Geological Quarterly, 2023, 67: 33
DOI: http://dx.doi.org/10.7306/gq.1703

The importance of transboundary aquifer management between Poland and Ukraine for the protection of common water

Tatiana SOLOVEY[1, *], Rafał JANICA[1], Vasyl HARASYMCHUK[2], Małgorzata PRZYCHODZKA[1], Halyna MEDVID[2] and Liubov YANUSH[3]

[1] Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-975 Warszawa, Poland; ORCID: 0000-0001-8949-4075 [T.S.]; 0009-0001-7142-5570 [R.J.] 0009-0003-2797-5238 [M.P.]

[2] Institute of Geology and Geochemistry of Combustible Minerals of National Academy of Sciences of Ukraine, Naukova 3A, 79-060 Lviv, Ukraine; ORCID: 000-0002-4377-2655 [V.H.]; 0000-0002-5059-245X [H.M.]

[3] State Enterprise "Zahidukrgeologiya", Mitskievich 8, 79-000 Lviv, Ukraine; ORCID: 0000-0002-4225-8646

Solovey, T., Janica, R., Harasymchuk, V., Przychodzka, M., Medvid, H., Yanush, L., 2023. The importance of transboundary aquifer management between Poland and Ukraine for the protection of common water. Geological Quarterly, 2023, 67: 33, doi: 10.7306/gq.1703

Associate Editor: Beata Jaworska-Szulc

Transboundary hydrogeological units between Poland and Ukraine within the Bug and San River basins are identified, based on harmonized geological and hydrogeological data used for development of a numerical simulation of groundwater flows across the state border. This numerical model shows that the cross-border exchange of groundwater in aquifers takes place in a limited area and the flow pattern can be disturbed by the groundwater exploitation. Abstraction at current levels slightly increases the transboundary groundwater flow from Poland to Ukraine and minimally reduces the flow in the opposite direction, though not reversing the direction of water flow at the border. The simulated drawdowns do not have a transboundary range, but negative effects on surface water resources are noticeable. Estimates show that groundwater runoff to rivers decreased and infiltration losses through the riverbed increased. The quantitative status of the transboundary aquifers has not deteriorated significantly under the current exploitation but in the light of ambitious maximum allowable values for water abstraction, and in the absence of joint resource management, this problem will arise in the near future. Joint management should focus on a broader legal consensus, improvement of institutional relations, and integration of monitoring and groundwater status assessment systems.

Key words: cross-border groundwater flow, transboundary aquifer, numerical modelling, sustainable exploitation, water management.

INTRODUCTION

The transboundary aquifers (TBAs) of the Polish-Ukrainian borderland are considered important in shaping the strategic groundwater resources of both countries (Solovey et al., 2021a). In addition, a transboundary groundwater reservoir within the Bug River catchment area was included in the world TBAs list published by UNESCO (IGRAC, 2021). Transboundary groundwater resources between Poland and Ukraine are largely uncharacterized due to the lack of data to date, differences in approaches to identifying TBAs and in stratigraphic classification methodologies, and limited institutional cooperation in managing TBAs between countries. Large errors become apparent when hydrogeological maps, hydrodynamic models, and resource calculations for the areas of TBA occurrence were performed without conducting joint international research (Dobkowska and Kapuściński, 2000).

Sustainable use of water resources is a global problem (Rejman, 2006; Sophocleous, 2010; Setegn and Donoso, 2012; Chaminé and Gómez-Gesteira, 2019) for which most of the management tools are available primarily for surface water resources (Fonseca et al., 2014; Wu et al., 2015; Du et al., 2022). Contemporary documents on water management plans clearly state that groundwater-dependent ecosystems (GDE) are an equal user of groundwater, for which groundwater should be protected against deterioration (KPRWP, 2020). Identification of conflicts in groundwater use is a new challenge in groundwater management (Wachniew et al., 2014). In addition, GDE study as such can only be effective as part of multidisciplinary work combining hydrogeology and ecology, together with geomorphological and biological approaches.

* Corresponding author, e-mail: tatiana.solovey@pgi.gov.pl

Received: April 24, 2023; accepted: June 29, 2023; first published online: November 6, 2023

When discussing transboundary groundwater, it is worth distinguishing several initiatives where TBA assessment was carried out in a comprehensive manner, combining interpretation of monitoring series and spatio-temporal numerical simulation (Voss and Soliman, 2014; Tóth et al., 2016; Pétré et al., 2019; Vaquero et al., 2021). Of particular importance is the use of numerical models that are not required by the Water Framework Directive (WFD) (EU, 2000 Directive 2000/60/EC), but should nevertheless be taken into account when identifying groundwater bodies (GWBs) and developing water management plans.

The management of transboundary groundwater resources should be carried out at international level, as promoted by the Water Convention (UNECE, 1992). Since the 1990s, in line with the Water Convention, work has been underway on the assessment and inventory of TBAs. As awareness of water safety and sustainability increases, countries are beginning to recognize the importance of the TBAs. The framework for this article comprises the TBAs of the Polish-Ukrainian borderland that meet the quantitative and qualitative criteria qualifying them for municipal use. An Upper Cretaceous aquifer plays a major role in this area. This aquifer is associated with an extensive geological structure: the Lublin Basin in Poland and Lviv Foredeep in Ukraine (Kowalski, 2007; Kamzist and Shevchenko, 2009), and is the main source of drinking water for the two large agglomerations of Lublin and Lviv. In addition, each country has identified a number of other, less resource-rich, aquifers that may cross the border. Limited international cooperation was largely related to the long-term affiliation of these countries to different geopolitical systems, and joint projects have emerged only in the last 10 years. The spatial and temporal scale of transboundary groundwater flows (Solovey et al., 2021b) have been identified, but no measures have yet been taken to prevent degradation of common groundwater resources in this area.

This work concerns research on the numerical hydrodynamic model of large-scale transboundary groundwater flow systems in the Polish-Ukrainian borderland. The objectives of the study were:

- development of a methodology for creating a common numerical model of TBAs.
- assessment of water balance and transboundary groundwater flows into TBAs in their natural state.
- determination of the impact of the current level of groundwater exploitation on the quantitative status of TBAs.
- provision of a scientific support in the development of practices for the joint management and protection of TBAs identified

INTERNATIONAL LEGAL FRAMEWORKS FOR TBA MANAGEMENT

UNECE WATER CONVENTION

The Water Convention, which establishes principles and norms for the protection and rational use of common freshwater resources by humanity, has been signed by Poland and Ukraine and is considered the international legal framework of cooperation. It is based on the provisions of the Convention and on fulfilling the requirements resulting from the Sustainable Development Goals (SDGs Poland and Ukraine have completed two reporting cycles: 2016–2018 and 2019–2021 (UNECE, National country reports on SDG indicator 6.5.2).

WATER FRAMEWORK DIRECTIVE 2000/60/EC

The WFD is the main document in the field of EU water policy. The WFD requires the implementation of integrated management of water resources according to the basin principle and establishes the goal of water policy – to achieve a good state of all water resources by reducing and stopping the discharge of untreated sewage into water bodies. River Basin Management Plans are a tool for achieving this task. The object of directed actions of the directive is all surface, underground, transitional, coastal waters and GDEs. The WFD recognizes that GDEs are affected by changes in the chemical and quantitative status of groundwater and the identification of these effects is an essential part of characterizing groundwater bodies.

As an EU Member State, Poland implemented the WFD in 2001 (Water Law, July 18th, 2001). The current legal act is the Act of 20 July 2017 – the Water Law, containing amendments introduced in 2022 (ISAP, 2022). By implementing the WFD, Poland introduced a new water management structure, establishing the State Water Holding “Polish Waters” at the national level.

Ukraine started implementing the provisions of the WFD by making changes to the Water Code of Ukraine initiated by the Law of October 4, 2016 (Zakon, 2016). The central authority for water management at the national level in Ukraine is the State Water Resources Agency of Ukraine (State Water Agency). By the WFD requirements, Ukraine introduced a new regional level of water resources management by creating a Basin Water Resources Management in each of the twelve water regions. To achieve its environmental goals, the development of River Basin Management Plans (RBMPs) until the end of 2023 became a priority task.

DIRECTIVE 2006/118/EC ON THE PROTECTION OF GROUNDWATER AGAINST POLLUTION AND DEPLETION

Directive 2006/118/EC of December 12, 2006, establishes the threshold values and standards that are intended for use when assessing the chemical status of groundwater. In addition to assessing the effects of pollutants, the WFD also requires consideration of the effects of water intakes on GWBs, interconnected surface water bodies, and ecosystems, as well as a quantitative status assessment. Directive 2006/118/EC contains also practical guidance on methods of determining threshold values, the framework for evaluating the chemical and quantitative state and method of determining ecologically significant trends.

POLISH-UKRAINIAN COOPERATION AND A FRAMEWORK FOR SHARED AQUIFER MANAGEMENT

Bilateral cooperation between Poland and Ukraine has been sanctioned by two bilateral agreements signed on January 24th, 1994 (Agreement…, 1994) and October 10th, 1996 (Agreement…, 1996). Based on the provisions of the Agreement (Agreement…, 1994) parties have established a Joint Commission for cooperation in the field of environmental protection. In 1996 (Agreement… ,1996) the Polish-Ukrainian Commission for Border Waters was established (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko—-ukrainska). A strategic goal of the cooperation was for the parties to ensure rational management of border waters and improvement of their quality, as well as ensuring the preservation of ecosystems. Based on the division of the cooperation area into four thematic areas, four working groups have been established. The working groups operate on a daily basis and experts involved are in direct contact. External experts in particular fields are invited to the group's work for a limited time as needed.

Another basis for cooperation between both countries is the Water Convention that has been ratified by Poland on March 15th, 2000 and accessed by Ukraine on October 8th, 1999. As the Polish-Ukrainian cooperation on the state level is implemented on the basis of the bilateral Agreement (1994, 1996), cooperation on the level of individual R&D entities is usually based on personal contacts and often results in establishing multiannual cooperation. However, this type of cooperation often remains fruitful only for the parties involved and as regards associated results.

MATERIAL AND METHODS

STUDY AREA

The research area, covering approximately 7,150 km^2, is located in southeastern Poland and northwestern Ukraine, at a junction of two megaregions – the East European Plain and the Carpathian Region (Fig. 1). Most of the area (91%) is <300 m a.s.l.; highlands (4%) – the Roztocze and Podillia Upland – reach a maximum of 400 m a.s.l.; and mountains (5%) of the Outer Carpathians have peaks reaching 610 m a.s.l. The humid temperate climate has evolved at the junction of two climatic regions: dry continental and humid mountainous. The average air temperature ranges from –3.5 to 5°C in January and from 16 to 18°C in July (Lorenc, 2005). Average annual rainfall varies from 500 mm in the north-east to over 1,200 mm in the south-west (Outer Carpathians), influenced by orographic effects. The

Fig. 1. Location of the study area (after Solovey et al., 2023)

whole area belongs to the Vistula catchment and consists of two sub-basins, the Bug and San.

The geological structure of the area is diverse, but there are generally three major geological structures: the East European Platform (in the north), the Carpathian Foredeep (in the centre) and the Outer Carpathians (in the south) (Żelaźniewicz et al., 2011). The Upper Cretaceous formations at the surface are usually exposed on the hills and are composed of carbonate rocks (chalk and marl) and Upper Maastrichtian carbonate-siliceous-clay deposits. The thickness of the Upper Cretaceous carbonate succession here reaches 700 m (Bielecka, 1967). In the Carpathian Foredeep the main unit is the Miocene molasse. The Outer Carpathians are characterized by the presence of flysch at the surface.

Quaternary deposits cover most of the study area and are characterized by significant diversity with thickness increasing towards the north (Fig. 2). In the drainage depressions, there are organic deposits, while in watershed areas there glacial deposits as well as limnic and limnoglacial glacial muds; river valleys are characterized by sand, gravel, and flood silts. Aeolian deposits are present on the hills. The thickness of the Quaternary cover is usually 2–10 m, though in the valleys of larger rivers the limnic and fluvioglacial deposits reach 30 m.

A characteristic feature of the northern part of the research area, which belongs to the Bug sub-basin, is the dominance of Mesozoic fissure-controlled aquifers. The Upper Cretaceous (K_2) aquifer is of key importance in shaping strategic drinking water resources, and in Poland is classified as the main groundwater reservoir with a regional range and large resources (Paczyński and Sadurski, 2007). The hydrogeological conditions in this area are reflected in the hydrogeological profile BB” (Fig. 3). Aquifer K_2 is continuous, often exposed at the surface, and largely covered by Quaternary deposits in the north. The drainage system is deep, the main drainage base is the Bug River and its tributaries. The depth of the intensive water exchange zone is 100–150 metres (Janiec, 1984). The water table is usually unconfined and its level depends on the topography. In river valleys the depth to the groundwater table is 0–10 m, at elevations 30–70 m. The transmissivity of the K_2 aquifer varies greatly, the highest values being related to tectonic zones (Krajewski, 1984).

The southern part of the research area, starting from Roztocze and covering the entire San sub-basin, is within the range of another aquifer unit – the Neogene Formation, which usually forms a common aquifer with the Cretaceous strata. The most important in terms of exploitation is the Lower Neo-

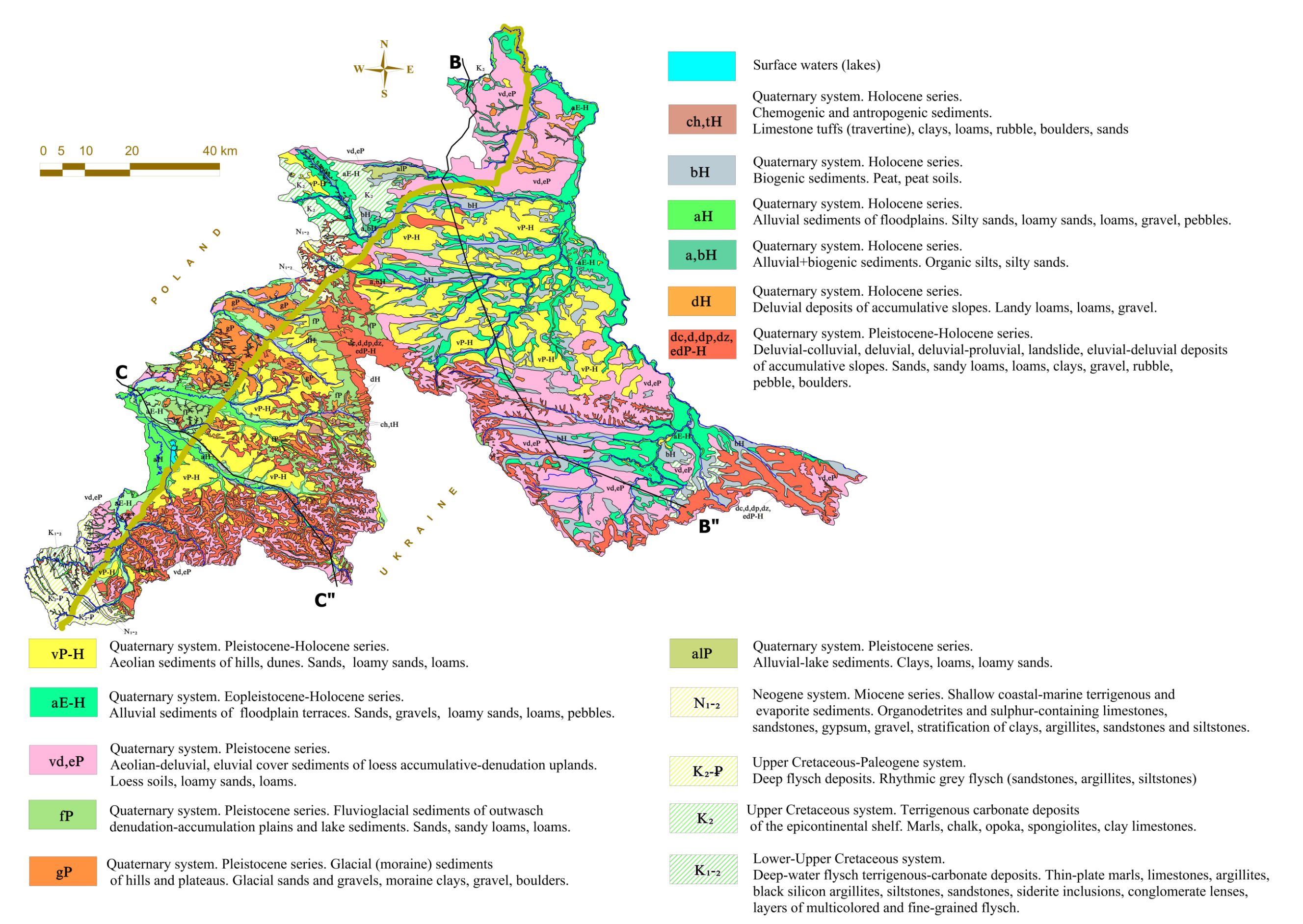

Fig. 2. Geological map of the study area and lines of hydrogeological cross-section shown in Figure 3 (line BB”) and Figure 4 (line CC”) (after Solovey et al., 2023)

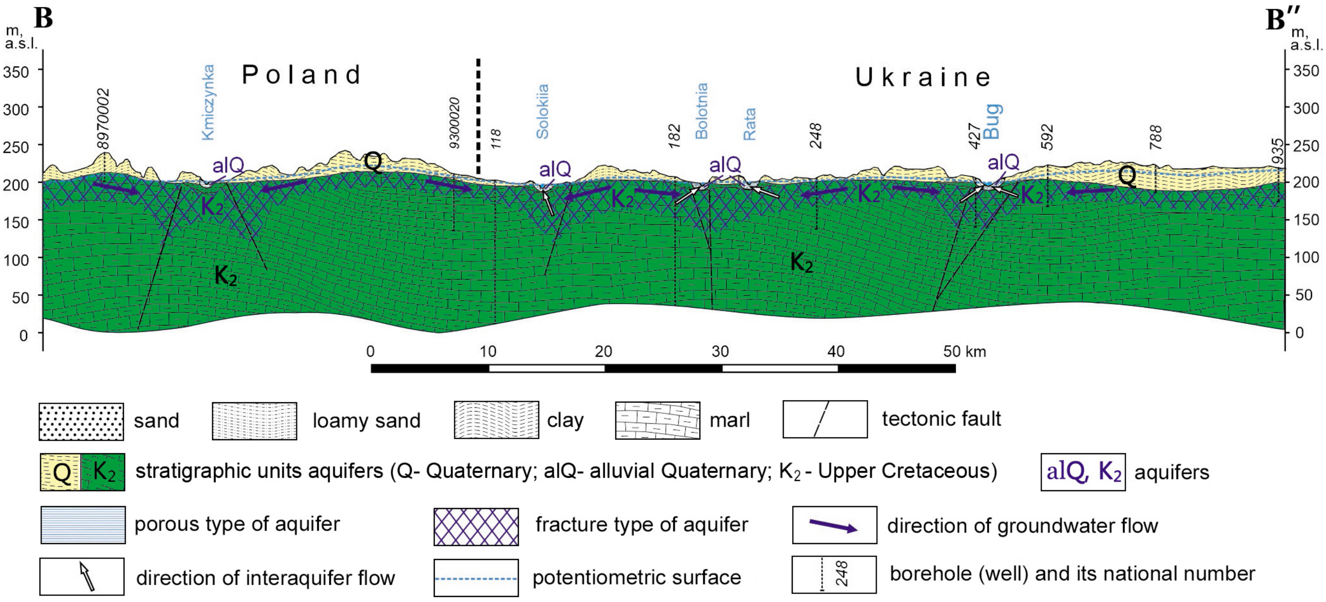

Fig. 3. Hydrogeological cross-section characteristic of the cross-border part of the Bug sub-basin (after Solovey et al., 2023)

gene aquifer, of Miocene age. It is represented by the Badenian (N1b1–N1b2) sandy deposits, sandstones, gypsum and red-algal limestones. The typical structure of an aquifer in this area is shown in Figure 4.

In Ukraine this aquifer is also associated with the presence of sulphate-bearing medicinal waters (Kamzist and Shevchenko, 2009). Roztocze is the recharge area of the Miocene aquifer, and the San River is the drainage base.

The Quaternary aquifer of operational importance in the research area occurs only locally, mainly in river valleys and in old buried structures. It comprises alluvial sandy deposits in the valleys of the Bug, San, Rata, Lubaczówka, Wisznia and Szkło valleys. The water table is unconfined and occurs at a depth of 0.4 to 10 m below ground level.

DATASETS AND METHODS

To develop a model of the transboundary groundwater flow, input data was obtained from Polish Geological Institute – National Research Institute archives. For the Ukrainian side, the geological data was obtained from the state-owned enterprise "Zahidukrgeologiya". This model is an integral part of the much wider task to establish joint management of transboundary aquifers under the EU-Waterres project (http:/eu-waterres.eu). The stage of data harmonization and integration was extremely important. To characterize the geometry of the sedimentary formations, geological information was obtained from datasets from 2,926 wells. A unified geological correlation process was developed and transboundary cross-sections were created to identify those aquifers that actually cross the boundary and have a water-bearing potential of operational importance. For the purpose of this study, a transmissivity of at least 50 m^2/d was adopted as criterion.

A common database was created, consisting of 17 groups of parameters, ranging from geological and hydrogeological characteristics to groundwater exploitation parameters, monitoring parameters and anthropopressure. Public access to this database has been made available – http://www.eu-waterres.eu/web-app/.

The terrain surface was mapped based on freely available satellite data from the SRTM30 DEM (https://earthexplorer.usgs.gov/) of 30 arc-seconds (resolution of ~1km). The ground-based average annual precipitation (P) and temperature (T) time series for 10 meteorological stations were compiled from meteorological annals of the historical data record (1971–2000). The spatially distributed recharge, independently estimated at the daily rate and based on meteorological data records from 10 stations, was the input set of the upper active cells top level.

To prepare a groundwater level map for the 2008–2021 period, water level measurements in wells, piezometers and open wells were taken from public databases (Groundwater Monitoring Database, 2022). The final selection included a dataset of 57 water monitoring points.

In order to determine the volume of groundwater exploitation for the period 2018–2021, measurements of water pumping in intakes were taken from publicly available databases. The final selection was a dataset with 200 water abstraction points.

MODEL DESIGN, BOUNDARY CONDITIONS AND CALIBRATION

The modelling software package *Groundwater Vistas ver. 6* (GV) was used for numerical modelling (Harbaugh, 2005). GV enables numerical calculations using the finite difference method to describe groundwater flow.

The principles of model development applied resulted from assumptions relating to regional models in a quasi-steady state. The groundwater flow modelling area covers 7,023.5 km^2, of which 2,065.25 km^2 is located in Poland and 4,958.25 km^2 in Ukraine. The boundaries of the model were drawn along surface watercourses and morphological watersheds. The size of the model area is 132 x 140 km horizontally and 150 m vertically, with a regular cell size of 500 x 500 m. The discretization

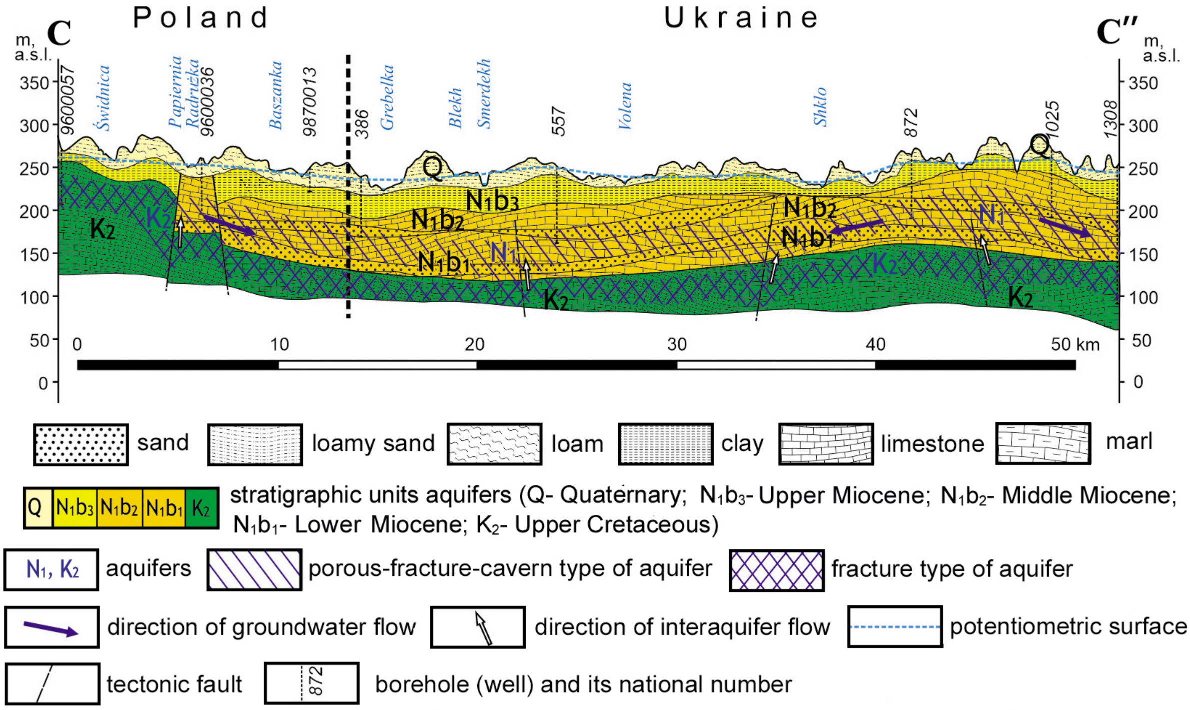

Fig. 4. Hydrogeological cross-section characteristic of the cross-border part of the San sub-basin (after Solovey et al., 2023)

of the research area surface along the vertical axis consisted of dividing the space into two layers of variable thickness. However, the second layer of the model occurs only in the area of the Lublin Basin and reaches a depth of 120 m. In the area of the Outer Carpathians and the Carpathian Foredeep, the water permeability of the centre within the deeper part of the active exchange zone (below 30–35 m) is negligible. Therefore, blocks in the second layer of the model in the Carpathian Mountains and the Carpathian Basin were excluded from the calculations. The outer boundary surface of the separated aquifers is open. The modelling area was limited by natural conditions of type III, where the General Head condition was used on sections of the border related to watershed zones, and the River condition was used on sections along the riverbeds. This solution made it possible to include the lateral underground inflow from the outside of the model in the calculations. The River condition was applied both to surface watercourses on the outer boundary surface and to watercourses inside the area modelled. It was used to map the impact of all the main watercourses forming the hydrographic network of the area with groundwater resources. In addition to conditions of the III type, conditions of the II type were also used. This condition was used to map the abstraction of groundwater (Well condition), recharge of the infiltration system (Recharge condition) and the relationship with the environment along selected sections of the outer boundary surface (zero flow condition).

The water-bearing system defined this way was supplemented with the following assumptions:

– the first aquifer is in direct contact with the surface water;
– the aquifers within the model are recharged mainly by percolation, locally by infiltration of surface waters;
– the water-bearing layers of the model are separated by a low-permeability layer, mapped by the filtration coefficient

$$T = k/m$$

where: T – vertical leakance (hydraulic conductivity divided by distance between nodes), k – separation layer filtration coefficient, m – separation layer thickness);

– the bottom of the second layer is impermeable;
– the groundwater velocity field is constant over time;
– the vertical component of groundwater flow velocity in an aquifer is negligible in relation to the horizontal component;
– vertical water exchange is taken into account by defining the influence of recharge, water exchange between model layers and surface water infiltration.

The permeability coefficient values for individual layers were based on both the results of pumping tests during groundwater extraction, and on data from the literature (Marciniak et al., 1998). The spatial distribution of the filtration coefficient in all layers of the model was interpreted on the basis of auto-fitting values with the PEST module using the pilot points method, distributed by triangulation between the target points (Doherty and Hunt, 2010). The input values were the mean values of the filtration coefficient in individual lithostratigraphic units.

The recharge component of the model was assessed using the constant volume method. This is based on using the value of the ground runoff to calculate the amount of water infiltrating within the catchment area. The long-term average value for the Bug catchment area was set at 60 mm/year, and for the San catchment area at 120 mm/year, and such values were adopted as the basis for calculating the infiltration value in individual blocks (Michalczyk et al., 2002). The calculated amount of infiltrating water at the model's surface was distributed on the basis of geological conditions (effective infiltration coefficient) identified by means of geological maps of surface formations.

Calibration involved a manual trial and error method. The basic criterion for model calibration was the compliance of the hydrodynamic state of the groundwater stream recorded during the drilling of hydrogeological wells and monitoring tests with the simulated state. The location of the groundwater table at 883 research points was analysed. In the model calibration procedure, the conductance of the river beds and the value of the filtration coefficient were modified.

It is assumed that the standard deviation of the differences between field measurements and the values calculated on the model should not exceed 15% of the measurement range. In the case analysed, this value is 2.8% (Fig. 5).

As one can conclude from Figure 5, the measured groundwater table ordinate in the field was found to be in line with the model's calculation results (mean error: 3.19 m; mean absolute error: 5.84 m; standard error: 8.71 m). In spatial terms, worse calibration results were obtained in the mountainous part of the study area, as this area was characterized by the most uncertainty in the geological model due to the lack of geological data and the uncertainty over the reference water levels.

RESULTS

The area of the Polish-Ukrainian borderland defined along the borders of the transboundary Bug and San River sub-basins (Fig. 1) is 20,144 km^2. The model created served as the basis for specifying the area where there is a transboundary continuity of usable aquifers with a transmissivity of at least 50 m^2/d, which is the assumed condition for the occurrence of significant transboundary flows. It was established that the modelling area covers only 36% of the above-discussed area and this was taken into account when assessing the transboundary groundwater flows. The Bug-San transboundary groundwater aquifer reservoir (TGR) is an open system and is essentially characterized by two transboundary streams diverging from Roztocze and Podillia Upland in the north-east – to the Bug River and south-west – to the San River (Fig. 6). The first groundwater circulation system with the Bug River drainage base consists mainly of the fractured K_2 aquifer (most often unconfined) and the connected alQ aquifer in the valleys of larger rivers. The second system – associated with the drainage base of the San River, a fractured-cavernous N_1 aquifer – combines the hydrodynamically connected N_1b_1 and N_1b_2 water-bearing aquifers. The waters of the N_1 and K_2 aquifers are often in hydraulic contact. The aquifer is mainly confined (drilled at a depth of 11.0–46.0 m, the potentiometric surface was at a depth of 5.0–13.0 m below the surface).

As this study is the first of its kind to assess transboundary flows in the Bug-San TAS, the focus is on addressing the fundamental problem: does the current level of groundwater exploitation cause the transboundary interception of resources? The simulation results are shown in sequential order, from the pre-operational state model to the current operation model.

TRANSBOUNDARY FLOW DIRECTIONS

The simulated groundwater table elevation follows the surface water circulation system and imitates the isolines of the terrain. In the Bug sub-basin, the groundwater level descends from NW to SE from ~290 m a.s.l. in Roztocze in the recharge zone, descending towards the valley of the Bug river to 170–200 m a.s.l. discharge areas (Fig. 7). In the southern part of the model within the San sub-basin, due to the surrounding mountains, the hydraulic gradient is the highest, almost three times higher than the analogous one in the Bug alluvial plains. In this area, the elevation of the groundwater table decreases from S to N due to the inflow of the Wiar River to the San River from 500 to 180 m a.s.l. In the northern, lower-relief part of the San sub-basin, the groundwater level descends from E to W under the influence of the tributaries of the Szkło and Wisznia rivers to the San from 280 to 180 m a.s.l. and in the direction from NE to SW under the influence of the tributary of the Lubaczówka River to the San from 290 to 200 m a.s.l.

Exploitation of groundwater in currently operating intakes (1128 wells) mainly concerns the K_2 aquifer or the combined Qal-K_2 (70% wells), the remaining aquifers are the Qal, N_1, Qal-N_1. Ukraine accounts for 76.5% of the total registered consumption from the Bug-San TAS. The spatial differentiation of

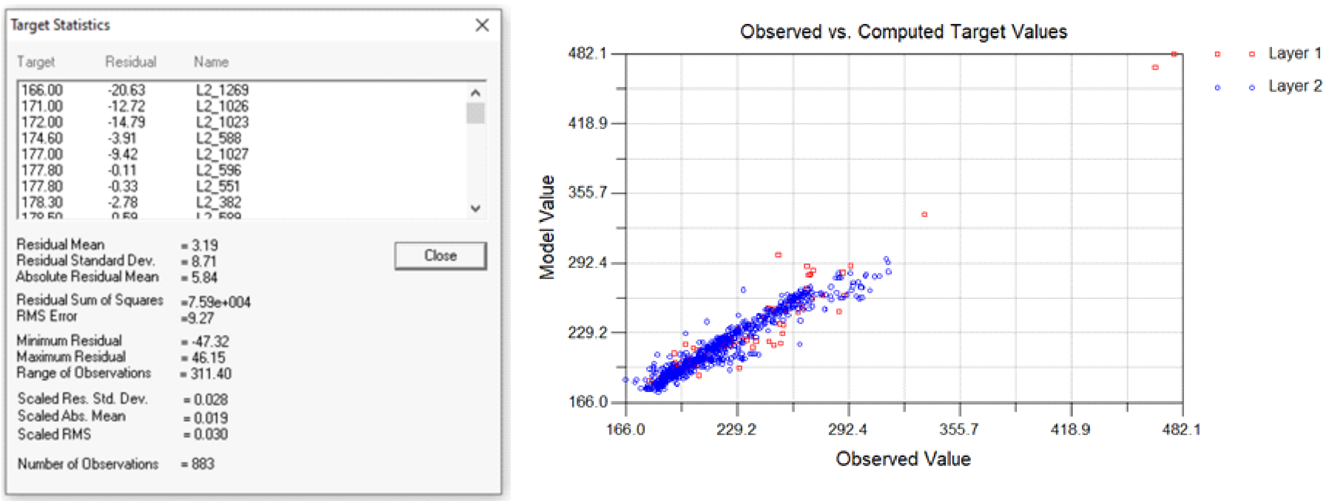

Fig. 5. Summary of the observed values of the ordinate of the groundwater table with the calculated values and a statistical summary of the model calibration process (after Solovey et al., 2023)

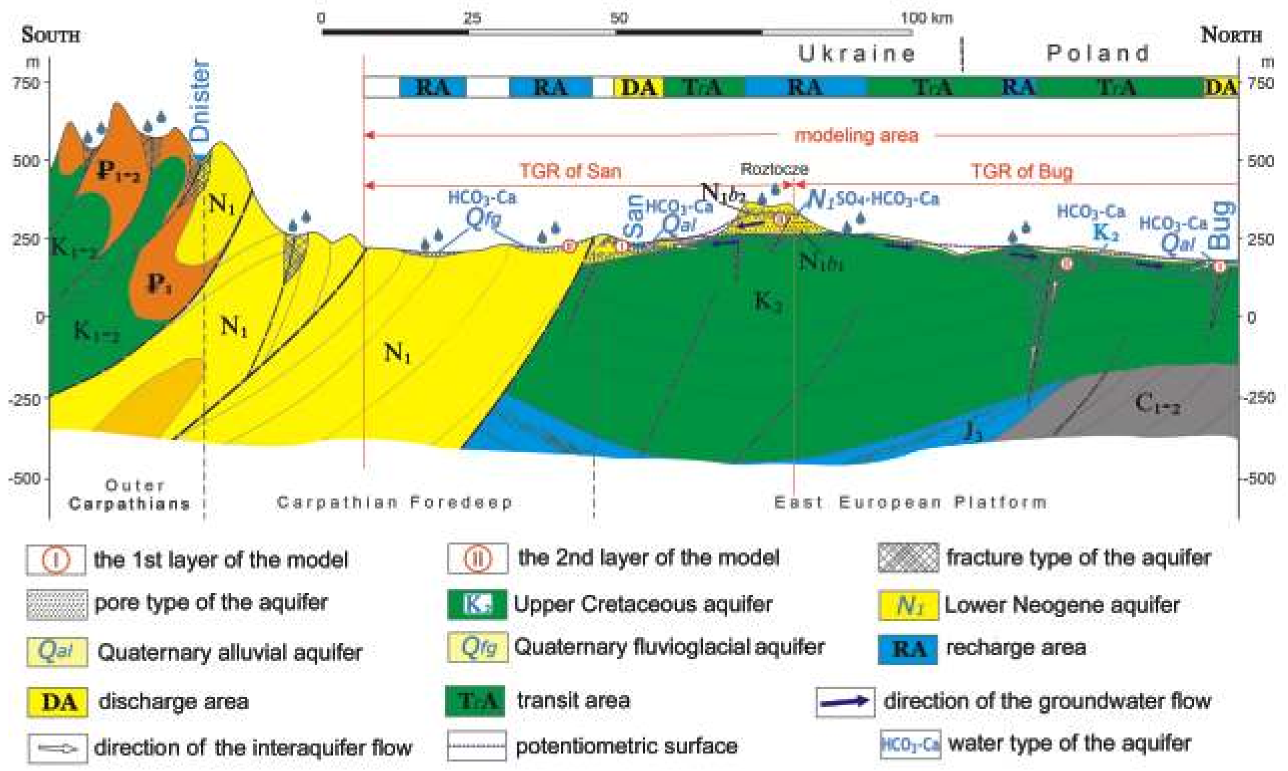

Fig. 6. Schematic diagram of groundwater flowpaths in the area modelled (after Solovey et al., 2023)

the exploitation volume at the average level from the last 4 years is shown in Figure 8.

A characteristic feature of the Polish part of the study area is the dispersion of the groundwater intake at unit volumes generally below 1,000 m^3/d. At this level of exploitation, no drawdown cones are observed on a scale noticeable in the regional model (Fig. 9). Only the group of intakes in the area of Tomaszów Lubelski with a total groundwater intake from the K_2 aquifer of a size of ~4 thousand m^3/d produces drawdown cones with a maximum lowering of the groundwater table of 3 m.

In the Ukrainian part, the exploitation of groundwater is concentrated in large municipal intakes at the level of 5,000–8,000 m^3/d (Fig. 8). This exploitation results in the formation of several drawdown cones with a size of 5–25 m in the K_2 aquifer (Fig. 9). It was established that the nature of the drawdown cone depends on the location of the intake in the hydrodynamic system. In the recharge zones, the intensity of the decrease was 6 to 8 times greater than in the drainage zone, with similar intake volumes at the level of 5,000–8,000 m^3/d.

The analysis of the change of the hydrodynamic field system as a result of exploitation showed that currently there are no cross-border drawdown cones noticeable on a regional scale. None of the simulated depressions go beyond the state border; moreover, they do not approach the state border within a radius of at least 7 km. Nevertheless, a cross-border impact cannot be ruled out due to the presence of intakes in the immediate vicinity of the border (~1 km) on both sides, the impact of which can be seen using local scale models. The transboundary K_2 aquifer in the Bug sub-basin is the most exploited and, consequently, vulnerable.

TRANSBOUNDARY FLOWS AND BUDGETS

The positive side of the water balance (rainwater and surface water infiltration) is balanced by three main negative components: evapotranspiration, river drainage and groundwater abstraction. The water balance was obtained from the numerical model in pre-exploitation conditions (Table 1) and for the current 2018–2021 years of operation (Table 2). Four sub-domains were used in the calculation:

- Bug sub-basin in PL (PL/Bug);
- Bug sub-basin in UA (UA/Bug);
- San sub-basin in PL (PL/San);
- San sub-basin in UA (UA/San).

The use of sub-domains makes it possible to compare the water balance between sub-basins and countries.

The coloured boxes show water flows that cross borders, while the non-shaded boxes comprise a budget within the country. In terms of the pre-exploitation balance, the Bug-San TAS groundwater resources are formed as a result of:

- rainwater infiltration (83.4% – Bug sub-basin; 87.4% – San sub-basin);
- surface water infiltration (9.4% – Bug; 9.1% – San);
- groundwater inflow from overlying subdomains (7.2% – Bug; 3.5% – San).

Outflow from the Bug-San TAS results mainly from:

- river drainage (93.1% – Bug; 94.9% – San);
- evapotranspiration (0.8% – Bug; 0.6% – San);
- groundwater outflow to overlying subdomains (6.1% – Bug; 4.5% – San).

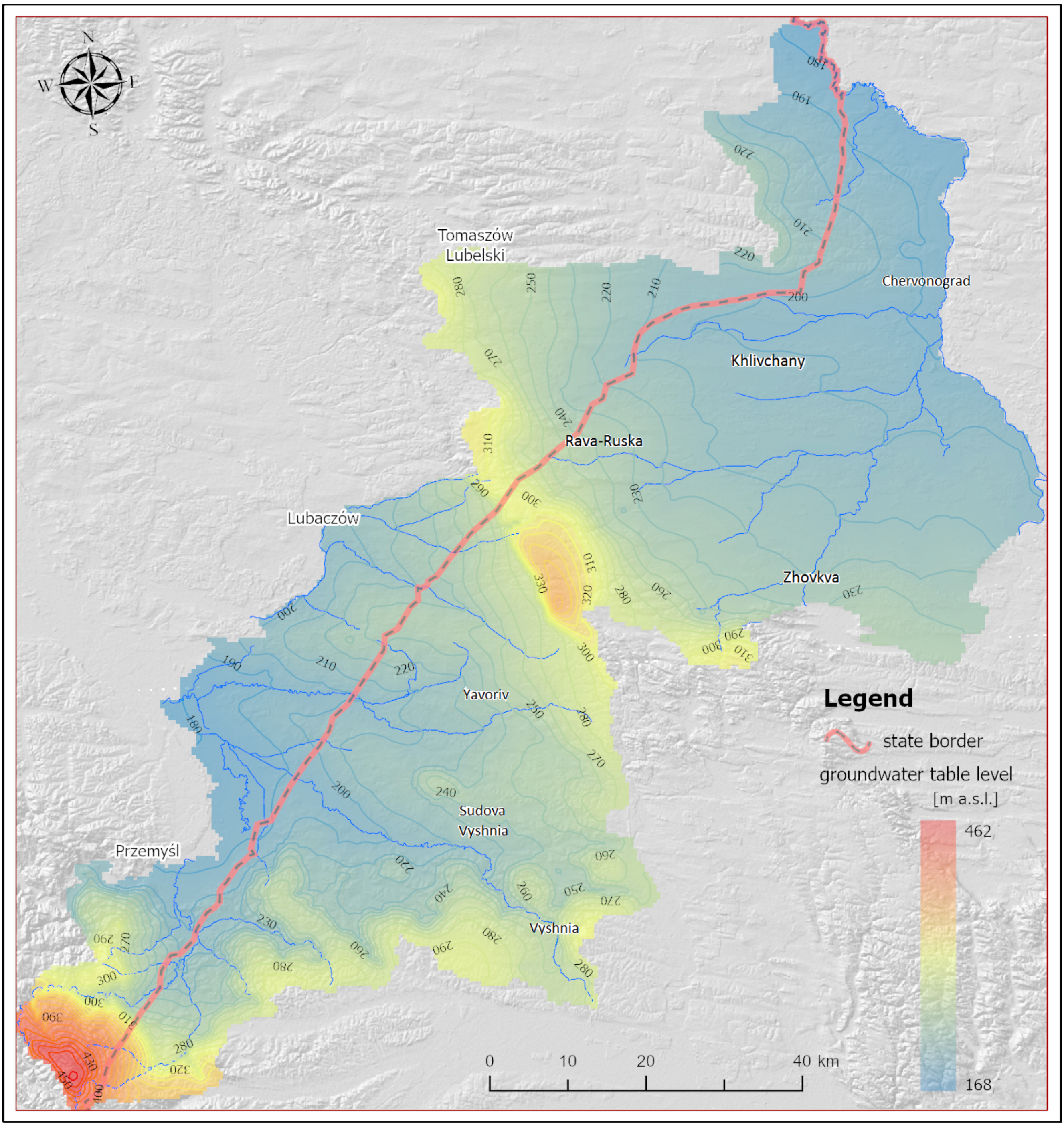

Fig. 7. Distribution of simulated groundwater heads (after Solovey et al., 2023)

The average daily intensity of groundwater exploitation is at the level of 46,032 m^3/d and accounts for 2.8% of the recharge of the Bug-San TAS, which can be considered a negligible share, but due to the unknown amount of unregistered consumption the actual situation is worse (Table 2). For the entire flow system in the water balance during operation, a reduction of 1–4% of groundwater runoff to rivers is observed (at 3,464 m^3/d in the San sub-basin and 31,863 m^3/d in the Bug sub-basin), which is mostly compensated by groundwater retrieved from the Bug-San TAS. Moreover, surface water infiltration does not increase much – at 1,957 m^3/d in the San sub-basin and 8,754 m^3/d in the Bug sub-basin. Combination of these two effects results in a loss of river water resources. The remaining components of the budget do not change significantly during operation.

According to the calculations, the transboundary data on the exploitation model is in particular (Fig. 10):

- total groundwater runoff from Poland to Ukraine – 42,350 m^3/d (78% – Bug sub-basin and 22% San sub-basin);

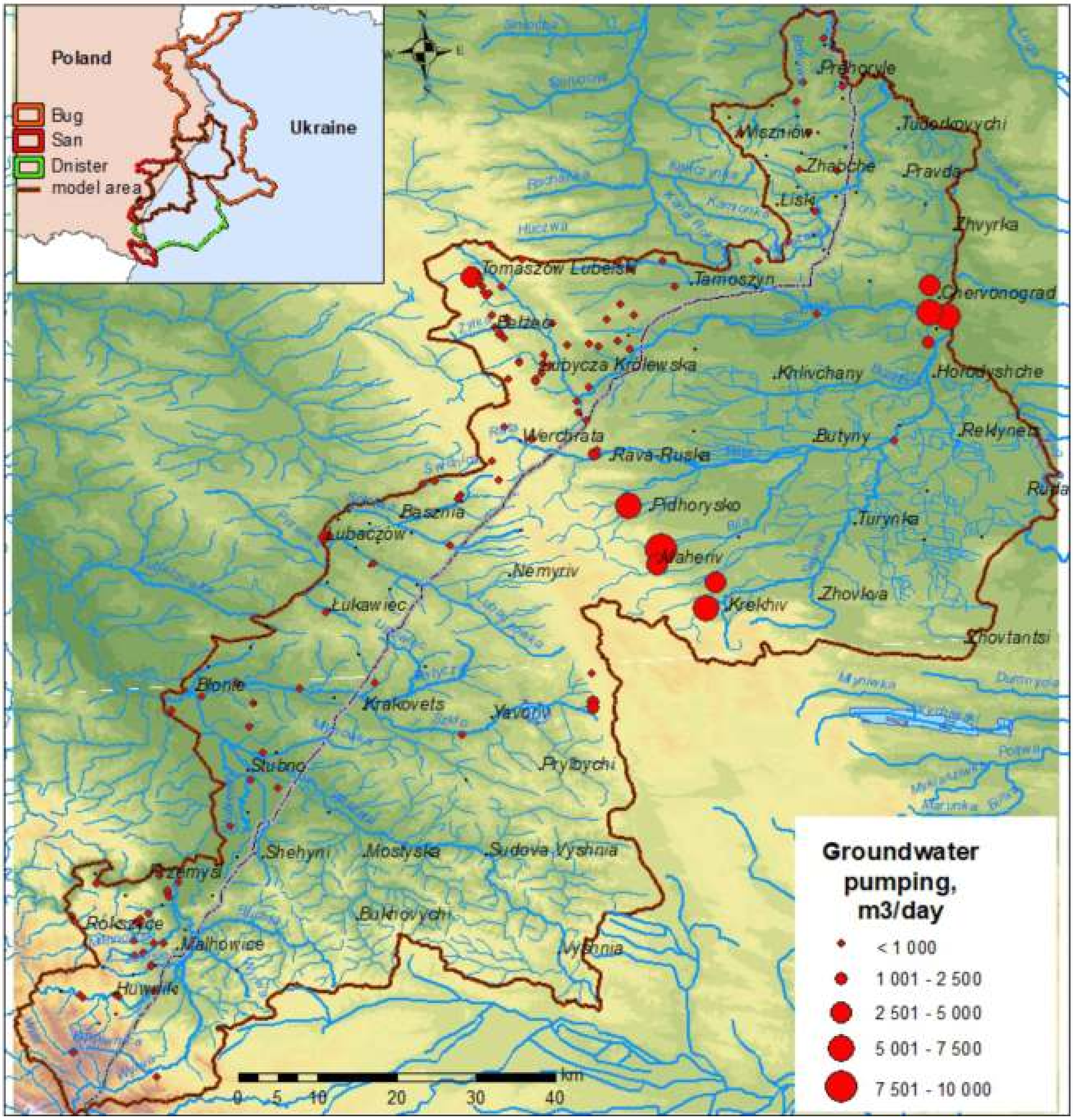

Fig. 8. Average daily groundwater pumping in the operating intakes, 2018–2021 (after Solovey et al., 2023)

– inflow to Poland from Ukraine – 28, 139 m^3/d (58% – Bug sub-basin and 42% San sub-basin).

Compared to the natural state, exploitation slightly increased the transboundary groundwater flow from Poland to Ukraine, but only in the Bug sub-basin by 138 m^3/d (+0.4%). On the other hand, the inflow from Ukraine to Poland decreased to 82 m^3/d (by –0.7%) and also concerns the Bug sub-basin. As a result, it can be concluded that the exploitation strengthened the effects of the transboundary groundwater flow to the detriment of Poland, but without reversing the direction of water flow at the border. In the Bug sub-basin, exploitation accelerated the outflow of groundwater from Poland to Ukraine and reduced the inflow to Poland.

DISCUSSION

DIFFERENCES IN APPROACHES TO IDENTIFYING, MONITORING AND ASSESSING THE STATE OF THE GWB

One of the main difficulties in building a common platform for the management of TBAs in the Polish-Ukrainian border area are the differences in approach to the identification of the GWB, monitoring methodologies and assessment of the condition of the GWB, and inconsistent hydrogeological databases between the two countries. In Poland, the GWB is distinguished on the basis of a hydrostructural criterion in relation to aquifers

Fig. 9. Simulated steady-state groundwater drawdown in the model layer 2 caused by water exploitation at the 2018–2021 level (after Solovey et al., 2023)

with a regional range and abundance enabling consumption significant for water supply to the population (Paczyński and Sadurski, 2007). GWB division does not differ vertically. The water-rich structure is of decisive importance in the case of a double or multi-story vertical aquifer structure. In total, 174 GWBs were distinguished, the boundaries of which were carried out along watersheds or major rivers. In Ukraine, a division into GWBs has been applied in two planes – horizontal and vertical, i.e. individual stratigraphic units with a separate division into GWBs. A different methodological approach to the identification of GWBs between Poland and Ukraine limits the possibility of data integration on a common basis and increases the difficulties in achieving joint management of groundwater resources planning. Moreover, they prevent the use of GWB units as partitions useful for the spatial organization of joint management of groundwater, which is the main concept of a GWB according to the WFD.

The scope, frequency and methodology of analytical research and field monitoring of groundwater are also an issue that requires harmonization between Poland and Ukraine. In Poland, monitoring is broken down into quantitative (groundwater table level and spring discharge measurements) and chemical (diagnostic and operational) monitoring. Measurements of the water table are carried out daily at the 1st order hydrogeological stations or once a week at the 2nd order hydrogeological stations. The obligatory parameters of chemical status monitoring are 55 indicators, of which 5 are generally physico-chemical, 37 are inorganic and 13 are organic (Regula-

Table 1

Water budget of the Bug-San TAS in the pre-exploitation model

m^3/d	PL/Bug	UA/Bug	PL/San	UA/San
Surface water infiltration (inflow)	18668	56144	57279	19221
Drainage through river (outflow)	147967	590015	460003	335358
Groundwater intake (outflow)	0	0	0	0
Rainwater infiltration (inflow)	151309	510095	396300	335798
Evapotranspiration (outflow)	721	5815	880	4070
Flows from PL/Bug to bordering zones	0	32843	1123	0
Flows from bordering zones to PL/Bug	0	11714	740	215
Flows from UA/Bug to bordering zones	11714	0	0	2583
Flows from bordering zones to UA/Bug	32843	0	0	11046
Flows from PL/San to bordering zones	740	0	0	9372
Flows from bordering zones to PL/San	1123	0	0	16293
Flows from UA/San to bordering zones	215	11046	16293	0
Flows from bordering zones to UA/San	0	2583	9372	0
Total inflow	182647	610128	470995	366974
Total outflow	182653	610126	470995	366983
Budget error	–6	2	0	–9

Transboundary flow from PL to UA	
Transboundary flow from UA to PL	

Table 2

Water budget of the Bug-San TAS in the current exploitation model

m^3/d	PL/Bug	UA/Bug	PL/San	UA/San
Surface water infiltration (inflow)	19.416	64.150	59.143	19.314
Drainage through river (outflow)	142.664	563.455	456,897	335.000
Groundwater intake (outflow)	5.833	34.884	4.967	348
Rainwater infiltration (inflow)	151.309	510.095	396.300	335.798
Evapotranspiration (outflow)	721	5.815	880	4.070
Flows from PL/Bug to bordering zones	0	32.981	1.118	0
Flows from bordering zones to PL/Bug	0	11.632	741	215
Flows from UA/Bug to bordering zones	11.632	0	0	2578
Flows from bordering zones to UA/Bug	32.981	0	0	1.1140
Flows from PL/San to bordering zones	741	0	0	9.369
Flows from bordering zones to PL/San	1.118	0	0	16.292
Flows from UA/San to bordering zones	215	11140	16.292	0
Flows from bordering zones to UA/San	0	2.578	9.369	0
Total inflow	183.313	618.365	472.854	367.059
Total outflow	183.318	618.364	472.854	367.066
Budget error	–5	1	0	–7

For explanations see Table 1

tion…, 2019). The frequency of sampling of monitoring points depends on their belonging to either diagnostic monitoring (once in the 6-year water management plan update cycle) or operational monitoring (carried out at least once a year). During the implementation of groundwater monitoring, the individual stages of sampling, measurement of physical and chemical parameters in the field, and chemical laboratory analysis are covered by the management system compliant with the international ISO/IEC 17025 standard, which guarantees compliance with uniform standards, unification of the procedure and quality control processes (PN-EN ISO/IEC 17025:2018-02, 2018). In Ukraine, similarly, groundwater monitoring is broken down into quantitative and chemical monitoring. Measurements of the water table are carried out in a manner and frequency comparable to that in Poland, 3–4 times a month, while the chemical monitoring is completely incompatible. The range of monitoring parameters is smaller, with only 22 indicators, but the sampling frequency is higher, at least once a year (DSTU 4808:2007,

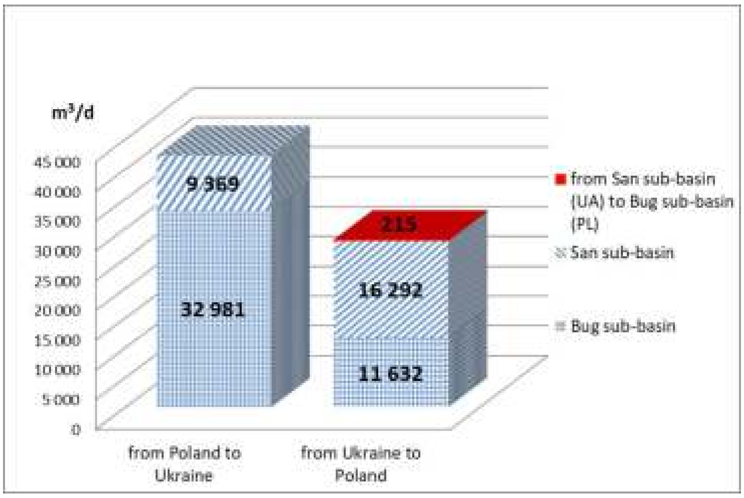

Fig. 10. Transboundary groundwater flow in the current exploitation model

2007). On the other hand, the key problem of the Ukrainian chemical monitoring system is its implementation through non-accredited laboratories and the unregulated method of collecting, preserving and transporting samples and field measurements. Moreover, there is no data quality control system, including use of control samples, and assessment of the quality of groundwater analysis results based on the ion balance. For these reasons, international recognition of the results of monitoring studies is difficult. Another significant factor in planning the joint management of groundwater resources is the approach to the assessment of a GWB. In Poland, the assessment of GWB status has been carried out since 2010, and the current methodology was updated in 2020 and includes nine classification tests, targeted at the needs of individual environmental components, groundwater users or consumers (Palak-Mazur et al., 2020). In Ukraine, the implementation of the WFD began 16 years later than in Poland, only in 2016 (Zakon, 2016). In addition, the implementation of the WFD in the context of groundwater is significantly different from the corresponding activities in the field of surface waters, where the development of water management plans in river basin districts is already underway. For groundwater, the implementation of WFD concerns only the first stage – the identification and characterization of a GWB. Therefore, currently Ukraine does not have a methodology for assessing the condition of GWBs, nor a monitoring program for GWBs.

RECOMMENDATIONS FOR TRANSBOUNDARY GROUNDWATER MANAGEMENT

The designation of cross-border GWBs is often quite subjective in practice. An effective solution to this problem may be the use of a numerical hydrodynamic model (Højberg et al., 2007; Doherty and Simmons, 2013). Many methodologies are consistent in terms of the data harmonization and joint monitoring needed to evaluate TBAs (Burchi, 2018; UNESCO, 2020). The current study highlights that these very important steps have already been taken in the Bug-San TAS to provide a solid scientific basis for the defining of the cross-border GWBs.

Many approaches to transboundary groundwater mnagement refer to sustainable water abstraction that does not disturb the long-term dynamic balance between recharge and discharge intensity (Zhou, 2009). In the cross-border area studied, this is extremely important due to the presence of the Lublin-Lviv groundwater reservoir with strategic drinking water resources. The simulation results show that the regional quantitative status of the Bug-San TAS does not deteriorate significantly at the current level of exploitation, but in the light of quite ambitious maximum allowable values for water abstraction and in the absence of joint management of groundwater resources, this problem will arise in the near future. It is recommended that the limiting values of the regional decline in groundwater level in the TBAs and border buffer zones be introduced into management practice. This practice is already implemented in the transboundary Upper Pannonian area between Austria, Hungary, Slovakia, Slovenia and Croatia (Nádor et al., 2012; Tóth et al., 2016). According to the simulation carried out in this study, we are dealing with a regional depression on both sides of the border, but further research is needed to determine its critical value. Within the Bug sub-basin, simulations indicate the occurrence of adverse transboundary interactions. The state of the system on local-scale models should be carefully examined there.

It is recommended to verify the water permits for the use of groundwater in the Bug-San TAS area, as the input data used for the calculation of the maximum abstraction values did not take into account the information on the other side of the border. Performing these calculations is possible with the use of the merged database obtained in this study.

Joint management of transboundary groundwater between Poland and Ukraine is essential. TBA status indicators can be very useful, the assessment of which should be based on information from the monitoring system, interpretation of the regional water balance and the risk of overexploitation. This methodology was tested in the study, effectively identifying problem areas and phenomena in the context of sustainable exploitation of transboundary groundwater resources.

Taking into account the fact that legislative solutions, although constituting the basis for any kind of cooperation between neighbouring countries, are often not fully implemented, it is necessary to make sure that they are constructed as perfectly as possible. Such an approach will limit the possibility of omitting or neglecting the issues that are not clearly defined, like the role of transboundary groundwater monitoring and transboundary groundwater management. Moreover, improvement of cooperation between entities responsible for groundwater monitoring and management as well as for periodic reporting to the EU is crucial. At the moment in Poland all issues connected with groundwater management are the responsibility of the Ministry of Climate and Environment while the Commission for Border Waters consists of the employees of the Ministry of Infrastructure. Such an approach may cause problems as regards the clear division of responsibilities, which might be avoided by simplification of procedures and exchange of information between entities.

Stronger cooperation of the administration on various levels with the scientific community should also be considered. At the moment these two worlds meet only occasionally and true cooperation barely exists. This goal might be achieved by actions such as better promotion of works of the Commission for Border Waters and increasing of transparency in appointing experts to support the work of the commission.

CONCLUSIONS

The Bug-San numerical model of the cross-border aquifer system is a unique tool for the quantification of cross-border groundwater flows between Poland and Ukraine. Four transboundary aquifers (porous alluvial, fractured Upper Cretaceous, fractured-cavernous Lower Neogene and porous Quaternary fluvioglacial) have been simulated together, to adequately account for the main water exchange processes that are triggered by two separate regional flow systems controlled by the Bug and San rivers. For the first time, an area with significant cross-border flows has been identified, which covers only 36% of the border area defined along the borders of the transboundary river sub-basins. The balance of interstate groundwater exchange turned out to be positive for Ukraine and negative for Poland. The volume of flow from Poland to Ukraine is over 1.5 times higher than from the opposite direction. The greatest cross-border flows are within the Bug sub-basin, in the fractured Upper Cretaceous aquifer. In the San sub-basin ~70% of the aquifer model has weak aquifer potential.

Exploitation of groundwater at the current level does not result in interstate capture of resources and the creation of transboundary drawdown cones, but there are noticeable effects on river water resources and transboundary groundwater flow. It was estimated that groundwater runoff to rivers decreased by 1–4% for the San and Bug sub-basins, respectively, and infiltration losses through the riverbed increased. The current consumption slightly increased the transboundary groundwater flow from Poland to Ukraine (in the Bug sub-basin by 0.4%) and decreased the inflow from Ukraine (in the Bug sub-basin by 0.7%). Exploitation enhanced the effects of transboundary groundwater, but without reversing the direction of water flow at the border.

This study, the first such assessment of the state of transboundary aquifers, provides important scientific support for the establishment of a joint management system for transboundary groundwater resources between Poland and Ukraine. Now, a broader legal consensus is needed, with improvement of institutional relations, integration of water monitoring and assessment systems to implement the proposed transboundary management in practice. Particular attention should be paid to GDEs as their sustainability depends on appropriate environmental policies and groundwater management practices. GDEs are often not sufficiently taken into account in the management of groundwater resources. With help of the TBA model created, a better understanding of the functioning of the GDE can be achieved.

Acknowledgements. The study was carried out within the project No.2018-1-0137 “EU-WATERRES: EU-integrated management system of cross-border groundwater resources and anthropogenic hazards” which benefits from a € 2.447.761 grant of Iceland, Liechtenstein and Norway through the EEA and Norway Grants Fund for Regional Cooperation. The scientific work is published as part of an international project co-financed by the program of the Minister of Science and Higher Education entitled “PMW” in the years 2020–2023; agreement No. 5152 / RF-COOPERATION / 2020/2.

The authors would like to express their gratitude to the reviewers, O. Shevchenko and A. Sadurski, for their careful reviews and useful comments.

REFERENCE

Agreement…, 1994. Agreement between the Government of the Republic of Poland and the Government of Ukraine on cooperation in the field of environmental protection.

Agreement…, 1996. Agreement between the Government of the Republic of Poland and the Government of Ukraine on cooperation in the field of water management in border waters.

Bielecka, M., 1967. Tertiary of the south-western part of the Lublin Upland (in Polish with English summary). Biuletyn Instytutu Geologicznego, **206**: 115–188.

Chaminé, H.I., Gómez-Gesteira, M., 2019. Sustainable resource management: water practice issues. Sustain. Water Resources Management, **5**: 3–9. https://doi.org/10.1007/s40899-019-00304-7

Convention on the Protection and Use of Transboundary Watercourses and International Lakes, Helsinki, 17 March 1992. https://unece.org/fileadmin/DAM/env/water/pdf/watercon.pdf

Dobkowska, A., Kapuściński, J., 2000. Dokumentacja hydrogeologiczna określająca dyspozycyjne zasoby wód podziemnych poziomu kredowego, trzeciorzędowego i czwartorzędowego na obszarze dorzecza Bugu granicznego (in Polish). Inw. 2611/2000 NAG, Przedsiębiorstwo Geologiczne Polgeol, Warszawa.

Burchi, S., 2018. Legal frameworks for the governance of international transboundary aquifers: pre- and post-ISARM experience. Journal of Hydrology: Regional Studies, **20**: 15–20. https://doi.org/10.1016/j.ejrh.2018.04.007

Doherty, J., Hunt, R.J., 2010. Approaches to highly parameterized inversion: a guide to using PEST for groundwater-model calibration. U.S. Geological Survey. https://doi.org/10.3133/sir20105169

Doherty, J., Simmons, C.T., 2013. Groundwater modelling in decision support: reflections on a unified conceptual framework. Hydrogeological Journal, **21**: 1531–1537. https://doi.org/10.1007/s10040-013-1027-7

Du, E., Tian, Y., Cai, X., Zheng, Y., Han, F., Li, X., Zhao, M., Yang, Y., Zheng, C., 2022. Evaluating distributed policies for conjunc-

tive surface water-groundwater management in large river basins: water uses versus hydrological impacts. Water Resources Research, **58**: e2021WR031352.
https://doi.org/10.1029/2021WR031352

EU, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.
https://eur-lex.europa.eu/eli/dir/2000/60

EU, 2006. Directive 2006/118/EC on the protection of groundwater against pollution and depletion
https://eur-lex.europa.eu/eli/dir/2006/118

Fonseca, A., Botelho, C., Boaventura, R.A.R., Vilar, V.J.P., 2014. Integrated hydrological and water quality model for river management: a case study on Lena River. Science of the Total Environment, **485–486**: 474–489.
https://doi.org/10.1016/j.scitotenv.2014.03.111

Groundwater Monitoring Database, 2022. Polish Geological Institute(https://geolog.pgi.gov.pl/).

Harbaugh, A.W., 2005. MODFLOW-2005, the U.S. Geological Survey Modular Ground-water Model – the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods.

Højberg, A.L., Refsgaard, J.C., Geer, F., Jørgensen, L.F., Zsuffa I., 2007. Use of models to support the monitoring requirements in the water framework directive. Water Resources Management, **21**: 1649–1672.
https://doi.org/10.1007/s11269-006-9119-y

IGRAC, 2021. Transboundary Aquifers of the World, Update 2021, Scale 1:50 000 000.

ISAP, 2022. Ustawa z dnia 7 lipca 2022 r. Prawo wodne (in Polish) (Act of July 7, 2022 Water Law.
https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20220001549

Janiec, B., 1984. Groundwater in the south-western edge of the Lublin Upland (in Polish with English summary). Wyd. Geol., Warszawa.

Kamzist, Zh.S., Shevchenko, O.L., 2009. Hydrogeology of Ukraine (in Ukrainian with English summary). Navchalnyi posibnyk, Inkos.

Kowalski, J., 2007. Hydrogeology with the basics of geology (in Polish with English summary). Wydawnictwo Uniwersytetu Przyrodniczego, Wrocław.

KPRWP, 2020. Opracowanie II aktualizacji planów gospodarowania wodami na obszarach dorzeczy wraz z dokumentami planistycznymi stanowiącymi podstawę do ich opracowania (in Polish). Nr Projektu: POIS.02.01.00-00-0016/16, PGW WP.

Krajewski, S., 1984. The fissure waters of the Lublin Cretaceous (in Polish with English summary). Przegląd Geologiczny, **32**: 359–364.

Lorenc, H., 2005. Climate Atlas of Poland (in Polish with English summary). IMGW, Warszawa.

Marciniak, M., Przybyłek, J., Herzig J., Szczepańska, J., 1998. Research on the filtration coefficient of semi-permeable formations (in Polish with English summary). Wyd. SORUS, Poznań.

Michalczyk, Z., Bartoszewski, S., Turczyński, M., 2002. The water conditions of the Polesie Region. Acta Agrophysica, **66**: 49–76.

Nádor, A., Lapanje, A., Tóth, G., Rman, N., Szőcs, T., Prestor, J., Uhrin, A., Rajver, D., Fodor, F., Muráti, J., Székely, E., 2012. Transboundary geothermal resources of the Mura-Zala basin: joint thermal aquifer management of Slovenia and Hungary. Geologija, **55**: 209–224.
https://doi.org/10.5474/geologija.2012.013

Paczyński, B., Sadurski, A., 2007. Regional Hydrogeology of Poland (in Polish with English summary). Państwowy Instytut Geologiczny, Warszawa.

Palak-Mazur, D., Stojek, M., Kowalczyk, A., Mikołajczyk, A., Felter, A., Piskorek, K., Połujan-Kowalczyk, M., Przytuła, E., Solovey, T., Janica, R., Galczak, M., Gidziński, T., Cabalska, J., Rojek, A., Kuczyńska, A., Razowska-Jaworek, L., Woźnicka, M., 2020. Update of the GWB condition assessment methodology along with the development of a methodology for analysing pollution trends reversal (in Polish with English summary). Państwowy Instytut Geologiczny, Warszawa.

Pétré, M.A., Rivera, A., Lefebvre, R., 2019. Numerical modeling of a regional groundwater flow system to assess groundwater storage loss, capture and sustainable exploitation of the transboundary Milk River Aquifer (Canada–USA). Journal of Hydrology, **57:** 656–670.
https://doi.org/10.1016/j.jhydrol.2019.05.057

PN-EN ISO/IEC 17025:2018-02, 2018 Ogólne wymagania dotyczące kompetencji laboratoriów badawczych i wzorcujących.

Regulation of the Minister of Maritime Economy and Inland Navigation of October 11, 2019 on the criteria and method of assessing the state of groundwater bodies. Journal of Laws of 2019, item 2148.

Rejman, W.E.U., 2006. Water framework directive versus real needs of groundwater management. Water Resources Management, **21**: 1363–1372.
https://doi.org/10.1007/s11269-006-9088-1.

Setegn, S.G., Donoso, M.C. eds., 2012. Sustainability of Integrated Water Resources Management: Water Governance, Climate and Ecohydrology. Springer International.
https://doi.org/10.1007/978-3-319-12194-9

Solovey, T., Harasymchuk, V., Janica, R., Przychodzka, M., Ryvak, T., Teleguz, O., Yanush, L., 2021a. Hydrogeological model of transboundary aquifers with significant groundwater exchange potential between Poland and Ukraine. ISARM2021 2nd International Conference, Transboundary Aquifers: Challenges and the way forward, 06–09 December 2021/UNESCO, Paris. https://isarm2021.org/book-of-abstracts/

Solovey, T., Janica, R., Przychodzka, M., Harasymchuk, V., Medvid, H., Poberezhskyy, A., Janik, M., Stupka, O., Teleguz, O., Panov, D., Pavliuk, N., Yanush, L., Kharchyshin, Y. et al., 2021b. Assessment of the resources of transboundary groundwater reservoirs for the 2 pilot areas. http://eu-waterres.eu/wp-content/uploads/2021/07/Output-1.Assessment-of-the-resources-in-2-pilot-areas.pdf

Solovey, T., Janica, R., Przychodzka, M., Harasymchuk, V., Przychodzka M., Yanush, L., 2023. Numerical Modeling of Transboundary Groundwater Flow in the Bug and San Catchment Areas for Integrated Water Resource Management (Poland–Ukraine). Journal of Environmental Informatics, 42: 123–142. https://doi.org/10.3808/jei.202300501

Sophocleous, M., 2010. Review: groundwater management practices, challenges, and innovations in the High Plains aquifer, USA-lessons and recommended actions. Hydrogeological Journal, **18**: 559-575. https://doi.org/10.1007/s10040-009-0540-1.

Tóth, G., Rman, N., Ágnes, R.S., Kerékgyártó, T., Szcs, T., Lapanje, A., Černák, R., Remsík, A., Schubert, G., Nádor, A., 2016. Transboundary fresh and thermal groundwater flows in the west part of the Pannonian Basin. Renewable and Sustainable Energy Reviews, **57**: 439–454.
https://doi.org/10.1016/j.rser.2015.12.021

UNECE, 1992. Convention on the Protection and Use of Transboundary Watercourses and International Lakes.
http://www.unece.org/env/water/text/text.html

UNESCO, 2020. Guidelines for Monitoring Strategies in Transboundary Aquifers: Goals, Methods and Tools. The Case of the DRIN project (ALB-MTN).

Vaquero, G., Siavashani, N.S., García-Martínez, D., Elorza, F.J., Bila, M., Candela, L., Serrat-Capdevila, A., 2021. The lake chad transboundary aquifer. Estimation of groundwater fluxes through international borders from regional numerical modeling. Journal of Hydrology: Regional Studies, **38:** 100935
https://doi:10.1016/j.ejrh.2021.100935.

Voss, C.I., Soliman, S.M., 2014. The transboundary non-renewable Nubian Aquifer System of Chad, Egypt, Libya and Sudan: classical groundwater questions and parsimonious hydrogeologic analysis and modeling. Hydrogeological Journal, **22**: 441–468. https://doi:10.1007/s10040-013-1039-3.

Wachniew, P., Witczak, S., Postawa, A., Kania, J., Żurek, A., Różański, K., Duliński, M., 2014. Groundwater dependent ecosystems and man: conflicting groundwater uses. Geological Quarterly, **58** (4): 695–706. https://doi: 10.7306/gq.1168

Wu, B., Zheng, Y., Wu, X., Tian, Y., Han, F., Liu, J., Zheng, C., 2015. Optimizing water resources management in large river basins with integrated surface water-groundwater modeling: a surrogate-based approach. Water Resources Research, **51**: 2153–2173. https://doi.org/10.1002/2014WR016653

Zakon, 2016. Act on the Implementation of Integrated Approaches to Basin Management, the Verkhovna Rada of Ukraine on October 4, 2016, no 1641-VIII. (https://zakon.rada.gov.ua/laws/show/1641-19#Text)

Zhou, Z., 2009. A critical review of groundwater budget myth, safe yield and sustainability. Journal of Hydrology, **370**: 207–213. https://doi.org/10.1016/j.jhydrol.2009.03.009

Żelaźniewicz, A., Aleksandrowski, P., Buła, Z., Karnkowski, P., Konon, A., Oszczypko, N., Ślączka, A., Żaba, J., Żytko, K., 2011. Tectonic subdivision of Poland (in Polish with English summary). Komitet Nauk Geologicznych PAN, Wrocław.

DSTU 4808, 2007. Dzherela tsentralizovanoho pytnoho vodopostachannya (in Ukrainian). Hihiyenichni ta ekolohichni vymohy shchodo yakosti vody i pravyla vybyrannya, 2007. Derzhavnyy Standart Ukrayiny. Ministerstvo rozvytku hromad ta terytoriy Ukrayiny.

EU-waterres: EU-integrated management system of cross-border groundwater resources and anthropogenic hazards”. http://www.eu-waterres.eu (accessed Aug 1, 2022).