the best infiltration conditions for precipitation, caused by small land slopes and permeable basement rocks. The infiltration conditions in flysch rocks are variable, while in the PKB area – usually poor.

Lake Czorsztyn is intensely drained by numerous springs, deeply incised stream valleys and the Dunajec river valley. The deeply incised Dunajec valley causes that it acts as a natural groundwater drainage base level. The construction of Lake Czorsztyn caused significant changes of the position of this base level and decrease of hydraulic gradients.

Material and methods

Remote sensing methods

Satellite data from the Landsat mission were used to determine land use and land management changes, and recognize particular phases of Lake Czorsztyn filling. For almost 50 years, satellites of the Landsat program have been conducting continuous surveillance of our planet. Such a long period of data acquisition allows for observing the environmental conditions before, during and after reservoir construction. Moreover, the Landsat satellites image Earth's surface in many ranges of the electromagnetic radiation spectrum, which allows

Table 1. Comparison of selected properties of surface water flowing into and out of the Czorsztyn Basin (based on data from the Regional Environmental Inspectorate in Cracow – http://krakow.pios.gov.pl/)

Period	Measurement site	BOD5 (mgO_2/dm^3)	COD-Mn (mgO_2/dm^3)	Ammonium nitrogen ($mgN\text{-}NH_4/dm^3$)	Kjeldahl nitrogen (mgN/dm^3)	Nitrate nitrogen ($mgN\text{-}NO_3/dm^3$)	Total nitrogen (mgN/dm^3)	Total phosphorus (mgP/dm^3)
2010–2012	Dunajec above the reservoir	2.3	2.6	0.21	0.61	1.11	1.76	0.076
	Dunajec below the reservoir	1.9	2.2	0.04	0.39	0.74	1.13	0.04
2014	Dunajec above the reservoir	1.7	2.6	0.04	0.36	0.74	1.11	0.048
	Białka	1.3		<0,02	0.30	0.55	0.83	0.027
	Niedziczanka	1.2		<0,02	0.33	0.75	1.06	0.032
	Dunajec below the reservoir	1.4	2.3	0.03	0.30	0.69	0.99	0.035
2016	Dunajec above the reservoir	1.9	3.3	0.167	0.5	1.1	1.6	0.05
	Białka	1.1	1.4	0.03	0.2	0.6	0.7	0.03
	Niedziczanka	1		0.3	0.2	0.5	0.6	0.03
	Dunajec below the reservoir	1.5	3.3	0.05	0.3	0.9	1.2	0.03

us to classify the surface with a spatial resolution that enables analysis on both regional and local scales. Data acquired by the program have been made available free of charge in 2009 (Woodcock et al. 2008, Claverie et al. 2015).

Two sets of satellite images were used to determine changes in land use and land management. The first set referred to the first stage of the project before the reservoir was filled. The second set shows the present day land use and land management. Classification of satellite images should encompass sets of spectral channels registered in the optical ranges of the electromagnetic radiation spectrum (radiation reflected from the surface). Images registered in full vegetation season were used in the analysis. The reason for this was the need to unify the spectral response in non-urbanized areas with farm land use. Conducting classification in non-vegetation periods would result in an increase of errors, caused by high complexity and similarity of the spectral response for urban areas, exposed rock surfaces and vegetation-free farmlands (Li et al. 2017).

The process of reservoir filling was imaged using 10 sets of images, registered in 1994–1997. In this case, due to the large and distinct contrasts in the values of reflectance indexes between water and land objects, scene choice was made regardless of the vegetation season. However, other restrictions included the presence of clouds, mist, and ice, and snow cover during the winter season.

Assessment of land use and land management before the reservoir construction and during the process of its filling was based on the classification of images registered by the Thematic Mapper (TM) scanner, mounted on the Landsat 5 satellite (Mika 1997, Loveland and Irons 2016, U.S. Geological Survey 2016) on 08.08.1994. The condition of present day land use and land management was documented on 10.08.2020 with the application of an image set acquired by the Operational Land Imager (OLI) scanner transported by the Landsat 8 satellite (U.S. Geological Survey 2016).

The image sets were downloaded from the U.S. Geological Survey – Earth Explorer portal (https://earthexplorer.usgs.gov/). The acquired collections were initially processed by the data distributor and made available as Collection 2 (C2) Level 2 Science Product (L2SP). The C2L2SP data are published as image sets showing the spatial distribution of the reflection index value from the surface and the surface temperature in the case of thermal images (U.S. Geological Survey 2020*a*, *b*).

Image classification was made with the application of QGIS 3.16 software with the Semi-Automatic Classification plug-in. It allows us to perform the classification of spectral channel sets using the Maximum Likehood method, one of the most common supervised classification methods (Richards 2013, Congedo 2020).

Hydrogeological methods

The first stage of hydrogeological analysis included constructing a database with archival and present-day water levels in the control wells, spring discharges and chemical composition of groundwater drained by springs located in the direct vicinity of Lake Czorsztyn. For 16 sites, the available data covered analyses from the time of reservoir filling (1994–1997) and its exploitation (1997–2020). In two sites (Dębno and Falsztyn), the monitoring data were from the period prior to reservoir construction, during its filling and exploitation. The oldest results were acquired from the unpublished archives of Professor Danuta Małecka, deposited in the Archives of the Faculty of Geology, University of Warsaw.

The performed analyses included the measurements of: groundwater temperature, reaction (pH), electrical conductivity (EC), redox potential (Eh) (in part of the analyses) and determination of water macro components. The water’s physical-chemical properties were determined using the multifunction meter CX-401 by Elmetron. The content of calcium, magnesium, chlorides and hydrogen carbonates in all samples was determined using the colorimetric method. The content of sulphates, nitrates, nitrites and ammonium ions was determined using the spectrophotometric method (Hach). The content of elements from the alkaline metals group was determined using the ICP-OS method. All analyses were performed in the Laboratory of Applied Geology at the Faculty of Geology, University of Warsaw.

The results of chemical analyses, both archival and those conducted during this study, have been verified with regard to reliability and data quality before further interpretation. The verification was performed according to the procedure of Witczak et al. (2013), Szczepańska and Kmiecik (1998) and Polish Norm PN-89/C-04638/02 (1989).

Aqueous geochemical models were performed for better recognition of potential changes of the hydrogeochemical conditions, which took place during Lake Czorsztyn construction, for water samples collected from springs with the longest observation series (in Dębno and Falsztyn). They were made using PHREEQC Version 3.6.2 (Parkhurst and Appelo 2013) with the phreeqc.dat. thermodynamic database. The models were made only for those samples in which temperature and reaction data were collected along with determination of the water components.

Speciation distribution and values of saturation indexes (SI) were calculated for each of the analyses. The speciation forms of components dissolved in water are a very sensitive proxy of hydrogeochemical conditions of a given area (Małecki 1998). The studies of Jóźwiak and Krogulec (2006) have documented the dominance of simple ions of alkaline elements (Na and K) and alkaline earth metals (e.g. Ca and Mg) in waters occurring in natural conditions. Similarly, chlorine occurs in a simple form as Cl^-. The contribution of multi element speciations, particularly sulphates, increases with anthropopression.

Equally sensitive proxies of changes taking place in the hydrogeochemical environment are saturation indexes (SI). SI values allow us to determine the trend if a given mineral phase will be dissolved, precipitated, or if the solution will remain in equilibrium. Negative SI values point to the potential possibility of dissolving mineral phases, whereas positive ones – to their precipitation. It is assumed that the groundwater equilibrium state with regard to a given mineral phase occurs at SI values in the range of ±%5 log K, where K is the equilibrium constant of the reaction in given thermodynamic conditions (Appelo and Postma 2005). Analysis of SI changes is presented on the basis of two carbonate minerals (calcite and dolomite). These minerals commonly occur in the study area, whereas, according to Allen (1997) and Clark (2015) even a small percentage (<0.1%) of carbonates in the rock causes their dissolution to have a dominating influence on the water chemistry.

Research results and discussion

Filling of Lake Czorsztyn began in July 1995. According to Landsat data (Fig. 2), the largest increase of reservoir area took place between July and September 1995 (during 41 days the reservoir increased its surface three-fold). In subsequent years, the speed at which the reservoir increased its area was stable, at about 29 ha per month, till its filling in 1997 to the designed normal damming conditions (529 m a.s.l.). The fastest increments of water volume accumulated in the reservoir took place between July and September 1995, from about 4.5 mln. m^3 (21.07.1995) to 29 mln. m^3 (07.09.1995). Large increments were also observed between April and August 1996 (Fig. 2).

Satellite data and the applied classification method allowed for distinguishing four land cover classes in the study area (Fig. 3.A–C). The *Water* class refers to water-covered areas whose spatial dimensions are larger than the pixel size (30 m). This class includes the reservoir surface and the Dunajec river. Due to ambiguous spectral response (the occurrence of many objects differing in reflection properties within one pixel), smaller streams were not included in this class. The *Artificial surfaces* class refers to built-up areas and surfaces covered by impermeable material. The *Forests* class includes woodlands and forested areas, whereas *Agricultural and open areas* embrace areas permanently used for agriculture (meadows and pastures), arable lands, exposed wastelands and rock surfaces (mountain tops and channels of shallow rivers) (Fig. 3).

The structure of land use and land cover underwent significant changes following the reservoir construction. Before the beginning of the essential part of the project, surface waters within the *Water* class covered about 1% of the area. Reservoir construction significantly increased the area covered by this class. In 2020, the area flooded by surface water covered 1,190 ha (i.e. 8% of the study area). Due to the dispersion of settlements, the built-up area has increased from 3 to 4%.

It should be emphasized that detection of smaller buildings in the images from 2020 was possible due to the higher radiometric resolution of the OLI scanner in comparison to the TM register mounted on the Landsat 5 satellite. Compared to 1987, the area covered by woodlands and forested areas increased by 4%, particularly in zones adjacent to the reservoir and in river valleys. The increased surface of built-up and forested areas was at the cost of agriculturally used areas, which points to a gradual transformation of the land management from farmlands that dominated in the period before reservoir construction to areas with touristic and recreational use (Fig. 3).

Changes of groundwater levels and spring discharges

We are aware that changes of the groundwater levels would be most accurately detected by a spatial analysis of the hydroisohypse pattern before and after the reservoir was constructed. However, due to the lack of archival data on the groundwater level for the entire area, the analysis was performed based on the data on the medium annual groundwater levels acquired in 1970–2004 from two dug wells that supply individual farms in close vicinity of Lake Czorsztyn. The first well is located in the Pieniny Klippen Belt in Niedzica Zamek at the elevation of 555.0 m a.s.l., i.e. 20.5 m above the maximal water damming level in the reservoir, whereas the second – in the Orawa-Nowy Targ Basin in Frydman, right near the embankment surrounding the reservoir

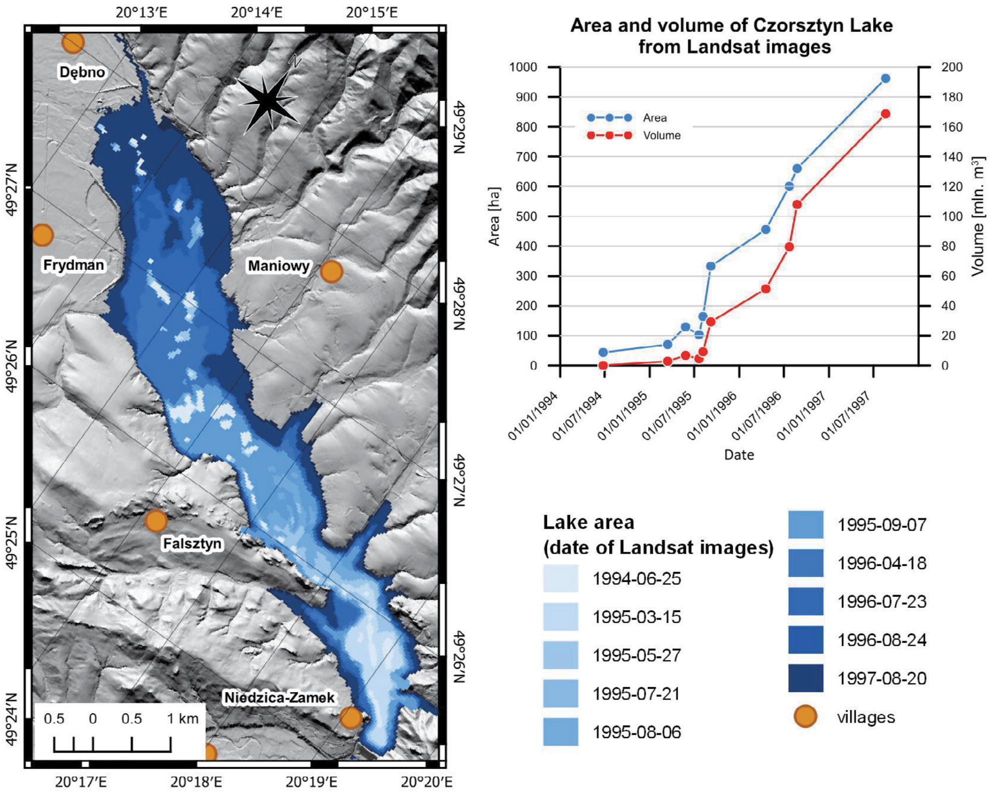


Fig. 2. Filling of the Czorsztyn Lake in 1994–1997 according to remote sensing data from the Landsat mission and a numerical model of the reservoir bottom surface

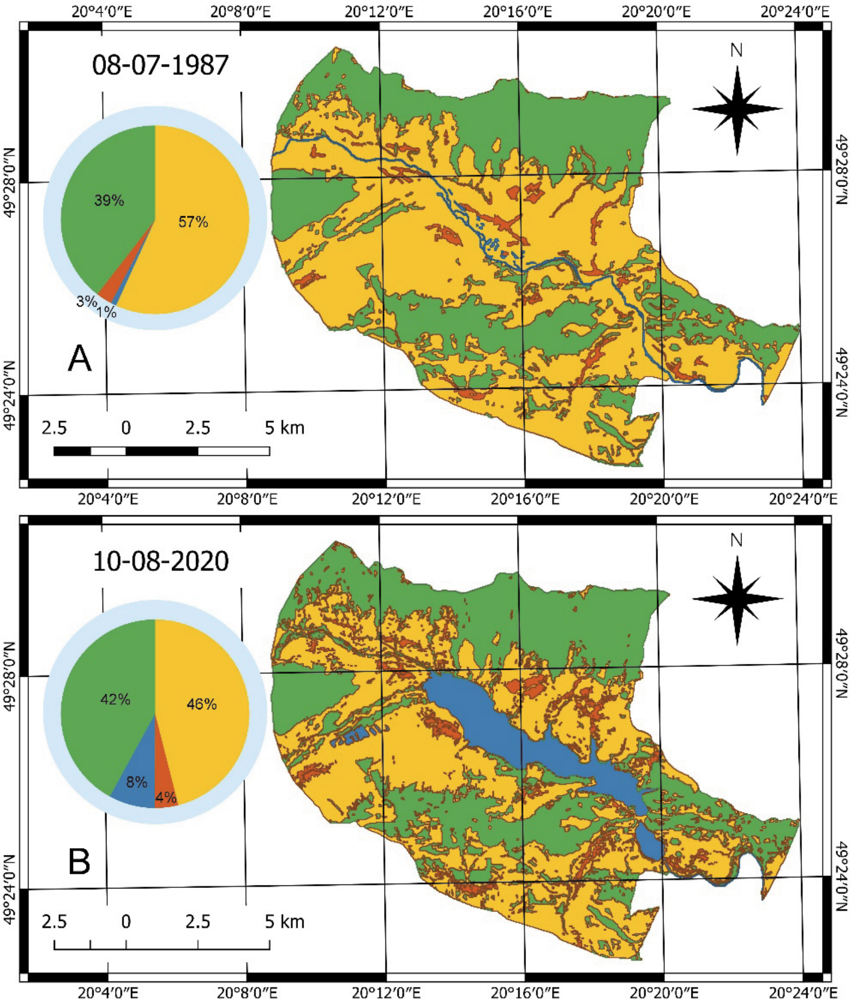
at the elevation of 527.4 m a.s.l., i.e., 7.1 m below the maximal water damming level in the reservoir (Fig. 1).

Stationary observations of groundwater levels in both wells have been subdivided into two periods: the first spanning the period of 1970–1996, that is before the reservoir was filled, and the second – 1997–2004, that is in the first years of its functioning (Fig. 4).

The groundwater level response to the reservoir construction in both wells is totally different. In the Niedzica Zamek, the well is situated much above the reservoir water level; here the average groundwater level essentially did not change, rising by 0.3 m, which can be explained by a slightly larger precipitation recharge in the second period (mean annual sum of precipitation at 797 and 808 mm). In contrast, in the Frydman well, a distinct decrease in groundwater level was observed in 1982–1997; it was caused by the transformation of the Dunajec valley during reservoir construction and decrease in the regional drainage base level. After the reservoir was filled, a radical increase of the average groundwater level by 3.7 m was observed. In this case, such a radical change of the groundwater level is evidence of a distinct influence of the reservoir on the groundwater level in its vicinity.

An equally important component of the assessment of groundwater dynamics changes is spring discharge. The control spring in Falsztyn (Zr2, Fig. 1), with stationary observations from the 1980s by Polish Geological Institute at weekly intervals, is an example of one of the most efficient springs in the Pieniny Mts. The Falsztyn spring is located at the cross-section of two dislocations, it drains fissure waters of Pieniny Klippen Belt. It lies within the Falsztyn village development, is enclosed and the flow takes place into a wide concrete channel. The noted discharge range is 0.2–3 L/s (sporadically above 3.5 L/s). The spring drains a local groundwater reservoir, i.e., the Spiskie Pieniny massif (Humnicki 2010).

The second control spring, monitored by Polish Geological Institute and located near Lake Czorsztyn, is the Dębno



C

Class symbol	Land cover and use	1987 Area [ha]	2020 Area [ha]
🟦	Water	143	1190
🟧	Artificial surfaces	412	602
🟩	Forests	5943	6326
🟨	Agricultural and open areas	8547	6927

Fig. 3. Structure of land use and land cover around the Czorsztyn Lake: (A) in 1987, (B) in 2020, and (C) compilation of the areas covered by particular classes of land use and land cover, determined on the basis of Landsat image classification

spring (Zr7, Fig. 1). It is one of the most efficient springs in the Podhale area (average discharge 7.7 L/s) (Chowaniec et al., 1997). Located within the Dębno village development on a private property, it drains pore waters of accumulation terraces in the mouth stretch of the Białka river valley.

Due to the availability of archival data, the analysis was performed for an interval spanning the years 1984–2020 (Fig. 5). Similarly, as for the wells, this interval was subdivided into the period before reservoir construction (1984–1996) and after its filling (1997–2020).

In the Falsztyn (Zr2) control spring located in the PKB at the elevation of 635 m a.s.l. (i.e. about 100 m above the maximal water damming in the reservoir), the average annual discharge increased by 22% from 0.9 L/s in the first period to 1.1 L/s after the reservoir was filled. Similarly, as in the wells, this may be explained by slightly higher precipitation recharge in the second period (mean annual sum of precipitation at 814 and 827 mm, respectively). In the course of average annual discharge, the wet years of 1989 and 2010, when the annual sums of precipitation exceeded even 1000 mm, clearly stand out. However, it should be emphasized that recharge is influenced not only by the total sum of precipitation but also by its type, intensity and annual distribution, which may cause the increase of average discharge to be percentage-wise larger than the increase of the average sum of precipitation.

Similar regularities have also been observed in the Dębno (Zr7) control spring, located in the Orawa-Nowy Targ Basin (Fig. 5). Average discharge increased from 8.4 L/s to 10.6 L/s (by 26%), and similarly, as for the Falsztyn spring, the wet years of 1989 and 2010 clearly stand out. The decrease of spring discharge in the early 1980s resulted from the transformation of the Dunajec valley caused by the Czorsztyn dam construction. Because the spring is located at the elevation of 531.8 m a.s.l., that is almost 3 m below the maximal water damming in the reservoir, discharge increase most probably was superimposed on reservoir impact. Such a relatively minor reaction seems to be caused, on the one hand, by the distance of the spring from the reservoir and the surrounding embankment, and, on the other hand, by the fact that the spring regime shapes recharge from the elevated part of the Orawa-Nowy Targ Basin and generally from the upper part of the Dunajec catchment, for which the Orawa-Nowy Targ Basin is the base level of surface water and groundwater drainage (Małecka 1981).

When analyzing discharge changes in the remaining springs located around Lake Czorsztyn, land morphology and hypsometric positions of the springs above the maximal water damming in the reservoir were considered. This issue is well illustrated by selected morphological cross-sections (Fig. 6).

From among 18 of the analyzed springs, only the Dębno (Zr7) spring is located below the maximal water damming level in the reservoir. As many as 16 springs are situated more than 10 m above the maximal water damming level in the reservoir, therefore the impact of the water level in the reservoir on spring discharge seems rather improbable. The available data do not allow us to assess how the reservoir water level influences spring discharge. Beside the intervals when the water level is deliberately reduced in the reservoir to minimal levels (as e.g. in 2008) and by increasing hydraulic gradients enforcing slightly larger drainage through the Dunajec river valley and slightly smaller through the springs, the spring discharges

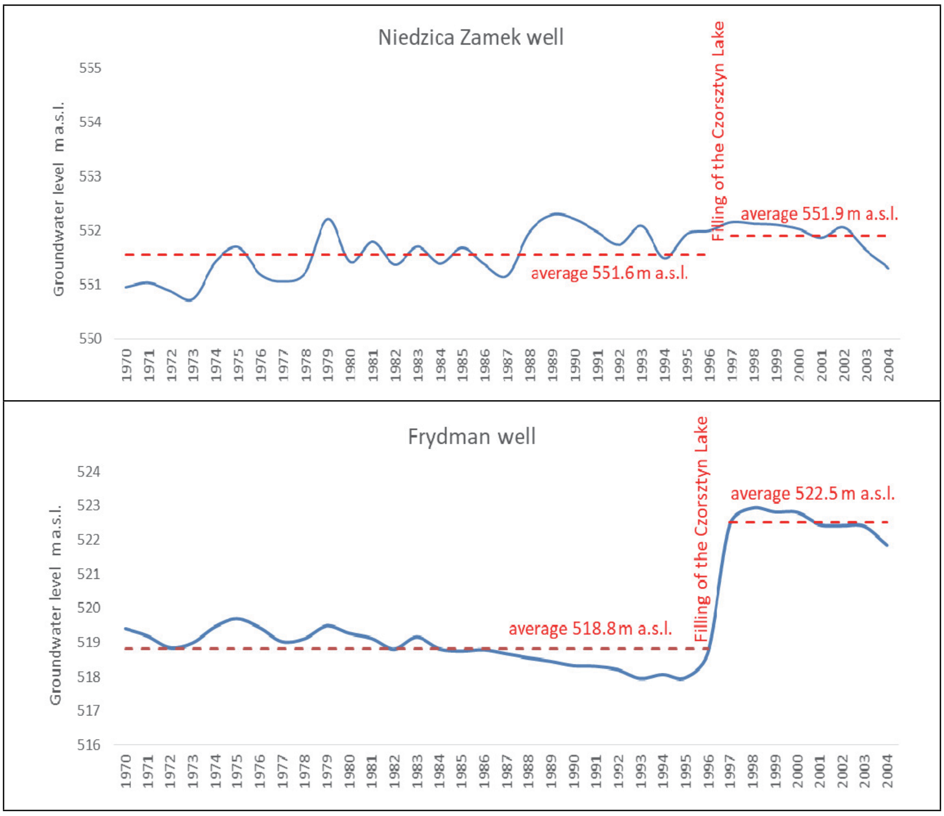


Fig. 4. Groundwater levels in the Niedzica Zamek and Frydman control wells (based on unpublished archival data of D. Małecka)

mostly depend on precipitation recharge and not on reservoir water levels.

It should also be emphasized that the reservoir impact on the groundwater level is restricted only to the closest vicinity of the reservoir in the Orawa-Nowy Targ Basin and is practically imperceptible in the remaining area.

Assessment of chemical composition changes in groundwater

A clear method of comparing the results of datasets are cumulative curves (Figs 7 and 8). The horizontal axes show the absolute values of selected ions and total mineralization

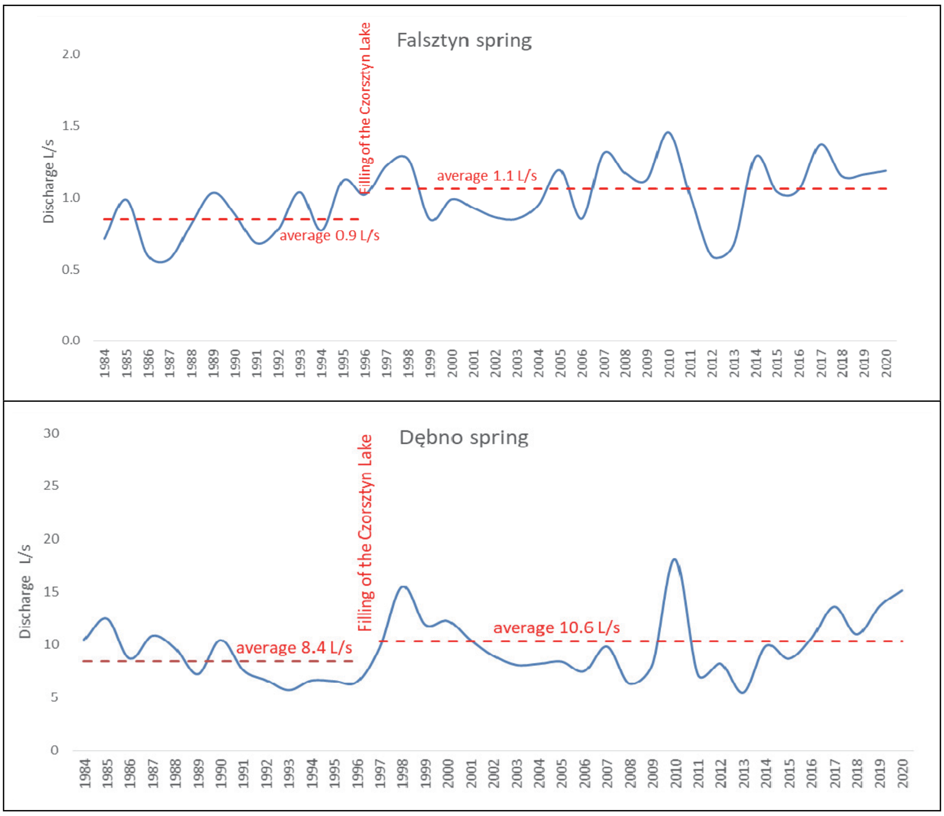


Fig. 5. Discharges of the Falsztyn (Zr2) and Dębno (Zr7) control springs (L/s), based on Polish Geological Institute data

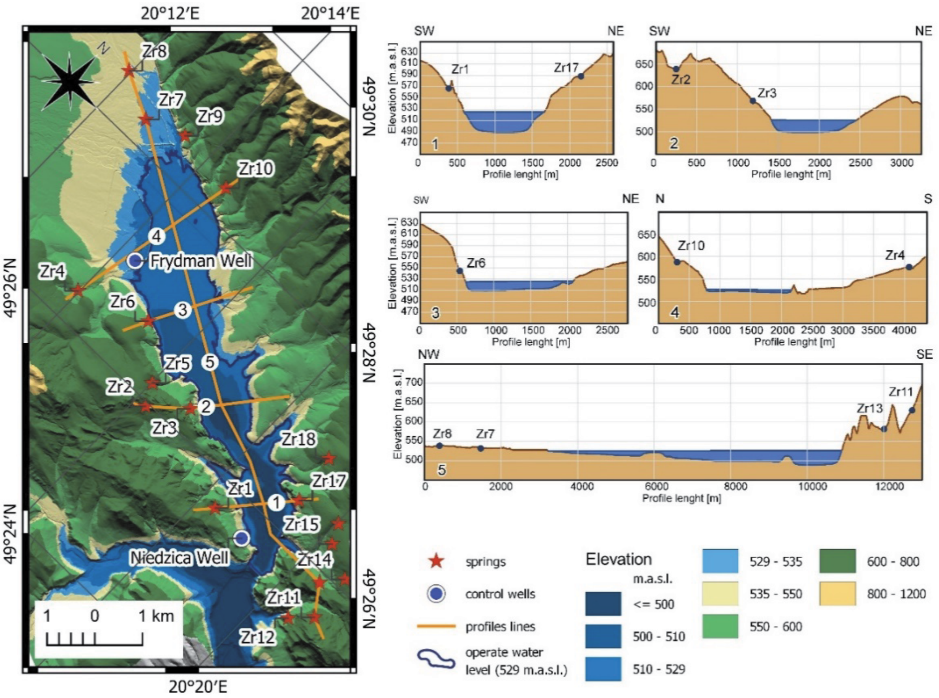


Fig. 6. Morphological cross-sections through the Czorsztyn Lake and the location of selected springs at normal water damming level (129 m. a. s. l.)

in mg/dm^3, whereas the vertical axes mark the percentage contributions of the analyses with contents of particular components lower than the given value, i.e., percentiles.

Cumulative curves were prepared separately for the analyses of the Dębno control spring, Falsztyn control spring (Fig. 7) and selected 16 springs located around Lake Czorsztyn (Fig. 8). The population of the analyses was subdivided into two periods: before and after damming of Lake Czorsztyn; a curve representing the results of control analyses from September 2020 was distinguished in the case of the selected 16 springs.

When comparing the two periods, before and after the reservoir was dammed, a slight trend in the decrease of Ca^{2+} content at simultaneous increase of Mg^{2+} content and a more distinct trend of Cl^- content decrease and SO_4^{2-} content increase may be observed in the Dębno spring (Fig. 7). Total dissolved solids (TDS) did not change. Similarly, for the period after the reservoir was filled, for the Falsztyn spring, the chloride curve shows a shift to lower values and the sulphate curve – a shift to higher values. In this case TDS also did not change.

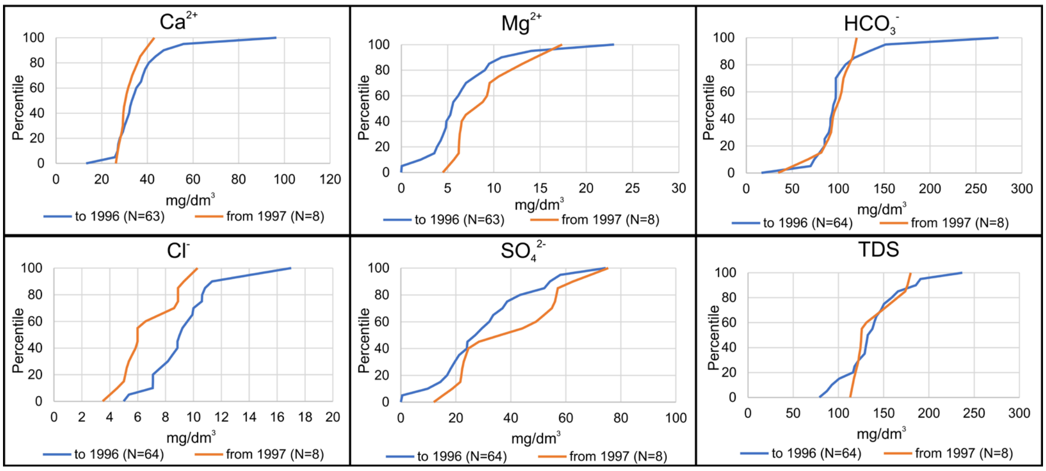
For the 16 springs located around the reservoir (Fig. 8), there is a clear trend of sulphate and nitrate content decrease, which is favorable with regard to groundwater quality, whereas the chloride content rose in point locations (even up to 28 mg/dm^3). The latter fact may be related to their location in the road impact zone in which chemicals based mainly on chlorides are used for winter maintenance.

A full groundwater characteristics requires defining the hydrogeochemical type, determined by ions that contribute to at least 20% mvals. Groundwater drained by springs from Lake Czorsztyn vicinity is dominated by hydrogen carbonate and calcium ions. The contribution of sulphate and magnesium ions is variable, the boundary value of 20% mvals is only sporadically exceeded. The contribution of chlorine and sodium ions is clearly subordinate and did not exceed the boundary value of 20% mvals in any locality. These proportions are well illustrated by Piper's charts (Fig. 9).

When analyzing the frequency at which particular groundwater types occur in 16 springs located around Lake Czorsztyn in different intervals, it can be assumed that two types: HCO_3–Ca and HCO_3–Ca–Mg always play the dominating role; this refers both to the interval before the reservoir was filled (68% analyses) and afterwards (95% analyses), as well as to the control analyses from September 2020 (100% analyses). Gradual decrease of the occurrence of water types with the sulphate ion above 20% mvals can be observed, which may indicate a trend of improving water quality in the area.

In detail, based on a larger number of analyses, the issue may be analyzed in the Falsztyn and Dębno control springs.

Dębno Spring (Zr7)



Falsztyn Spring (Zr2)

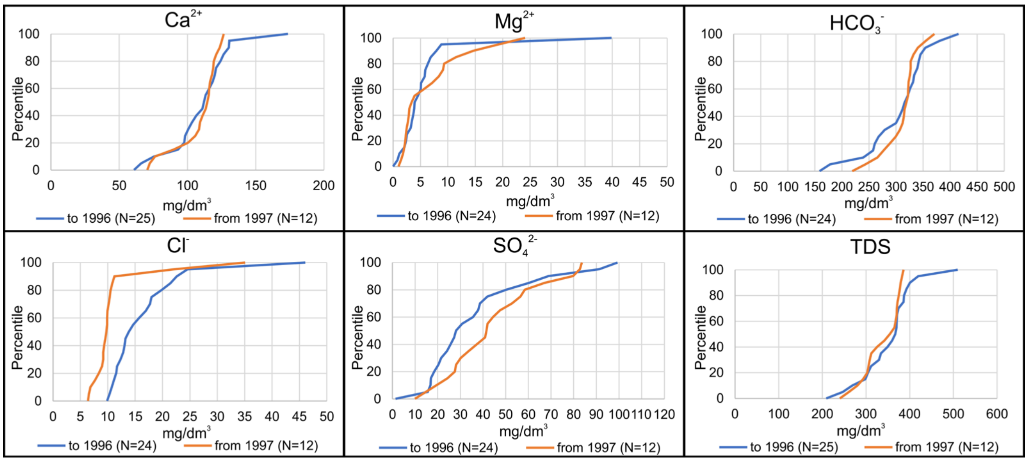


Fig. 7. Cumulative concentrations curves of basic macro components and water mineralization in the Dębno (Zr7) and Falsztyn (Zr2) springs

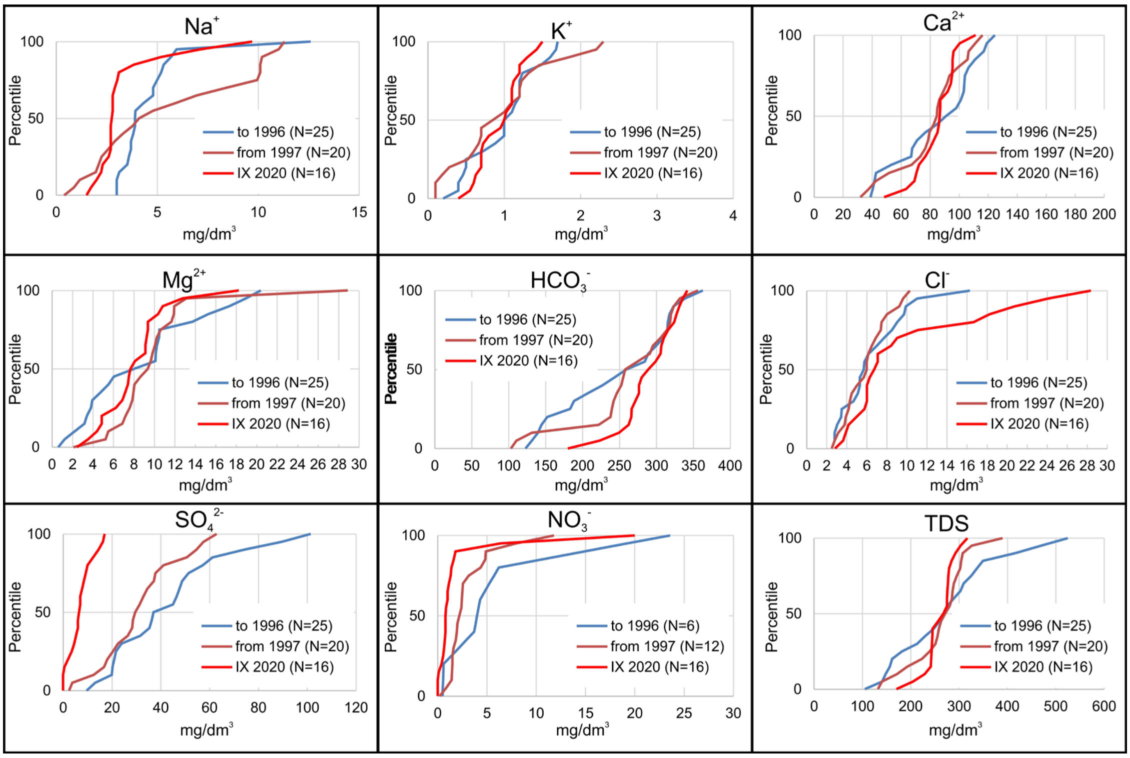


Fig. 8. Cumulative curves of concentrations of basic macro components and water TDS in selected 16 springs around the reservoir

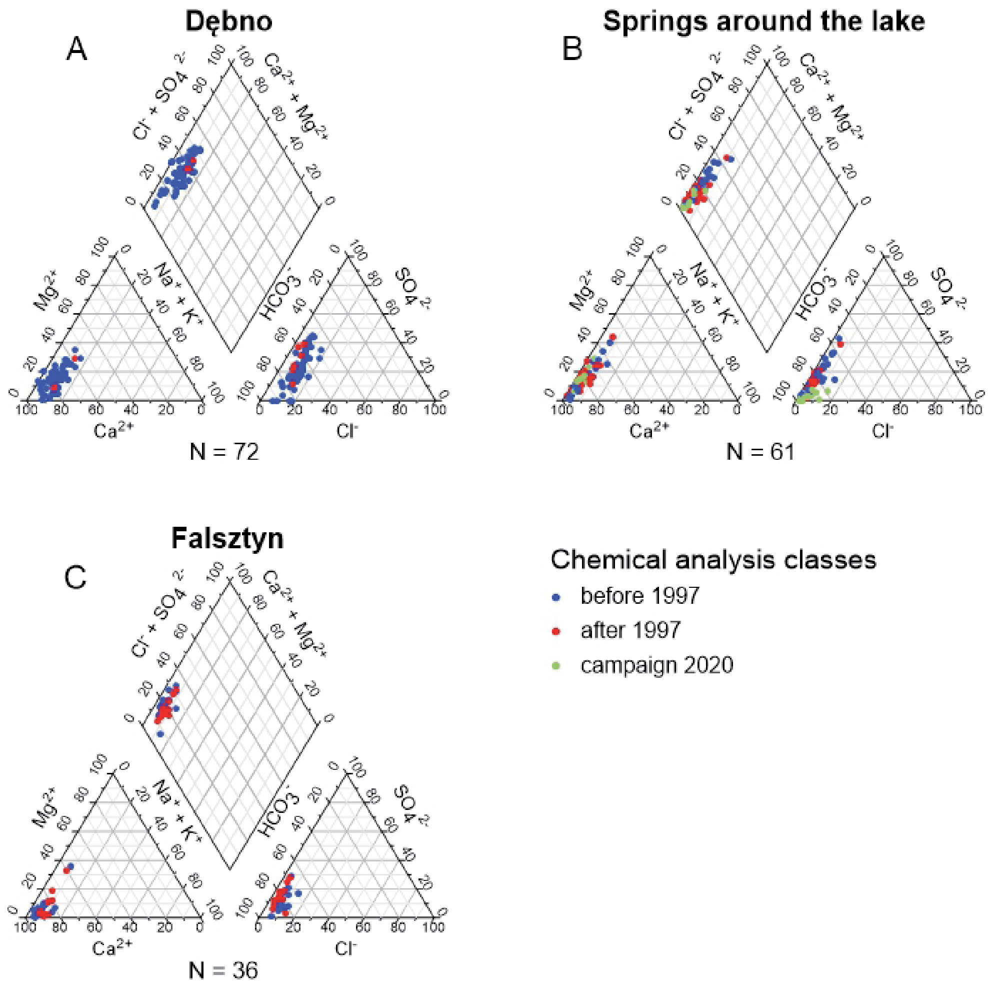


Fig. 9. Proportions of the concentrations of main groundwater components drained by springs in milligram equivalents

Type HCO_3–Ca dominated in both intervals in the Falsztyn spring (83% analyses before 1997 and 75% analyses after 1997). Types HCO_3–SO_4–Ca (12 and 16% analyses respectively) and HCO_3–Ca–Mg (sporadic cases) were much rarer. Filling of Lake Czorsztyn did not change the frequency at which water hydrochemical types occur. Analogous conclusions can be drawn when analyzing the Dębno spring. Before 1997, the most common water types were: HCO_3–SO_4–Ca–Mg or HCO_3–SO_4–Ca (66%) and HCO_3–Ca (25%), and similarly, after 1997 (75% and 25%, respectively).

When assessing concentrations of the main water types in the two intervals (before and after the reservoir was filled) and the control analyses made in 2020, no significant changes were observed in the proportions of their occurrence; in general, stability of their composition was noted at an only slight trend to change the contribution of sulphates on the cost of chlorides.

Methods of hydrogeochemical modelling, such as speciation modelling, were used in the hydrogeochemical assessment of the analyzed waters; it allowed us to assess the impact of geogenic and anthropogenic conditions in the development of the water solution composition (Table 2).

Simple ion forms dominate in the analyzed water, which may point to natural conditions at which their chemical composition developed. No considerable changes in the

Table 2. Percentage contribution of the speciations of selected elements before (before 1996) and after (after 1997) the filling of the Czorsztyn Lake (average values n=113)

Period	before 1996	after 1997	before 1996	after 1997	before 1996	after 1997
	Dębno spring		Falsztyn spring		16 springs	
Carbon						
CO_2	24.55%	26.44%	19.24%	13.35%	13.57%	9.38%
HCO_3^-	74.63%	72.75%	79.14%	84.81%	84.65%	88.38%
$CaHCO_3^+$	0.46%	0.38%	1.28%	1.31%	1.16%	1.19%
$MgHCO_3^+$	0.21%	0.24%	0.13%	0.18%	0.21%	0.23%
$NaHCO_3$	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
CO_3^{2-}	0.08%	0.10%	0.08%	0.14%	0.16%	0.32%
$CaCO_3$	0.06%	0.06%	0.12%	0.18%	0.22%	0.44%
$MgCO_3$	0.01%	0.02%	0.01%	0.02%	0.02%	0.04%
Calcium						
Ca^{2+}	95.88%	95.91%	95.04%	94.57%	94.52%	95.24%
$CaSO_4$	3.19%	3.23%	2.40%	2.59%	2.86%	1.23%
$CaHCO_3^+$	0.82%	0.73%	2.32%	2.46%	2.20%	2.56%
$CaCO_3$	0.11%	0.14%	0.24%	0.37%	0.42%	0.97%
Chlorine						
Cl^-	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Potassium						
K^+	99.86%	99.85%	99.87%	99.87%	99.85%	99.94%
KSO_4^-	0.14%	0.15%	0.13%	0.13%	0.15%	0.06%
Magnesium						
Mg^{2+}	95.84%	95.91%	94.58%	94.19%	94.28%	95.17%
$MgSO_4$	3.03%	3.09%	2.31%	2.49%	2.84%	1.21%
$MgHCO_3^+$	1.06%	0.93%	2.98%	3.12%	2.64%	3.07%
$MgCO_3$	0.06%	0.07%	0.14%	0.21%	0.23%	0.55%
$MgOH^+$	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%
Sodium						
Na^+	99.80%	99.81%	99.68%	99.66%	99.69%	99.73%
$NaSO_4^-$	0.12%	0.13%	0.11%	0.12%	0.12%	0.05%
$NaHCO_3$	0.07%	0.06%	0.21%	0.22%	0.18%	0.21%
$NaCO_3^-$	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%
Sulphur						
SO_4^{2-}	90.04%	90.66%	82.62%	83.02%	84.33%	84.57%
$CaSO_4$	7.39%	6.42%	16.18%	15.31%	13.57%	13.20%
$MgSO_4$	2.49%	2.82%	1.17%	1.53%	2.02%	2.16%
$NaSO_4^-$	0.05%	0.07%	0.07%	0.09%	0.05%	0.06%
$AlSO_4^+$	0.00%	0.01%	0.00%	0.00%	0.01%	0.00%
KSO_4^-	0.01%	0.02%	0.04%	0.05%	0.01%	0.02%

contribution of particular speciations were observed when analyzing the component forms in the subdivision into two populations before and after Lake Czorsztyn filling.

An assessment of SI values in the analyzed water in relation to the mineral phases comprising the aquifer shows that water drained by the Dębno spring is undersaturated with regard to calcite and dolomite. Water drained by the Falsztyn spring is undersaturated with regard to dolomite, whereas with regard to calcite it is in thermodynamic equilibrium. Such variability of SI values is related to the lithology of rocks building the aquifer drained by both springs. The Falsztyn spring is recharged with groundwater occurring in Lower and Middle Jurassic limestones of the PKB klippe series, whereas the Dębno spring drains the sand-gravel fluvial deposits of the accumulation-erosional terraces of the Dunajec and the Białka rivers. During the filling of Lake Czorsztyn and in the first year of its functioning, periodical breaks in the hydrochemical relationships between the water and the rock environment have been observed; they were recorded in the increase of SI values, even to the oversaturation state of the analyzed waters with regard to carbonates (Table 3).

We consider these changes as being caused by variations in groundwater circulation conditions, which, in turn, were caused by the initial decrease of the groundwater drainage base level during reservoir construction, followed by its rapid increase during reservoir filling. Changes in SI values were observed also in the Falsztyn spring, located much above the reservoir damming level, which testifies for the change of hydrochemical conditions on a much larger area than the observed changes in groundwater level or spring discharge.

Summary and conclusions

The presented studies covering three intervals: prior to Lake Czorsztyn construction, during its filling and during its 25-year exploitation have allowed us to draw the following conclusions:

- Discharges of springs located within the direct catchment area of Lake Czorsztyn largely depend on precipitation recharge and not on the water level in the reservoir. The only exception refers to intervals when the water level in the reservoir decreases to a minimum state. This resulted in an increase of hydraulic gradients which forced increased groundwater drainage by the Dunajec valley.
- The domination role of precipitation rather than the reservoir water levels in shaping spring discharges results from the surrounding morphology and hypsometric positions of springs above the maximal damming levels in the reservoir.
- The reservoir's influence on the groundwater levels is restricted only to the closest vicinity of the reservoir in the Orawa-Nowy Targ Basin. In the remaining area it is almost insignificant.
- Assessment of the concentrations of the main components of the analyzed waters during the three study intervals

Table 3. Changes of saturation indexes with regard to carbonates during the construction and exploitation intervals of the Czorsztyn Lake

Dębno spring

Data		23-12-69	29-06-70	17-10-70	25-10-71	10-12-88	23-06-91	23-11-91	17-07-92	24-02-92	18-06-93	05-11-93	25-06-94	30-06-94	15-07-94	19-04-95	14-07-95	06-11-95	29-06-96	05-07-96	18-07-96	16-11-96	08-11-97	16-07-98	12-11-98	15-05-99	12-11-99	20-06-01	24-01-02	26-09-20	equilibrium state
Calcite	equilibrium									0.35								-0.13					0.02		-0.29						± 0,42
	under-saturated	-1.06	-0.53	-1.18	-1.15	-1.35	-1.18	-1.75	-0.52		-2.05	-0.75	-2.34	-1.62	-1.76	-1.71	-1.01		-1.22	-1.73	-1.43	-0.71		-1.39		-1.30	-1.93	-1.36	-1.87	-2.28	
Dolomite	equilibrium									0.01													-0.33		-0.70						± 0,84
	under-saturated	-2.32	-2.32	-2.76	-2.71	-3.56	-3.01	-4.49	-1.79		-4.39	-2.14	-5.21	-3.25	-3.98	-4.07	-2.61	-1.41	-2.77	-4.34	-3.43	-1.85		-3.34		-3.06	-4.55	-3.26	-4.32	-5.18	

← construction → ← filling → ← eksploatation →

Falsztyn spring

Data		10-12-88	17-07-92	18-06-93	05-11-93	25-06-94	30-06-94	15-07-94	19-04-95	13-07-95	07-11-95	29-06-96	08-07-96	16-11-96	08-11-97	16-07-98	01-08-98	12-11-98	15-05-99	19-06-99	12-11-99	20-07-00	18-09-00	20-06-01	23-01-02	26-09-20	equilibrium state
Calcite	oversaturated										0.59				0.76			0.56									± 0,42
	equilibrium	-0.17	-0.37		0.29		-0.22	-0.27		-0.06		0.26	0.28	0.22		-0.17	0.39		-0.28	0.03	-0.08	-0.12	0.11	-0.15	-0.31	0.03	
	undersaturated			-0.62		-0.73			-0.64																		
Dolomite	oversaturated														1.13												± 0,84
	equilibrium				-0.46						-0.04	-0.64	-0.69	-0.77			-0.15	0.13									
	undersaturated	-1.70	-2.09	-2.94		-2.84	-1.60	-1.54	-2.72	-1.43						-1.93			-1.54	-1.92	-1.59	-1.86	-1.50	-1.77	-1.37	-1.48	

← construction → ← filling → ← eksploatation →

and during the control analyses performed in 2020 did not show essential changes in their proportions. Two hydrochemical groundwater types dominate: HCO_3–Ca and HCO_3–Ca–Mg. A slight trend of decreasing contribution of waters with the sulphate ion has been observed, which points to a general trend of improved water quality.

- Local slight increase of chloride content should be linked to zones of road impact maintained during the winter with usage of chemical agents largely based on chlorides.
- During reservoir filling and in the first year of its exploitation, periodical changes of hydrochemical conditions have been observed, recorded in the increased values of groundwater saturation indexes, even to oversaturation with regard to carbonates. These changes have also been observed in the spring located much above the reservoir water level. We assume that these phenomena may be caused by changes in the groundwater circulation, resulting from lowering of the base level during reservoir construction, followed by its rapid increase during the filling phase.

The performed assessment of the reservoir impact on the natural environment refers only to hydrogeological issues and does not cover other elements of inanimate nature. Assessment of the entire dataset shows that Lake Czorsztyn construction did not cause degradation of groundwater volume and chemistry. Additionally, changes in land use and significant improvement of water-sewage management in the area, imposed by reservoir construction, obviously influenced the improvement of groundwater chemistry. Initial doubts related to the negative influence of the reservoir on the environment have not been confirmed.

We are aware that the obtained results are characteristic and dependent on environmental conditions in a given area, but we assume that they may have a universal character and be translocated in other areas and similar objects with comparable natural conditions. The presented studies are also crucial in the discussion on the assessment of the functioning of large retention reservoirs.

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Ocena oddziaływań Zbiornika Czorsztyńskiego na wody podziemne w ćwierćwiecze jego funkcjonowania

Streszczenie: Powstanie sztucznego zbiornika wodnego oddziałuje na wszystkie elementy środowiska. Na przykładzie Zbiornika Czorsztyńskiego oceniono jego oddziaływanie na wody podziemne oraz zmiany wymuszone przez jego budowę w zagospodarowaniu terenu. W ocenie wykorzystano długoletnie obserwacje chemizmu i stanów zwierciadła wód podziemnych oraz wydajności źródeł, obejmujące okres sprzed budowy zbiornika, z czasu jego napełniania oraz 25-letniej eksploatacji. Zmiany zagospodarowania przestrzennego wywołane budową zbiornika określono metodami teledetekcyjnymi. Konsekwencją budowy zbiornika była zmiana użytkowania powierzchni terenu. Wzrosła powierzchnia obszarów zabudowanych i leśnych kosztem terenów rolniczych. Dominującą rolę odgrywają dwa typy wód podziemnych HCO_3–Ca oraz HCO_3–Ca–Mg, dotyczy to zarówno okresu przed jego napełnieniem (68%), jak i po jego napełnieniu (95%), a także w odniesieniu do analiz kontrolnych z 2020 roku (100%). Udokumentowano stopniowy zanik występowania typów wód z udziałem jonu siarczanowego powyżej 20% miliwali, co wskazuje na tendencję poprawy jakości badanych wód. Ponadto zmiany wartości wskaźników nasycenia wód, względem faz mineralnych budujących warstwę wodonośną, w czasie budowy zbiornika i na wczesnym etapie jego eksploatacji, wskazują na ich modyfikacje hydrochemiczne. Zaobserwowano obniżenie zwierciadła wód gruntowych spowodowane przekształceniem doliny Dunajca w czasie budowy zbiornika i związanego z tym obniżenia regionalnej bazy drenażowej. Po napełnieniu zbiornika nastąpił wzrost rzędnej zwierciadła wody. Oprócz oddziaływania zbiornika można to tłumaczyć również większym zasilaniem opadowym. Powstanie Zbiornika Czorsztyńskiego spowodowało stopniowe przekształcenia w użytkowaniu terenu z rolniczego w kierunku turystyczno-rekreacyjnym. Zmiany te oraz zalanie doliny rzecznej wodami powierzchniowymi nie spowodowało zasadniczych zmian ilościowych i jakościowych wód podziemnych. Natomiast związane z budową zbiornika uporządkowanie gospodarki wodno-ściekowej przyczyniło się do zauważalnej tendencji poprawy ich jakości.