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Numerical Modeling of Transboundary Groundwater Flow in the Bug and San Catchment Areas for Integrated Water Resource Management (Poland–Ukraine)

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ABSTRACT. On the Polish–Ukrainian borderlands, there is the Lublin–Lviv transboundary groundwater aquifer system, which is of key importance in shaping strategic groundwater resources. Due to the particular importance of this aquifer system, the two neighboring countries are obliged to undertake joint actions to protect it. The integrated management of the Lublin–Lviv aquifer system seems difficult due to the significant spatial and temporal scale of groundwater flows in the region. To support internationally integrated management, a transboundary geological model was developed. Based on this model, a hydrogeological conceptual model has been developed, which allowed for a numerical model of groundwater flow to be calculated. The model research helped diagnose potential problems by determining the scope of the area with cross-border flows and quantifying the flows between Poland and Ukraine. In addition, the numerical model was used to define the optimal cross-border management unit and the conditions needed to sustainably exploit the Lublin–Lviv aquifer system. Basing on the research results it was concluded that groundwater flows in transboundary aquifers very on a regional scale and that the range of areas of importance for transboundary groundwater flows is much smaller than the pre-selected partial catchments of the Bug and San Rivers. The results of this study may significantly contribute to the preparation of joint water management plans.

Keywords: numerical modeling, transboundary groundwater flows, joint management, EU-waterres

1. Introduction

The internationally integrated water resource management of transboundary aquifers (TBAs) is becoming more and more desirable due to the growing global trend of groundwater consumption, exceeding the threshold values for sustainable abstraction (Lipponen and Chilton, 2018). To avoid future international disputes and to maximize the rational and fair use of common TBAs, there is a need for a thorough and comprehensive assessment of the development potential of groundwater resources in these aquifers.

Global identification of TBAs began in 2000 under the coordination of the Internationally Shared Aquifer Resources Management (ISARM) Committee under UNESCO's International Hydrology Program (Burchi, 2018). According to the assessment provided by the International Center for Groundwater Resource Assessment (IGRAC), it is estimated that there are 591 TBAs worldwide, including 72 in Africa, 73 in the Americas, 129 in Asia and Oceania, and 317 in Europe (IGRAC, 2021).

The TBA inventory has contributed to wider cooperation between countries sharing aquifers, but the level of understanding of common aquifer systems remains limited. The current problems faced by TBAs researchers concern the development of rules and criteria for acceptable joint abstraction of groundwater from TBAs, including their protection against pollution and depletion. In this case, the most important task is to determine the threshold value for the regional decline in groundwater levels in the TBAs and the border buffer zone. Another challenge is the development of numerical hydrodynamic models to determine the state of TBAs and to test water management plans. Numerical models have proven to be efficient tools to understand the groundwater dynamics system, which is important in the aspect of estimation of groundwater fluxes through international borders (Voss and Soliman, 2014; Tóth at al., 2016; Vaquero et al., 2021).

This article focuses on the problem of joint management of the transboundary groundwater between Poland and Ukraine — two countries from different geopolitical systems, which further complicates the matter. In Poland, as an EU member state, the legal basis is the EU Water Framework Directive (WFD), while in Ukraine the Water Convention (UNECE, 1992) provides the legal and institutional framework, though the WFD is gradually being implemented. As a result, the countries show some heterogeneity in their approach to assessment, regulatory concepts, and obligations.

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Issues related to transboundary water between Poland and Ukraine are decided in accordance with a bilateral agreement: Agreement on Cooperation in the Area of Water Management in Border Waters (Agreement, 1996). Under it, a regularly operating Polish-Ukrainian commission for border waters was established. Based on a review of the archived minutes of this commissions' meetings, conclusions were drawn about its active work in terms of surface waters and the almost total disregard for the issue of transboundary groundwater. A similar situation can be traced by analyzing scientific publications. The only existing official data on this topic is the recognition of the alluvial aquifer in the Bug River Valley as a TBA in the Polish-Ukrainian borderland by placing it in the list of the world's TBAs published by UNESCO in 2011 (IGRAC, 2021). In addition to the alluvial aquifer of the Bug Valley — included in the world TBA list — the Upper Cretaceous (K_2) aquifer also plays a major role in this flow system. The K_2 aquifer is of key importance in strategic drinking water resources, and in Poland it is classified as the main aquifer system with a regional range and large resources (Paczyński and Sadurski, 2007). This aquifer system is a part of an extensive geological structure: the Lublin Basin in Poland and Lviv Cretaceous Depression in Ukraine. The Lublin-Lviv aquifer system extends approx. 26,000 km^2 and occurs at a depth of 1 to 90 m b.g.l. Due to the particular importance of the saquifer system, the two neighboring countries are obliged to undertake joint actions to protect this extremely valuable groundwater resource, which must ensure the supply of drinking water in the long term.

In this perspective, the aim of this article is to analyze, based on a numerical model, the transboundary groundwater flows in major TBAs under both natural and operational conditions, which should result in the definition of criteria for the sustainable management of groundwater resources.

2. Study Area

The region in question is near the Polish-Ukrainian border in the southeastern part of Poland and the northwestern part of Ukraine, in the basins of the Bug, San, and Dniester rivers (Figure 1). According to the geographical division, the study area is located on the border of two megaregions: the East European Plain and the Carpathian Region (Solon et al., 2018). The average annual rainfall in the last forty years ranged from 500 mm in the East European Plain to 1,600 mm in the Outer Carpathians, while evaporation amounts to 450 and 520 mm/year, respectively (Lorenc, 2005). The northern part of the study area — the Polesie mesoregion — is flat with a predominance of wetlands, a poorly developed network of rivers, and dense drainage canals and lakes, including the famous Shatské lake complex, belonging to the Ramsar protected area. The central part of the study area is in the Volyn Upland and Roztocze. Its characteristic feature is alternating hills and vast depressions and valleys. In the south of the study area, in the San and Dniester catchments, the highlands transform into the Outer Carpathian flysch. The name "flysch", introduced into the literature by Studer, is used to refer to marine geosynclinal sediments of considerable thickness (Kelling et al., 2007).

2.1. Hydrology

Hydrographically, the study area is unique due to its location in the European watershed, which ensures that the Bug and San basins belong to the Baltic Sea basin, while the Dniester basin belongs to the Black Sea. These river basins are represented in the study area with their upper parts (springs). In the Bug catchment there is a slight hypsometric differentiation in the area of 150 ~ 180 m above sea level; in the San and Dniester catchments the absolute heights range from 210 to 1200 m above sea level, due to the mountainous nature of the catchment. Due to the orographic factor, the Bug and its tributaries in the study area show minimal longitudinal slopes (0.01 ~ 0.5‰), which slows down the outflow of water and contributes to the formation of fluviogenic wetlands. The average annual river runoff in the study area in the Bug catchment is about 120 mm; the unit runoff varies from 3 to 4 l/s/km^2; and the share of groundwater in the river runoff is about 50% (Nazaruk, 2018). In the catchments of the San and Dniester, the main factor influencing the amount of runoff and the features of the river regime is atmospheric precipitation, which — combined with the low retention capacity of the Carpathian flysch and the dense erosion network — favor the occurrence of rapid surface runoff. The average annual river runoff in the San catchment in the foreland area is approx. 170 ~ 200 mm; this increases with the average height of the catchment, giving the upper part a runoff layer of 660 ~ 780 mm and a unit runoff of 23 ~ 27 l/s/km^2 (Michalczyk et al., 2002). The share of underground recharge of rivers in this area ranges from approx. 21 to 45%, and the lower values are characteristic of the mountainous part of the catchment area.

2.2. Geology and Hydrogeological Conditions

The geological conditions in the study area are very diverse due to the presence of three geostructures in the contact zone: the East European Platform (in the north), the Carpathian Foredeep (in the center), and the Outer Carpathians (in the south). Within the platform, the cover is formed by Ediacaran, Cambrian, Silurian, and Devonian sediments, on which the Carboniferous sediments are inconsistent. They are covered with Jurassic and Upper Cretaceous sediments and covered locally with Neogene and Paleogene sediments. The Carpathian Foredeep is a young geological structure, constituting a fragment of the Carpathian Foredeep, filled with Miocene molasses. The Outer Carpathians are characterized by the presence of flysch on the surface (Kolodii, 2004). Their stratigraphic profiles in this region include the Upper Cretaceous, Palaeogene, and Lower Neogene layers. Quaternary cover occurs on the ground surface in most of the study area (Figure 2). In the drainage depressions, it is formed by organic sediments; in watershed areas — glacial sediments. Eolian sediments are present on the hills. The thickness of the Quaternary cover is usually 2 ~ 10 m. Only in the valleys of larger rivers do the series of limnic and fluvioglacial sediments reach 30 m (PGI-NRI, https://geologia.pgi.gov.pl/karto_geo/).

The hydrodynamics of groundwater in the study area are diverse and result from its complex geological and morphological structure. The Bug area is characterized by better conditions for forming groundwater resources than the San and Dniester basins, due to the extensive geological structure — the Lublin-

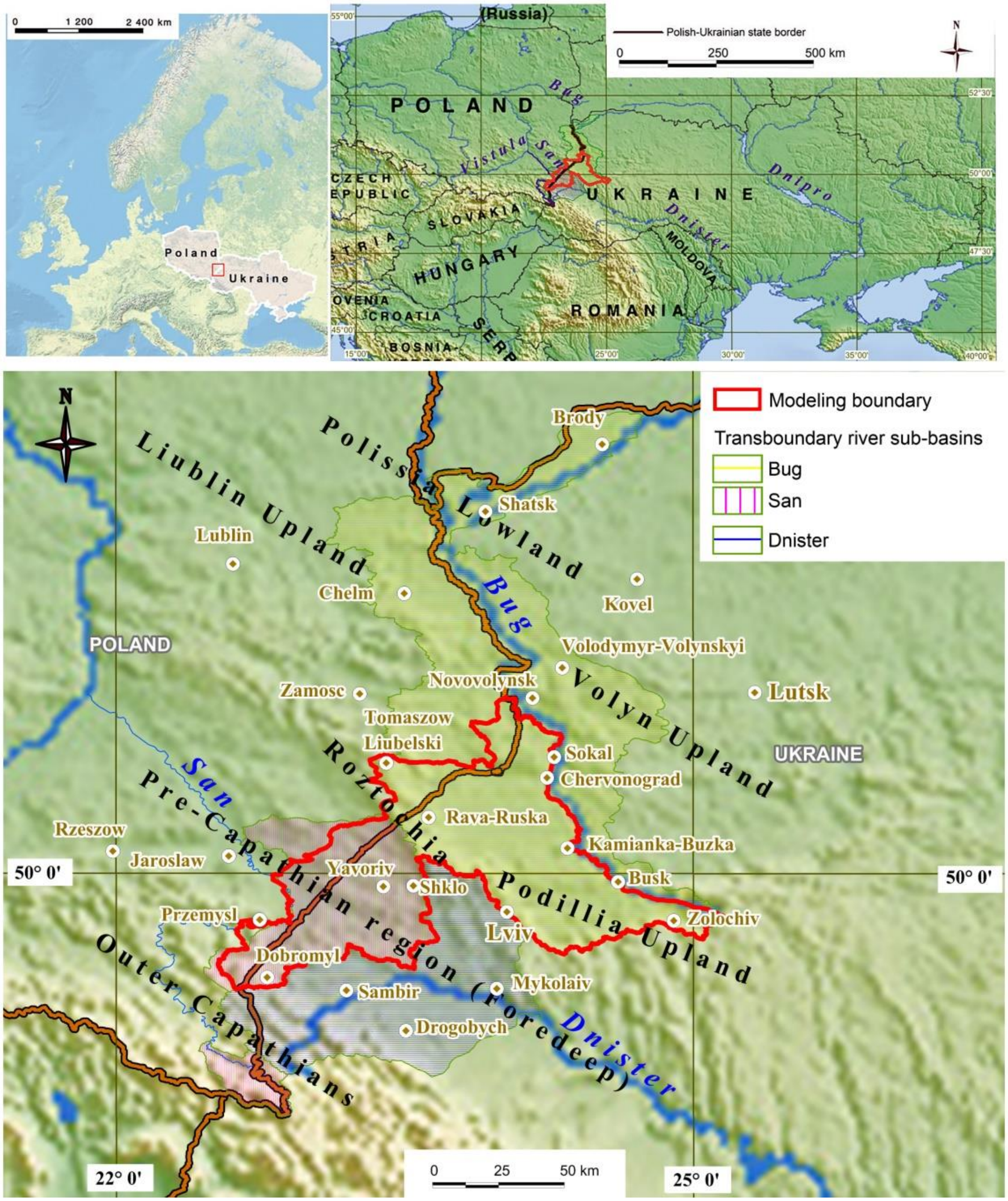

Figure 1. Location of the study area.

Lviv Basin, which has plentiful water. A characteristic feature of the basin is its slight folding and the thickness of the Cretaceous formations, which are characterized by strong fracture and cavity. Up to the lower limit of intensive water exchange (approx. 120 ~ 150 meters), the basin is built by the Upper Cretaceous formations with a thickness of 500 ~ 700 m, formed in carbonate facies (marl, marly limestones, chalk, and gaize), of which the greatest thickness is reached by the Maastrichtian formations (Buchatska, 2009). In the study area of the Bug catchment, two principal aquifers were identified, which often are in hydraulic connection (Figure 3). A principal aquifer is defined as a regionally extensive aquifer that has the potential to be used as a source of drinking water.

The first from the top, Quaternary (Q) aquifer occurs on a local scale and is hardly used. It is built of alluvial sandy sedi-

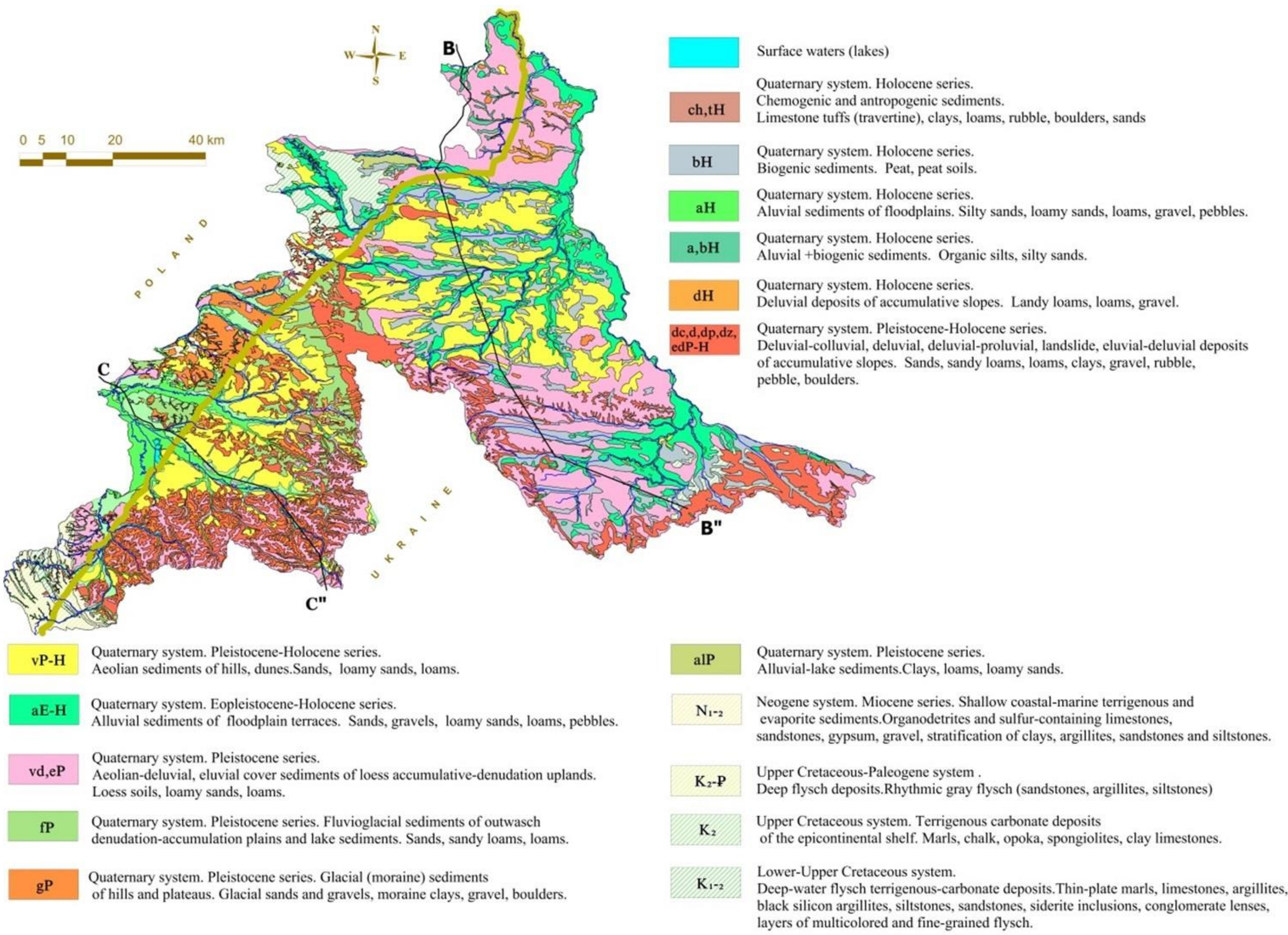

Figure 2. Geological map of the study area and lines of hydrogeological cross-section shown in Figure 3 (line BB") and Figure 4 (line CC").

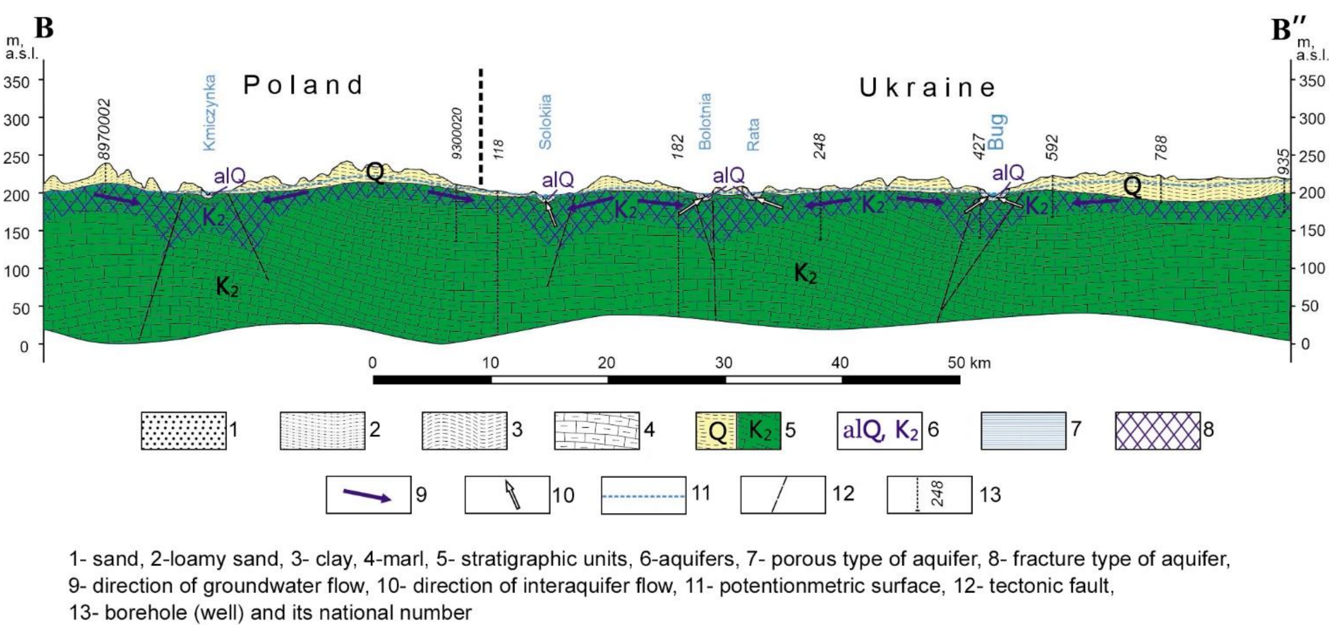

Figure 3. Hydrogeological cross-section of the cross-border part of the Bug catchment area.

ments in the river valleys of the Bug and its tributaries — the Rata, Solokiia, and others — are built from fluvioglacial sands in the watershed zone (Pankiv et al., 2013). The water table is unconfined and occurs at a depth of 0.4 m in river valleys and up to 12 ~ 15 m below ground level in the watershed zone. In the area of the greatest accumulation of alluvial sediments (the Bug River valley), its thickness is 15 ~ 20 m. The second aquifer, K_2, is the main usable aquifer; it has a sustained spread. Within Poland, the Upper Cretaceous aquifer is usually unconfined, while in Ukraine it is mainly confined. The recharge takes place particularly in the elevated areas of Upper Cretaceous sediment outcrops. The main discharge base is the Bug River and its tributaries. The thickness of the aquifer K_2 ranges from tens of meters to 100 ~ 150 m (within tectonic zones and river valleys). The depth of the groundwater table is set at +1.5 to 10 m in river valleys and up to 20 ~ 40 m in watersheds (Kamzist and Shevchenko, 2009).

In the study area of the San catchment, almost half of the area is devoid of aquifers due to the spread of flysch formations in the Carpathians and in the Foredeep — a thick layer (up to 3,000 m) of low-permeability sediments (clay, loam, silt, and fine-grained sands). Three local useable aquifers were identified here (Figure 4).

The largest part of the area is occupied by the Q aquifer. The aquifer is built of alluvial sand sediments and by fluvioglacial formations and sediments (gravel and sand). The water table is unconfined. In river valleys it occurs at the depth of 0.5 m and in the watershed area at ca. 10 m below ground level. Lower Neogene (Miocene) aquifer is the most important from the exploitation point of view. It plays the important role of supplying drinking water to the Lviv agglomeration. It is represented by Middle Miocene Ba denian formations: sandy, sandstones, gypsum, and calcareous-lithotamic sediments. Its groundwater table is mostly 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). In Ukraine this aquifer is also associated with the presence of sulfate medicinal waters. Roztocze is the recharge area of the Miocene aquifer and the San River is the drainage base. The third aquifer is the K_2, which is common on the border with the Bug catchment area. In the study area of the Dniester catchment, most of the terrain is devoid of aquifers that occur only locally.

3. Data and Methodology

3.1. Conceptual Hydrogeological Model

The methodology used to develop a conceptual hydrogeological model was based on defining the main components of the structure of the aquifer and the course of processes taking place in it (Michalak et al., 2011). As a result of the schematization of hydrogeological conditions, it was found that the structure of the aquifer modeling area in the active exchange zone was adequately represented by a two-layer system of aquifers (Figure 5):

- First layer — alluvial (alQ) aquifer in the valleys of large rivers;
- Second layer — spatially heterogeneous: in the north within the East European platform, it is a K_2 fractured aquifer; in the central part within the southwestern border of the East European platform and Carpathian Foredeep, it is a Lower Neogene (N_1) fractured/porous aquifer; and in the south within the inner part of the Carpathian Foredeep, it is a Quaternary (fgQ) porous aquifer.

The first layer comprises of various types of alluvial sand and gravel; therefore, the aquifer has good permeability (the *k* was 0.022 ~ 1.7 m/h). As a rule, these formations are not covered with impermeable sediments, so the water table is unconfined. The average thickness of an alQ aquifer is 5 m, rarely exceeding 30 m.

The second layer, the K_2 aquifer, is fractured and generally unconfined groundwater table type in Poland and a confined one in Ukraine. It is built mainly of marls, limestones, and chalk. The bottom of the active water exchange zone is located at a depth of 100 ~ 150 m below ground level.

The second layer, the N_1 aquifer, combines hydrodynamically connected N_1b_1 and N_1b_2 water-bearing layers (limestones, sandstones, sands, and gypsum). It is a fractured/porous aquifer with a confined groundwater table. Its top is at a depth of 5 to 50 m underground. The thickness of the N_1 aquifer is approximately 10 ~ 40 meters.

The second layer, the fgQ aquifer, is common in the local and shallow (approx. 2 ~ 20 m thick) level of fluvioglacial formations, serving as a usable aquifer in the Carpathian Foredeep on accumulation plains and in river valleys. It is a porous aquifer with an unconfined groundwater table.

3.2. Input Data

The identification and definition of TBAs began with the harmonization of geological and hydrogeological spatial data between Ukraine and Poland to obtain unified units. The geological data, retrieved and compiled from a number of hydrogeological and geological maps, were mainly provided by Polish Geological Institute and enterprise "Zahidukrgeologiya" (Fedoseev, 1994; Matskiv et al., 2003; Gerasimov et al., 1994; PGI-NRI, https://geologia.pgi.gov.pl/karto_geo; PGI-NRI, https ://epsh.pgi.gov.pl/epsh/).

To characterize the geometry of sedimentary formations, geological information was obtained from 2,926 wells logs datasets (Figure 6). The definition of the transboundary nature of aquifers was based on hydrogeological cross-sections, thanks to which the lateral spread and vertical structure of aquifers and impermeable layers were determined.

The ground-based average annual precipitation (*P*) and temperature (*T*) time series for 10 meteorological stations in the basin were compiled from the meteorological annals of the historic data record (1971 ~ 2000). In order to prepare a groundwater level map for the 2008 ~ 2021 period, water level measurements in wells, piezometers or open wells were taken from public databases (PGI-NRI, https://epsh.pgi.gov.pl/epsh/) and reports. The final selection included a dataset of 57 water monitoring points.

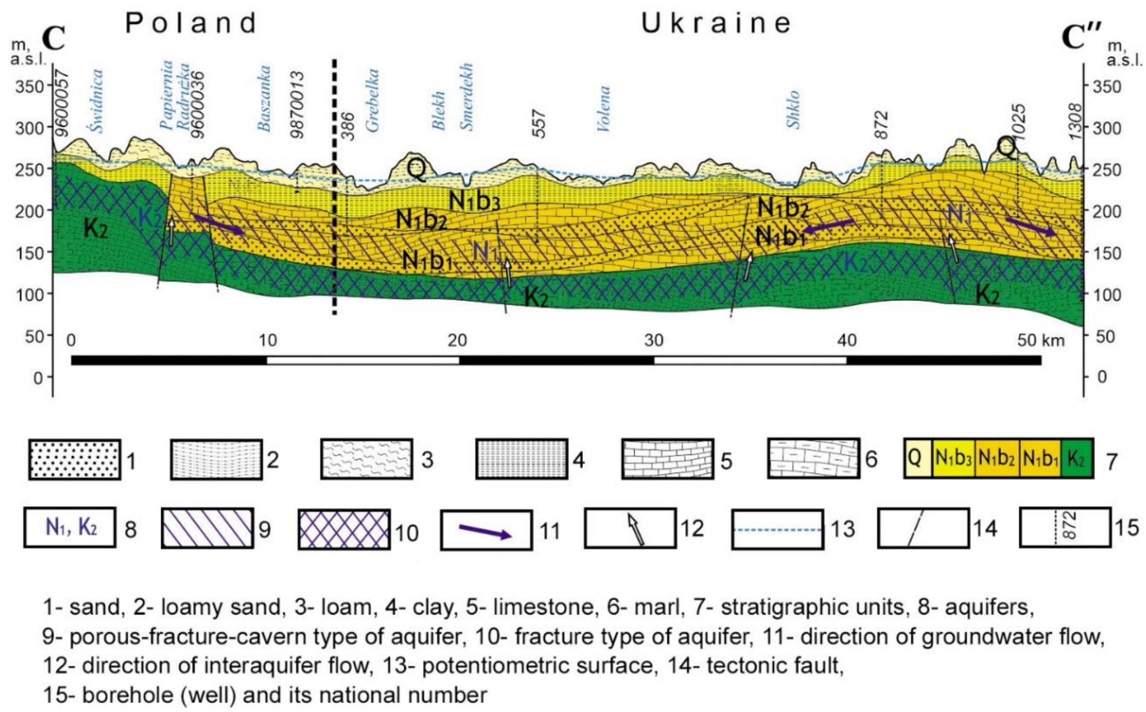

Figure 4. Hydrogeological cross-section characteristic of the transboundary part of the San catchment.

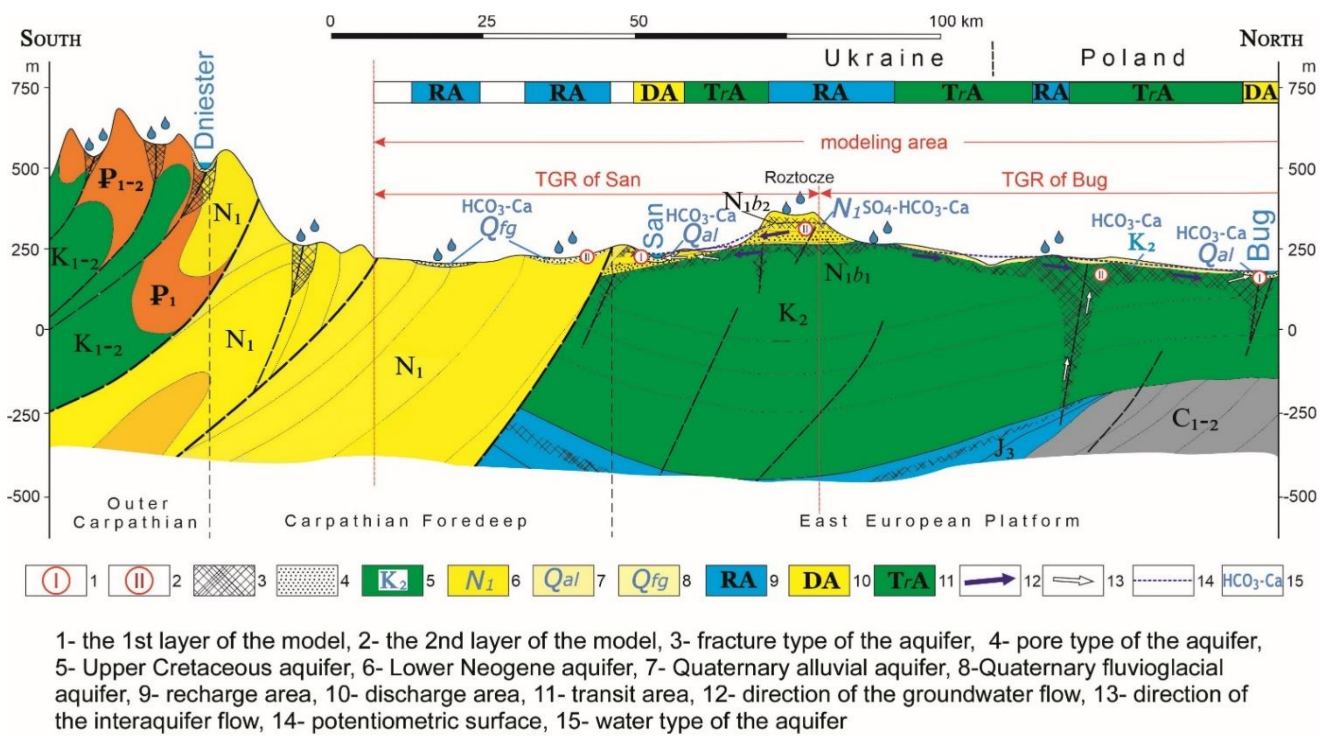

Figure 5. Schematic diagram of groundwater flowpaths in the modeling area.

In order to conclude on 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. The modeling software package Groundwater Vistas ver. 6 (GV) was used for numerical modeling (USGS, 2005). GV enables numerical calculations using the finite difference method to describe groundwater flow.

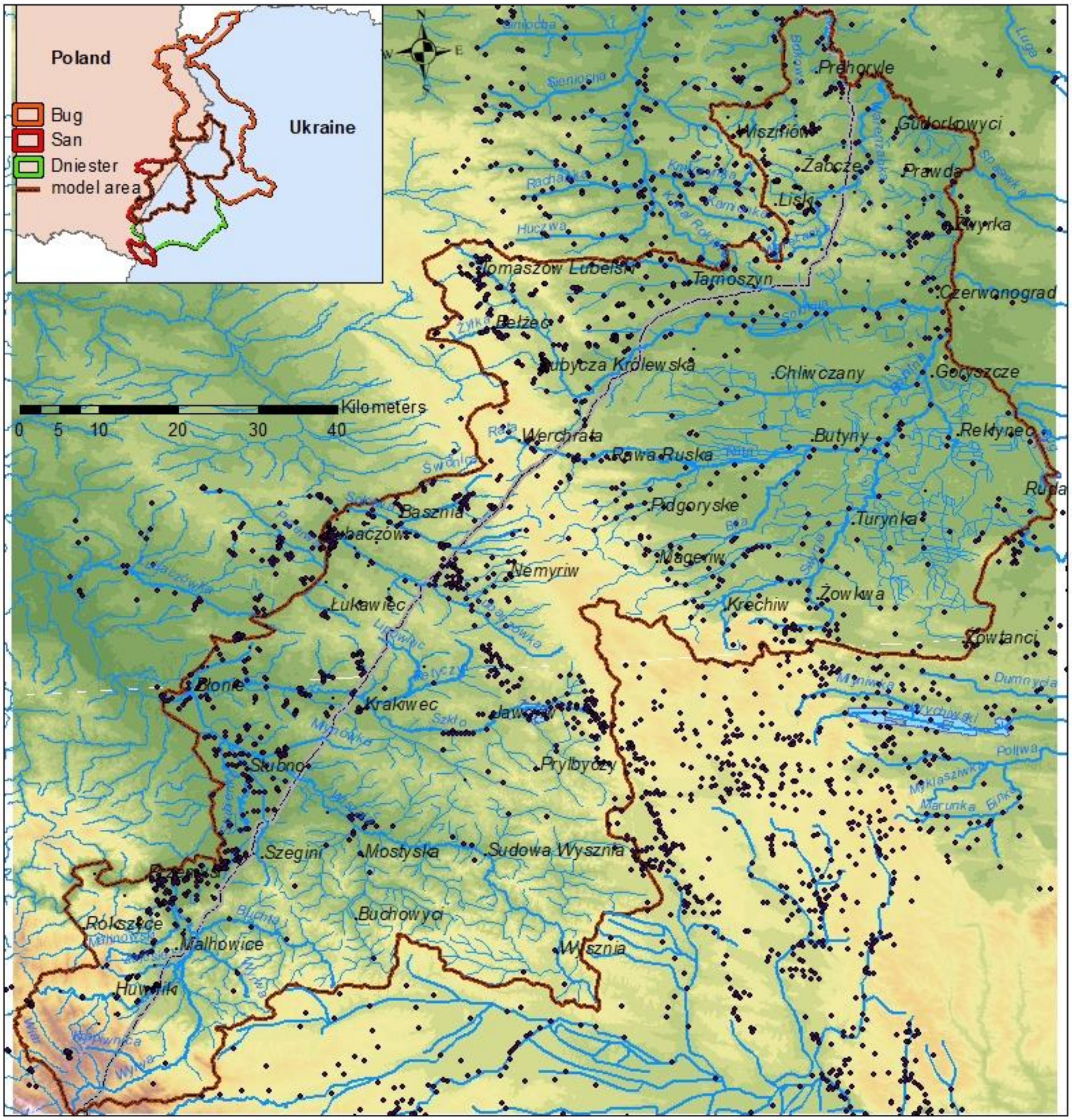

Figure 6. The location of water wells.

3.3. Numerical Model Design and Boundary Conditions

The originally assumed model boundaries within the three catchments — Bug, San, and Dniester (26,073 km^2) — were narrowed during the analysis to an area of approx. 7,150 km^2, 70% of which are in the catchment Bug and 30% are in San (Figure 1). This reduction in the area was dictated by the limitation to the area where there is a transboundary continuity of aquifers with a transmissivity of at least 50 m^2/d, which is the assumed condition for the occurrence of significant transboundary flows (Solovey et al., 2021).

There are three types of transboundary hydrogeological settings in the Polish-Ukrainian borderland. The first type (Figure 7a) is where the river that drains the aquifer in question serves as an inter-state border, in our case the Bug in the Polesie and the San in the Carpathians. In this situation, transboundary groundwater flow is impossible and joint management measures are less justified. For this reason, the northern part of the Bug catchment area and the southern, mountainous part of the San River basin were removed from the model area.

In the second and third types (Figures 7b and 7c), the hydrogeological situation is such that recharge in one country contributes to aquifer storage and eventual drainage in a neighboring country. In this situation, human activity in supply areas in one country may have negative effects on a neighboring country. Joint characterization and management are necessary in these cases, which justifies modeling the area. The complete exclusion from the model area of the Dniester catchment was dictated by the lack of aquifers of a transboundary nature.

The transformation of the conceptual model (2.5D) into a numerical model was carried out using a rectangular grid that is uniform for all layers, in which the blocks are 500-m squares. The grid consists of 264 columns and 280 lines and provides 221,760 calculation blocks for the entire model, of which 66,994 remain active.

The model was developed for a regional scale and it consists of the two computational layers described above with an unconfined and confined groundwater table remaining in hydraulic contact through semi-permeable formations. The first layer is in direct contact with surface waters. In areas lacking the first layer, the second layer is in hydraulic contact with the surface water. The aquifers within the model are recharged mainly by percolation and, locally, by infiltration of surface waters.

The geometry of the individual layers of the model and the level of the groundwater table were determined from the transboundary continuous hydrogeological cross-sections, detailing the data from archival boreholes and geological documentation. 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 about 1 km).

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

- The water-bearing layers of the model are separated by a low-permeability layer, mapped by the filtration coefficient ($T = k/m$, where k is the separation layer filtration coefficient and m is the separation layer thickness).
- The bottom of the second aquifer is tight.
- The groundwater velocity field is constant over time.
- The vertical component of the groundwater flow velocity is neglected in relation to the horizontal one.

The authors decided to model the area limited by the natural conditions of the second type (Q = 0), based on watersheds, and the third type, based on the course of surface waters (Enemark et al., 2019). Thus, the boundary of the model from the north to the east was carried out along the Bug riverbed to its source, then along the European Watershed, and then along a lower-order watershed, thus separating the border section of the San catchment in Poland. The distribution of the boundary conditions in the model blocks is presented in the Figure 8.

3.4. Source and Sink Terms

The main factors determining the hydrodynamic state of the system are water supply or extraction, treated as the source/sink term in the groundwater flow equation. In the research area the direct water recharge, river — aquifer exchange and water pumping are considered as the predominant source/sink term.

The direct water recharge depends on the rainfall, evapotranspiration and surface geological structure. The direct water recharge was calculated using the constant volume method (Laborde, 2010) on the basis of the underground outflow to the San and Bug rivers. The spatial distribution of recharge was estimated in accordance with the size of the effective infiltration coefficient for individual units of the surface geological structure. The direct water recharge values obtained in this way for the model blocks range from -2.55×10^{-5} to 9.33×10^{-4} m^3/day. This value is positive if the groundwater is being re- charged, negative if there is a withdrawal.

The river aquifer exchange was simulated using head-dependent flux conditions. These conditions were considered at the Bug, San Rivers and tributaries, and the major lakes. For the river boundary conditions, riverbed conductance values (used in Groundwater Vistas) were based on river bed sedimentary deposit properties; riverbed bottom and head of the river were obtained from DEM. Lakes and dams were simulated by a constant head condition.

The groundwater abstraction rate is considered a local sink. The amount was estimated at a yearly rate according to the registered water intake in individual intakes taken from publicly available databases (www.eu-waterres.eu/web-app). Taking into account the regional scale of the model, the total abstraction was applied uniformly for the entire computational block and individual intakes were not modeled. Groundwater abstraction was presented in the form of the type II condition (Q < 0).

3.5. Hydraulic Parameters

The initial values of the hydraulic parameters (k, T, m) of aquifer formations assigned to layers and active cells were based on the field observations deriving from the collected pumping tests (Table 1) (Marciniak et al., 1999). The spatial distribution of the hydraulic conductivity values 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 (USGS, 2010). The assumed hydraulic conductivity values were 1.3 ~ 16.0 m/day for the first layer of the model and 0.6 ~ 19.9 m/day for the second. The assigned values are summarized in Table 2.

The calibration was carried out primarily on the values of the hydraulic conductivity of the aquifers determined in the model (Table 2), as well as on the parameters of bottom sediments of surface waters (Doherty, 2015).

3.6. Calibration of the Numerical Model

During calibration, the independently estimated recharge, boundary conditions and hydraulic parameter values were adjusted to more closely match the simulated groundwater table to the observed one. The model was calibrated on the basis of data sets from 883 wells (potentiometric surface for the 2008 ~ 2021 period) and qualitative criteria. Calibration by trial-and-error was carried out by modifying the hydraulic conductivity values to fit field observations. The assessment of the accuracy of the fit between the observed and simulated groundwater levels was measured using scaled RMSE (%), which are good indicator to evaluate simulation performance.

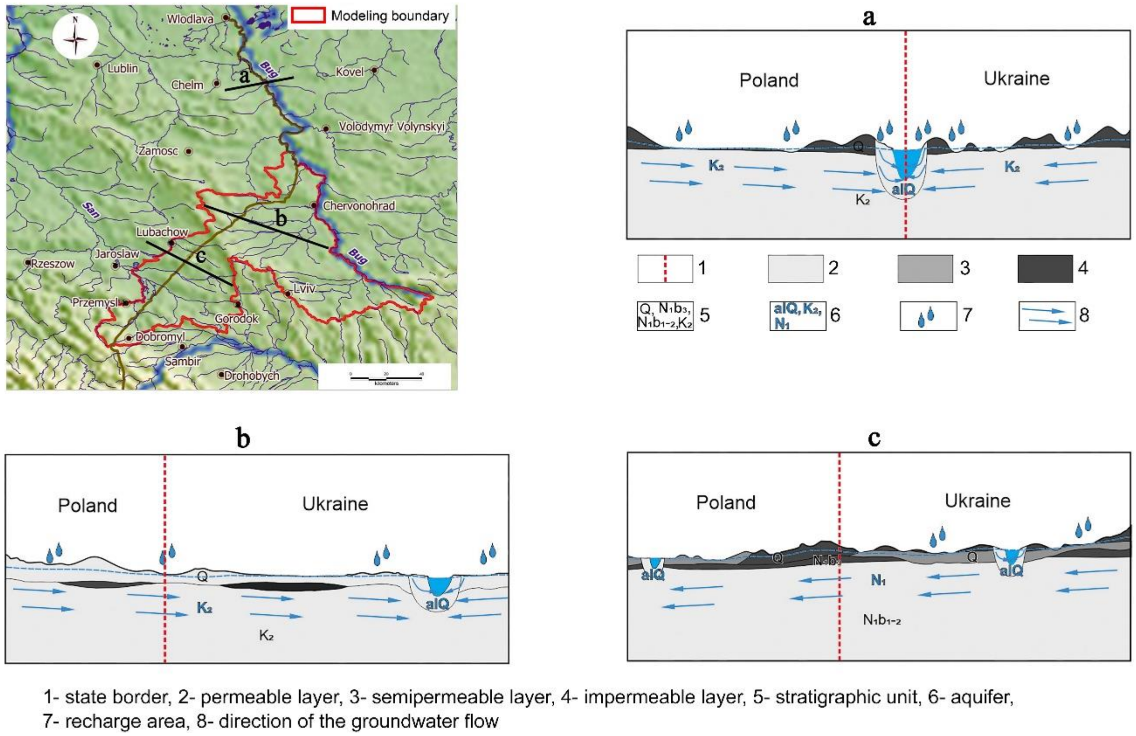

Figure 7. Types of transboundary hydrogeological settings characteristic of the study area. a) Transboundary groundwater flow is impossible; b) Recharge in Poland contributes to aquifer storage in Ukraine; c) Recharge in Ukraine contributes to aquifer storage in Poland.

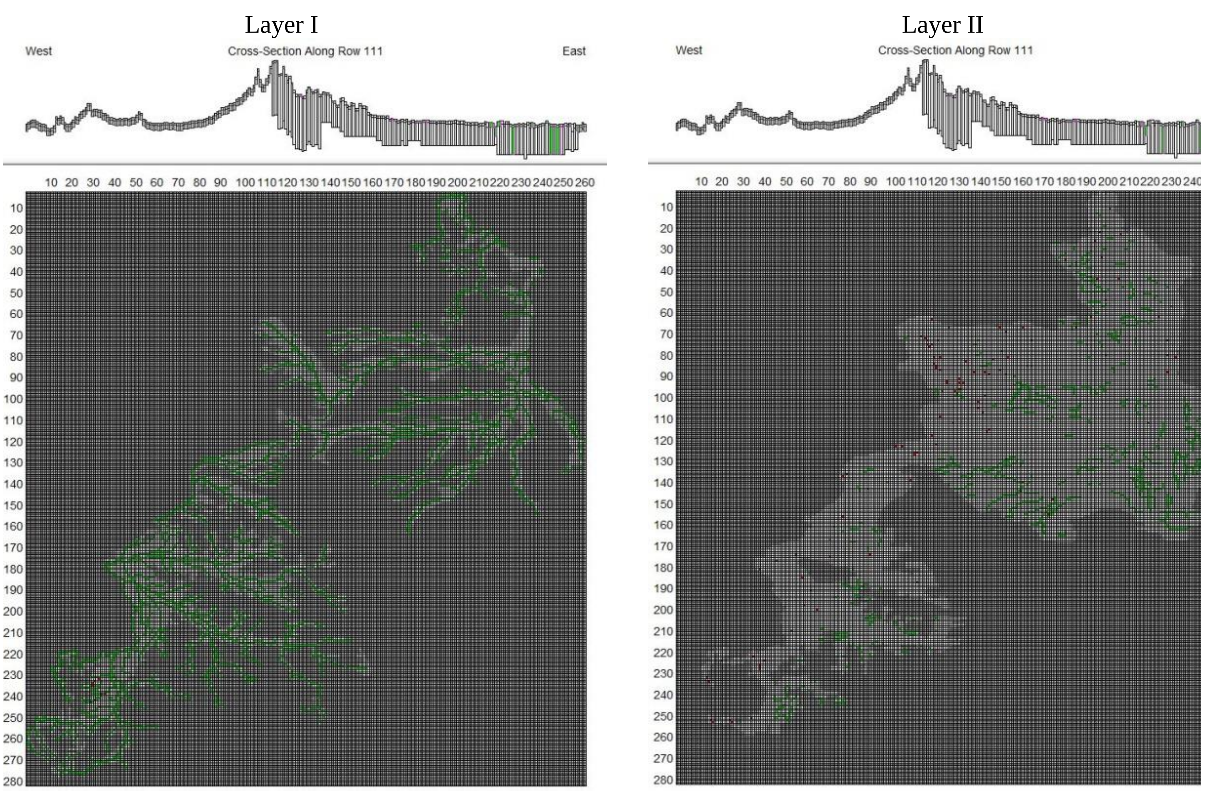

Figure 8. Model boundary conditions in modeled layers. Green color marks block with condition III (river), dark gray color marks blocks with condition II (Q = 0).

Table 1. Summary of Aquifer Formation Hydraulic Parameters; The alQ, fgQ, N_1 and K_2 Aquifers

Aquifer unit	Thickness, m	Hydraulic conductivity (k), m/h	Transmissivity (T), m^2/h
alluvial Quaternary (alQ)	2 ~ 5	0.022 ~ 1.70	1.00 ~ 20.00
fluvioglacial Quaternary (fgQ)	2 ~ 20	0.420 ~ 1.25	0.05 ~ 10.00
Lower Neogene (N_1)	10 ~ 40	0.001 ~ 0.10	0.01 ~ 4.20
Upper Cretaceous (K_2)	10 ~ 115	0.001 ~ 92.16	0.05 ~ 50.00

Table 2. Aquifer Formations; Initial Filtration Coefficient Values and Values Adopted after Calibration

Aquifer unit	Initial values, *k* (m/h)		After calibration, *k* (m/h)
	Min	Max	
alQ	0.022	1.70	0.054 ~ 0.666
K_2	0.001	92.16	0.025 ~ 0.830
N_1	0.001	0.10	0.025 ~ 0.208
fgQ	0.420	1.25	0.208 ~ 0.625

4. Results

4.1. Model Calibration

As one can conclude from Figure 9, the measured groundwater level 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. However, the generally prevailing factors limiting the credibility of the model in this area included the following:

- limited definition of the structure and hydrogeological parameters of the first aquifer;
- uneven spatial distribution of hydrogeological points;
- lack of simultaneous hydrogeological measurements at all measurement points; and
- large terrain height differences.

The criterion of model reliability is the standard deviation of the differences between field measurements and the computed groundwater levels. Final scaled RMSE was 2.8%, which is lower than the recommended threshold value of 5% (Anderson and Woessner, 1992).

4.2. Water Balance and Simulation of Groundwater Abstraction Scenarios

Based on the steady-state model, a simulation of hydrodynamic conditions was performed for three scenarios:

- Scenario I — natural conditions without the exploitation of groundwater;
- Scenario II — with the exploitation of groundwater while pumping all currently operating intakes at an average level from the period 2018 ~ 2021 (Figure 10, Tables 3 and 4); and
- Scenario III — in terms of groundwater abstraction from all currently active intakes in the amount of exploitable resources (Figure 11, Tables 3 and 4). Thus, this scenario considers the maximum permissible exploitation rate.

The data on allowable and actual annual water abstraction in the two countries are publicly available on the EU-Waterres geoportal (https://eu-waterres.eu/web-app). The elevation of hydraulic head in the main exploitation aquifer (MEA) in the study area within the Bug catchment is calculated at ~290 m a.s.l. — in Roztocze in the recharge zone, descending towards the valley of the Bug River to 169 ~ 200 m a.s.l. (Figure 12). In the San catchment, apart from Roztocze, the recharge area is also located in the Carpathians, which covers the southern part

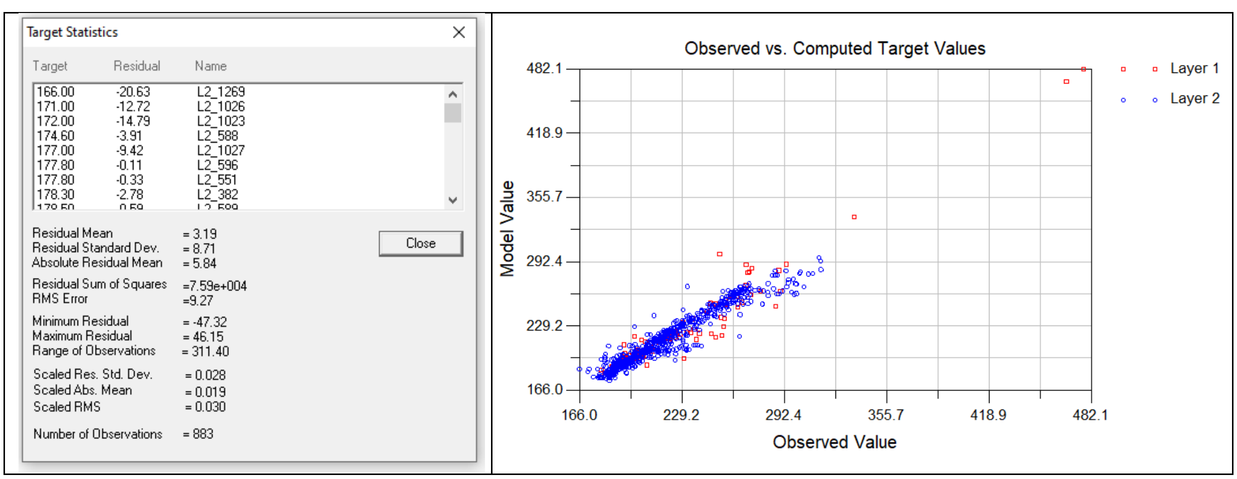

Figure 9. Observed vs. calculated groundwater tables.

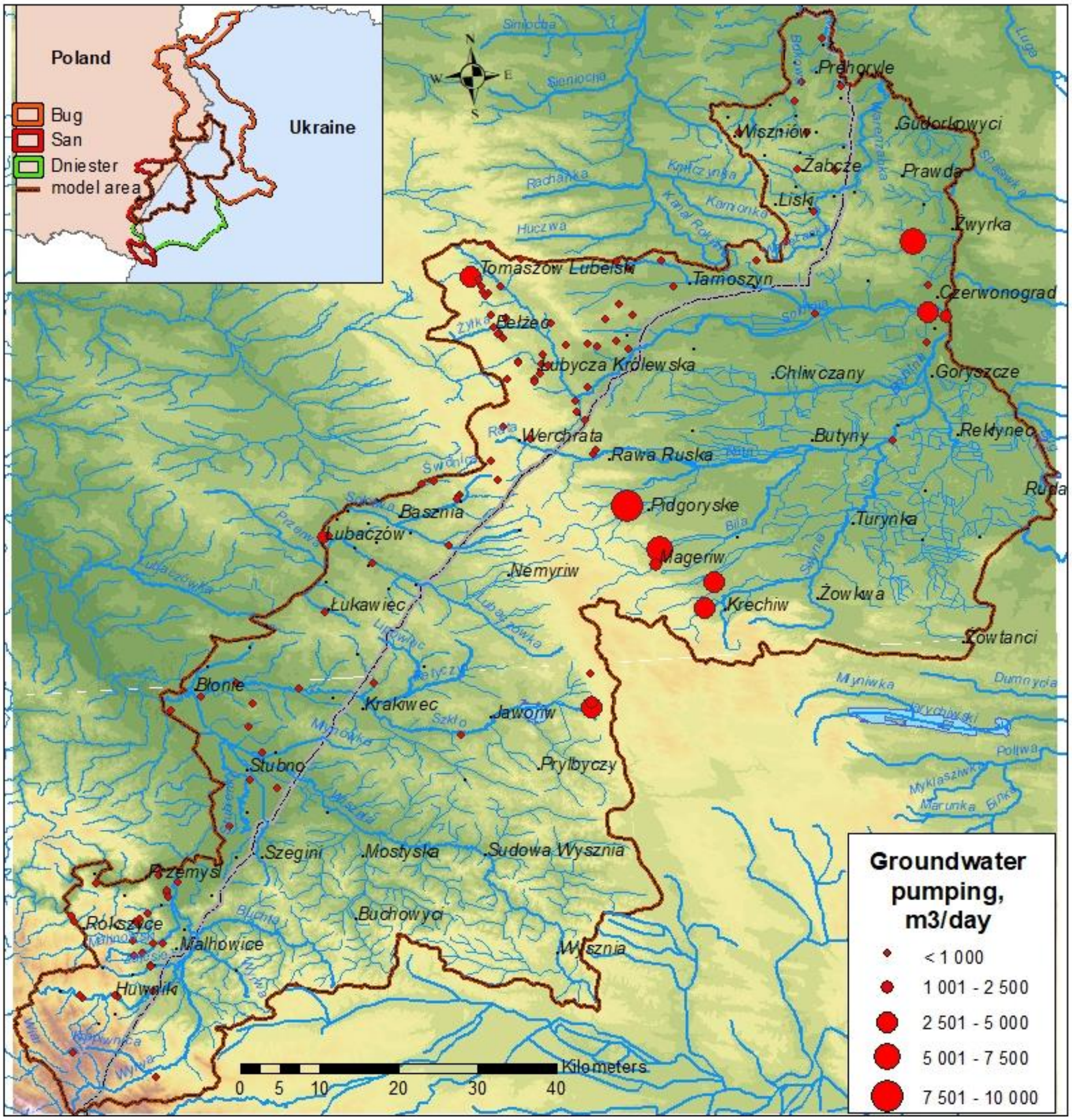

Figure 10. Average daily groundwater pumping in the operating intakes, 2018 ~ 2021 (Scenario II).

of the study area. In this area, the elevation of hydraulic head in the MEA reaches its maximum values of ~506 m a.s.l., descending towards the valley of the San River to 180 m a.s.l.

The steady-state calibrated model was used to simulate the decrease in the elevation of hydraulic head in the MEA caused by the current (Scenario II) and the maximum allowable (Scenario III) levels of groundwater exploitation compared to natural conditions. In the case of Scenario II, due to the exploitation of the currently operating intakes at the average level from the last four years, a regional decrease in the elevation of the hydraulic head in the MEA was simulated, from 1 to 25 m (Figure 13a).

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/day. With this level of exploitation, no decrease in the groundwater table is observed on the scale noticeable in the regional model. Only the group of intakes in the Tomaszów Lubelski area, with a total groundwater extraction of approx. 4,000 m^3/day, creates a depression cone with a maximum local lowering of the groundwater table by 3 m.

In the Ukrainian part, groundwater consumption is concentrated in large municipal intakes with the dominance of unreg-

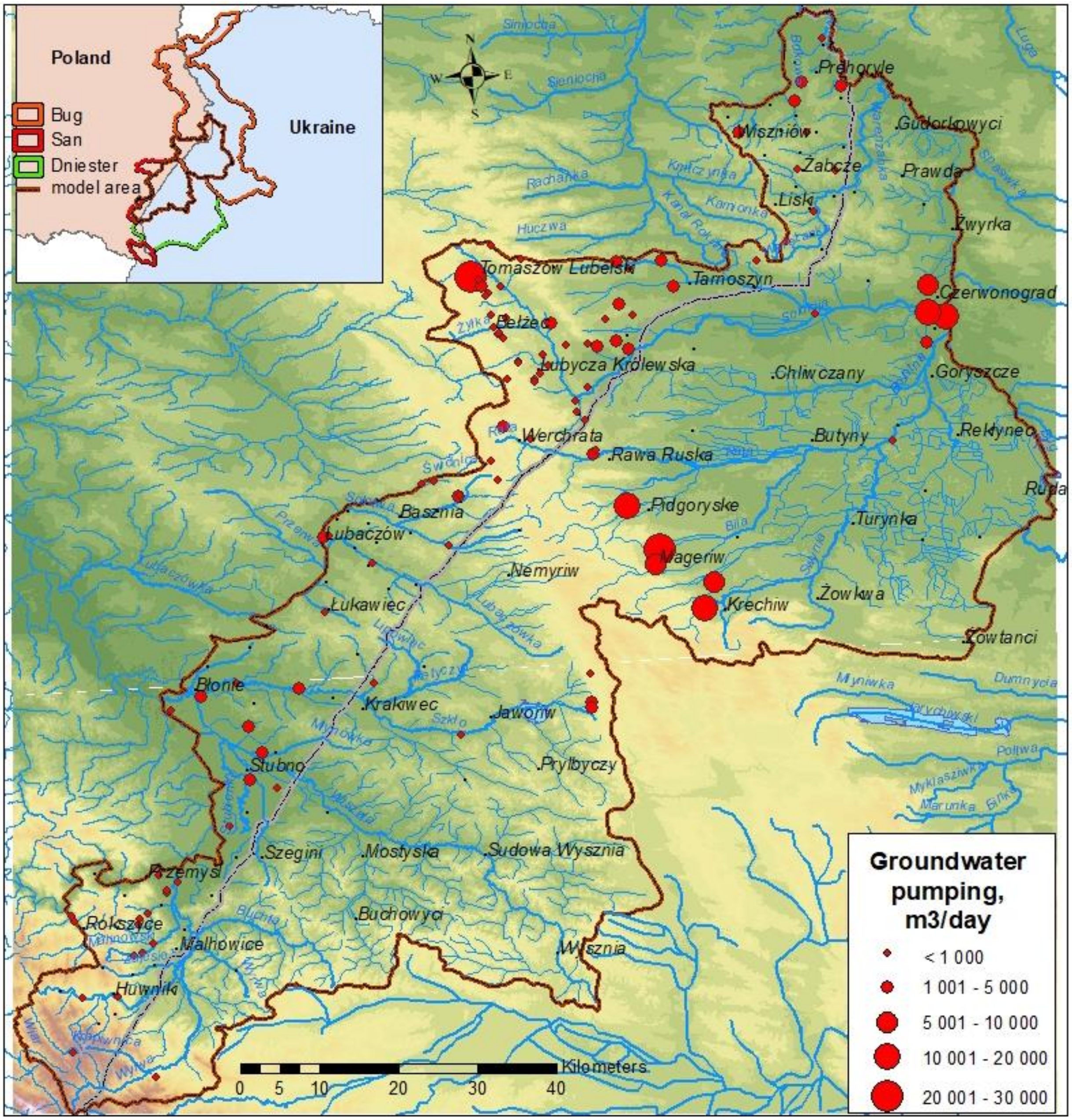

Figure 11. Maximum allowable groundwater pumping for operating intakes (Scenario III).

istered consumption from individual wells. The highest local decreases (5 ~ 25 m) were found around municipal intakes that consume over 5,000 m^3/day. These intakes are located in the Bug catchment area, and supply the Lviv agglomeration with drinking water. Moreover, for the entire study area, it was established that the nature of the depression cone depends on the location of the intake in the hydrodynamic system. In the recharge zones, the decrease was 6 to 8 times higher than in the drainage zone, with similar amounts of consumption at the level of 5,000 ~ 8,000 m^3/day. At the present level of exploitation, no drowdown cones have ranges that exceed the state border.

In the case of Scenario III, presenting the maximum permissible level of groundwater abstraction (Figure 13b), greater decreases (up to 100 m) and larger drowdown cones are possible, including those related to transboundary impacts. This may indicate that the maximum allowable exploitation resources of some intakes were specified too high.

In Poland, almost 75% of the intakes in the study area (Figure 11) are characterized by a relatively low permissible level of groundwater exploitation (generally below 2,000 m^3/day). In the remaining 25% of intakes, the exploitation is as high as 5,000 m^3/day. Only the intake in Tomaszów Lubelski reaches approx. 23,000 m^3/day. In Ukraine the exploitation is usually slightly higher than in Poland due to the predominance of large

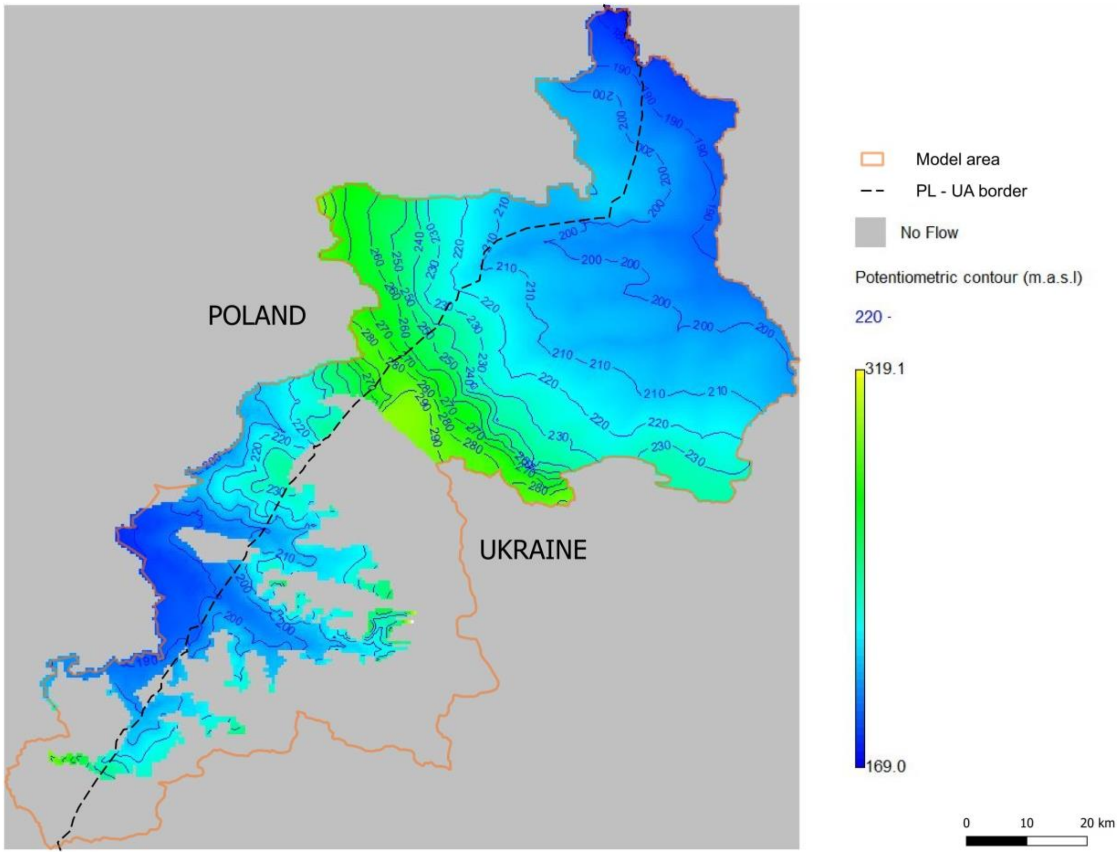

Figure 12. Hydraulic head contour lines of the main exploitation aquifer (Layer 2) for the current state (Scenario II - Average daily consumption of groundwater in the operating intakes, 2018 ~ 2021).

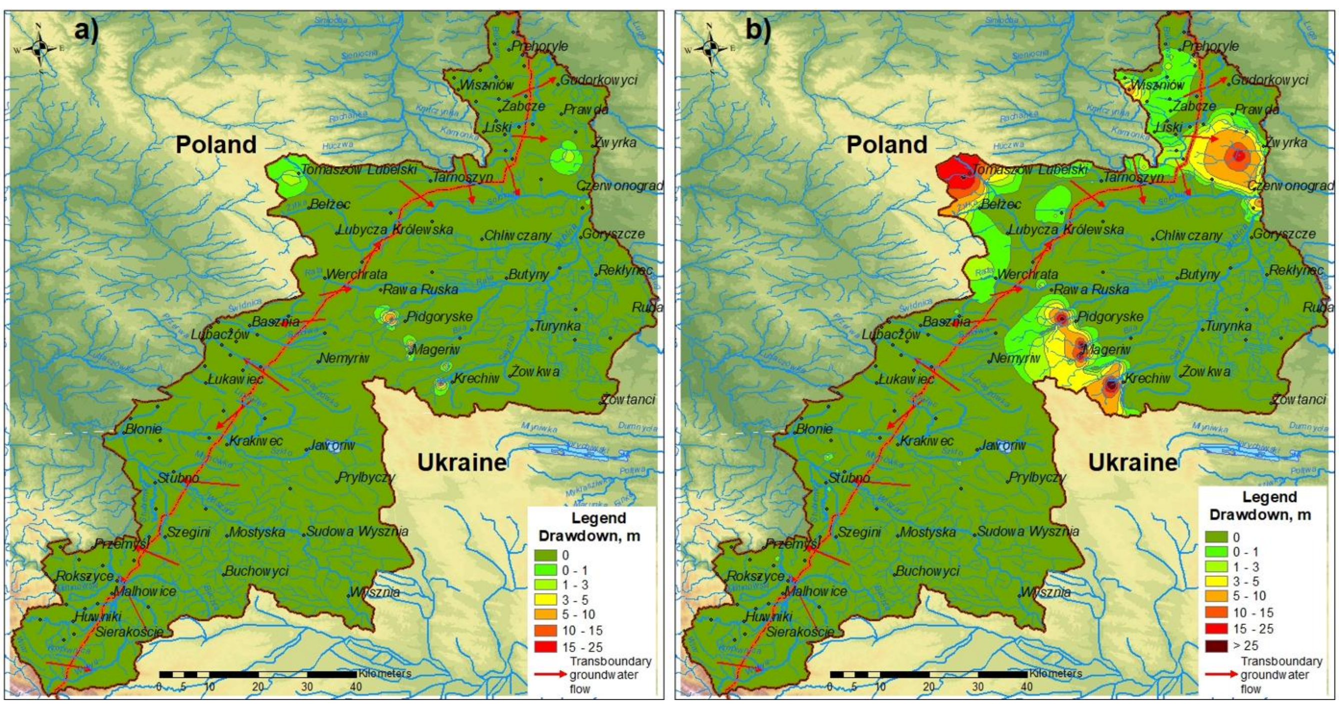

Figure 13. Simulated drawdown (m) in the Bug–San MEA caused by two exploitation scenarios: a) - Scenario II (current exploitation) and b) - Scenario III (maximum permitted exploitation).

Table 3. The Groundwater Flow Balance for Bug River

Balance component		Scenario I [m^3/day]	Scenario II [m^3/day]	Scenario III [m^3/day]
Inflow	Rainwater infiltration:	(661.404)	(661.404)	(661.404)
	in Poland	151.309	151.309	151.309
	in Ukraine	510.095	510.095	510.095
	Surface water infiltration:	(74.812)	(83.566)	(153.136)
	in Poland	18.668	19.416	34.359
	in Ukraine	56.144	64.150	118.777
	Lateral inflow:	(56.558)	(56.708)	(56.913)
	in Poland	33.583	33.721	33.658
	in Ukraine	22.975	22.987	23.255
	Total inflow	**792.774**	**801.678**	**871.453**
Outflow	Evapotranspiration:	(6.536)	(6.536)	(6.536)
	in Poland	721	721	721
	in Ukraine	5.815	5.815	5.815
	Drainage through river:	(737.982)	(706.119)	(613.931)
	in Poland	147.967	142.664	102.530
	in Ukraine	590.015	563.455	511.401
	Groundwater extraction:	(0)	(40.717)	(203.392)
	in Poland	0	5.833	61.042
	in Ukraine	0	34.884	142.350
	Lateral outflow:	(48.263)	(48.309)	(47.611)
	in Poland	12.837	12.750	12.090
	in Ukraine	35.426	35.559	35.521
	Total outflow	**792.781**	**801.681**	**871.470**

Table 4. The Groundwater Flow Balance for San River

Balance component		Scenario I [m^3/h]	Scenario II [m^3/h]	Scenario III [m^3/h]
Inflow	Rainwater infiltration:	(732.098)	(732.098)	(732.098)
	in Poland	396.300	396.300	396.300
	in Ukraine	335.798	335.798	335.798
	Surface water infiltration:	(76.500)	(78.457)	(84.363)
	in Poland	57.279	59.143	64.956
	in Ukraine	19.221	19.314	19.407
	Lateral inflow:	(29.371)	(29.357)	(29.107)
	in Poland	10.495	10.487	10.132
	in Ukraine	18.876	18.870	18.975
	Total inflow	**837.969**	**839.912**	**845.568**
Outflow	Evapotranspiration:	(4.950)	(4.950)	(4.950)
	in Poland	880	880	880
	in Ukraine	4.070	4.070	4.070
	Drainage through river:	(795.361)	(791.897)	(781.231)
	in Poland	460.003	456.897	447.231
	in Ukraine	335.358	335.000	334.000
	Groundwater extraction:	(0)	(5.315)	(20.977)
	in Poland	0	4.967	20.177
	in Ukraine	0	348	800
	Lateral outflow:	(37.666)	(37.757)	(38.409)
	in Poland	17.248	17.248	17.341
	in Ukraine	20.418	20.509	21.068
	Total outflow	**837.977**	**839.919**	**845.567**

municipal intakes in water supply system. In 65% of the intakes, this constitutes over 1,000 m^3/day, and in 30% over 10,000 m^3/day is consumed (Figure 11). The connection of individual drowdown cones and a cumulative effect can be observed here. Two large drowdown cones of a cross-border nature will form in the Bug catchment area — in the northern part in the Chervonograd-Sokal agglomeration area (5 ~ 25 m) and in the central part, the combined cones of the Lviv agglomeration intakes (maximum decrease: 100 m).

With this level of exploitation, the drowdown cones can cover almost a half of the study area within the Bug catchment.

The local decrease of the groundwater table in most cases will not exceed 1 ~ 3 m, but locally in the areas of the intakes with an acceptable level of exploitation of 2,000 ~ 5,000 m^3/day, the maximum decrease can reach 10 m and around the largest intakes it may be 25 m. In the San catchment, only a few intakes with approved consumption of approx. 2,000 ~ 4,000 m^3/day will generate local drowdown cones with a maximum decrease of up to 5 m. Drowdown cones can of course be much higher.

Scenario III shows that the determination of exploitable groundwater resources for some intakes located within the TBAs was carried out without considering the hydrodynamic conditions and water abstraction outside the country. The model simulations (Figure 13b) show that in the northern part of the study area, an extensive and cross-border drowdown cones (with a decrease of 5 ~ 25 m) may develop. In this situation, the intakes on the Polish side may be within the reach of the depression cone of the Chervonograd-Sokal agglomeration, which would increase the depression by another 3 m.

Based on model studies, it was established that under natural conditions, groundwater resources in the border part of the Bug catchment area (Scenario I, Table 3) are formed as a result of the infiltration of atmospheric precipitation (74.3% in Poland; 86.6% in Ukraine), the infiltration of surface waters (9.2% in Poland; 9.5% in Ukraine), and the inflow of groundwater from abroad and from the San basin (16.5% in Poland; 3.9% to Ukraine). Groundwater outflow from the aquifer mainly results from drainage by surface waters (91.6% in Poland; 93.5% in Ukraine), with a negligible role of evapotranspiration (0.5% in Poland; 0.9% in Ukraine) or the outflow of groundwater abroad and to the San basin (7.9% in Poland; 5.6% in Ukraine).

In the border part of the San catchment, under natural conditions (Scenario I, Table 4), groundwater resources are formed because of the infiltration of atmospheric precipitation (85.4% in Poland; 89.8% in Ukraine), the infiltration of surface waters (12.3% in Poland; 5.1% in Ukraine), and the inflow of groundwater from abroad and from the Bug catchment area (2.3% in Poland; 5.1% to Ukraine). Among the components of groundwater runoff, similarly to the Bug catchment area, drainage by surface waters prevails (96.2% in Poland; 93.2% in Ukraine).

For the entire flow system in the water balance, during the exploitation of groundwater (Scenarios II and III, Tables 3 and 4), a decrease in groundwater runoff to rivers and the effect of surface water infiltration into the aquifer compensating for the extraction can be observed. The other components of the budget do not change significantly during groundwater exploitation.

At the current level of groundwater exploitation in the border region of the Bug catchment (Scenario II, Table 3), the total Polish-Ukrainian groundwater extraction (at the level of 40,717 m^3/day) causes a slight increase (approx. 8,900 m^3/day) of the inflow component of the balance by increasing the infiltration of surface water into the aquifer. This is the result of the numerical model consistent with the assumption of the type III condition in calculating blocks, which are the segment of the aquifer edge touching the river bed (Michalak et al., 2011). In the outflow part of the balance sheet, well exploitation plays a minor role in total water runoff (5.08%) and is negligible (622%) compared to the amount of rainwater infiltration. Currently, almost 86% of groundwater abstraction is concentrated in the Ukrainian part of the study area of the Bug catchment.

In the border region of the San catchment, the current level of groundwater exploitation (Scenario II, Table 4) is 5,315 m^3/day, which is 9 times lower than in the Bug catchment. It mainly (94%) involves the Polish part of the San catchment. As a result, the infiltration of surface waters into the aquifer slightly increases (approx. 2,000 m^3/day), and the outflow of groundwater to rivers decreases (approx. 3,500 m^3/day).

In Scenario III (Tables 3 and 4), addressing the peak levels of exploitation, the infiltration of surface waters to the aquifer in the Bug basin more than doubles and is about 10% higher in the San basin. Moreover, the outflow of groundwater to rivers decreases by 3.3 and 20% in the catchment areas of the San and Bug rivers, respectively, compared to the natural state.

4.3. Transboundary Groundwater Flows

The variants of the simulation show that with the current level of exploitation (Scenario II), the transboundary groundwater flow is similar to natural conditions (Scenario I). In particular, the total groundwater runoff from Poland to Ukraine is 42,350 m^3/day, 78% of which is in the catchment area of the Bug and 22% of which is in the San catchment (Figure 14). On the other hand, the inflow to Poland from Ukraine amounts to 27,924 m^3/day, of which 58% concerns the Bug catchment area, and 42% the San River.

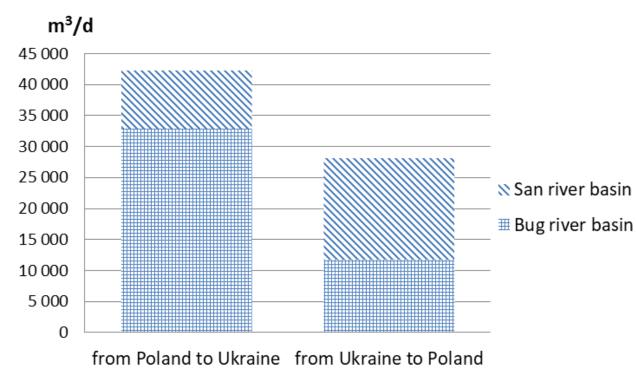

Figure 14. Transboundary groundwater flow (Scenario II).

As shown in Figure 14, the total outflow of groundwater from Poland to Ukraine is 1.5 times greater than in the opposite direction (Scenario II). In the division into catchment areas, it was found that the outflow of groundwater from Poland to Ukraine is more important in the catchment area of the Bug than in that of the San, especially in forming the resources of the Bug River in the upper section and those of the Lublin-Lviv aquifer system in Ukraine. The inflow here occurs through the Upper Cretaceous aquifer, and also in the valleys of the Rata and Solokiia Rivers, left-bank tributaries of the Bug. An additional role is played by the alluvial aquifer. In the border part of the San basin, the transboundary exchange of groundwater is almost half that of the Bug basin. The groundwater flows occur through the Lower Neogene fractured/porous aquifer, as well as in the valleys of the Szklo and Wisznia Rivers, the right-bank tributaries of the San; an additional role is played by the alluvial aquifer.

5. Discussion

5.1. Model Limitations

The numerical model has numerous conditions, limitations, and sources of uncertainty. First, it must be considered that it is based on the assumption that the hydrodynamic system remains static. Therefore, it is useful for simulating the effects of individual exploitation scenarios, but it does not help to determine the dynamics of process development or the time required to achieve a state of equilibrium (Pétré et al., 2019). Another limitation is the regional scale of the model, which stems from the level of generalization and simplification of the actual aquifer. Regional models are created to show the trend of changes and to initially estimate them, not to precisely calculate their size, which is the task of local models (Doherty and Simmons, 2013). When translated into water resource management, regional models are effective in strategic planning to consider the nature of restrictions, though local models should be used in setting limits. On the other hand, the uncertainty of hydrogeological data as well as the scope and incompatibility of databases in neighboring countries also impose certain limitations. The main source of uncertainty in hydrogeological data is the uneven coverage of the area with hydrogeological sites, which results in conclusions about the geometry and parameters of the aquifer that are based solely on extrapolation (though this is still a significant improvement over extrapolation of data towards the boundary in one-sided studies). This applies to both countries in the southern part of the model area — the Carpathians — where due to the few boreholes and the mountainous nature of the terrain, the interpretation of geological and hydrogeological conditions is less credible. Significant elevation differences affect such important data as the ordinate of the borehole, which in turn translates into errors in the ordinates of tops, bottoms, and water tables. Minor localization errors of wells documented before the era of GPS locators and numerical terrain models can result in elevation changes of tens of meters. On the other hand, in the Carpathian Foredeep part of the San catchment in Poland, the Lower Neogene aquifer is poorly recognized in terms of hydrogeology, while on the Ukrainian side it has a high abundance and is well recognized. Therefore, the extent of the aquifer unnaturally ends at the state border. As a result, errors related to poor recognition of the aquifers' structure are reflected in the groundwater flow model. It can certainly be stated that in the San catchment area, this fact explains the tendency to underestimate the simulated groundwater flows in its pre-mountain and mountain parts. Additional uncertainty of the hydrogeological data is caused by the lack of simultaneous measurements in all reference sites and errors in the ordinates in archived well data.

5.2. Regional Groundwater Flow Dynamics

The presented model uses the conceptual assumption of the water budget (Tóth, 2009). The conducted analysis uses many components of the water budget (Michalak et al., 2011) and adds new scenarios of the predictable demand for groundwater. The simulation results of the water budget model indicate that groundwater abstraction will have the greatest negative impact on the flows of the Bug River. The outflow of groundwater to the river at the current level of exploitation decreased compared to the natural state by approx. 4% against the background of an increase in surface water losses on infiltration through the river bed — by 11%. In fact, the situation is worse due to the unknown amount of unregistered abstraction. Importantly, the exploitation of groundwater at the current level does not result in interstate capture of resources and the emergence of transboundary drowdown cones, but there are noticeable effects of impacts on transboundary groundwater flow. Exploitation increased (by +0.4%) the outflow of groundwater from Poland to Ukraine and decreased the inflow to Poland (by −0.7%). The greatest uncertainty in this study was caused by taking into account groundwater abstraction at the maximum permissible level. In fact, this scenario is unlikely because there is no situation where all the intakes are pumping at this level at the same time. This analysis provides important information on the extent of transboundary drowdown cones and regional declines in groundwater levels in TBAs, which should be taken into account primarily by the authority issuing water permits for the use of groundwater (Jakeman et al., 2016). Our results indicate that permits are revalued because the input data used for the maximum abstraction calculation did not take into account information on the other side of the border.

5.3. Implications for Groundwater Management

The modeling results have important implications for the integrated management of transboundary groundwater resources. The simulated groundwater flow across the Polish-Ukrainian border demonstrates the transboundary nature of the Bug-San aquifer system. It therefore seems appropriate to consider joint management between Poland and Ukraine, especially since the Polish-Ukrainian Commission on Border Waters has declared this issue a priority. Nevertheless, in previous reports to the Commission under the Water Convention, Poland did not report the presence of TBAs and Ukraine has reported inappropriate aquifers (UNECE, 2020a, 2020b, 2020c). Moreover, when analyzing the protocols of the Polish-Ukrainian Commission on border waters, it can be stated that the issues related to groundwater are almost completely ignored (UNECE, 2018a, 2018b). Therefore, the discussion of the results of this study in the context of the integrated Polish-Ukrainian management of transboundary groundwater resources is a call for a broader discussion on the topic at hand.

There is no trade water right in Poland and Ukraine. The only legal document where the groundwater extraction limit is registered is the water permit. The user may not transfer or sell the excess allocated water resources to other users, although he has paid for the reservation of water in accordance with the limit. This issue is neglected because there is no shortage of groundwater resources in the Polish-Ukrainian border area and there is no incentive to use the trade water rights to solve cross-border water conflicts. Our simulations show the likelihood of conflicts when all users start using the allowed limits. It is recommended to create a joint Polish-Ukrainian platform for the coordination of water permits, as the conducted research confirmed the impact of groundwater exploitation on the neighboring country's water resources. Considering the fact that Ukraine is in a disadvantageous situation in the Bug sub-basin, because it is located in the lower reaches of the river, and in the San sub-basin the situation is the opposite, both countries are motivated to implement the water rights system. The concept of interstate trade in water rights would include compensation for the downstream state for excess water used in the upstream state.

5.4. Delineation of Transboundary Groundwater Bodies

Based on the model, the following considerations arise:

- defining spatial units — transboundary groundwater bodies (TGWB) — for the integrated management of groundwater resources; and
- designing a representative groundwater monitoring network to assess transboundary impacts.

Relevant units for cross-border management would be as follows (Figure 15):

- Bug TGWB — the northern part of the model area within the Bug catchment, and
- San TGWB — the southern part of the model area within the San catchment.

The division of this area into two separate TGWB is justified by different hydrogeological conditions, which is reflected in the state of the aquifer system assessed on the basis of the numerical model.

In the Bug TGWB, the main aquifer is the Upper Cretaceous aquifer, which is commonly found to be mostly uninsulated from the surface. The locally occurring alluvial Quaternary aquifer

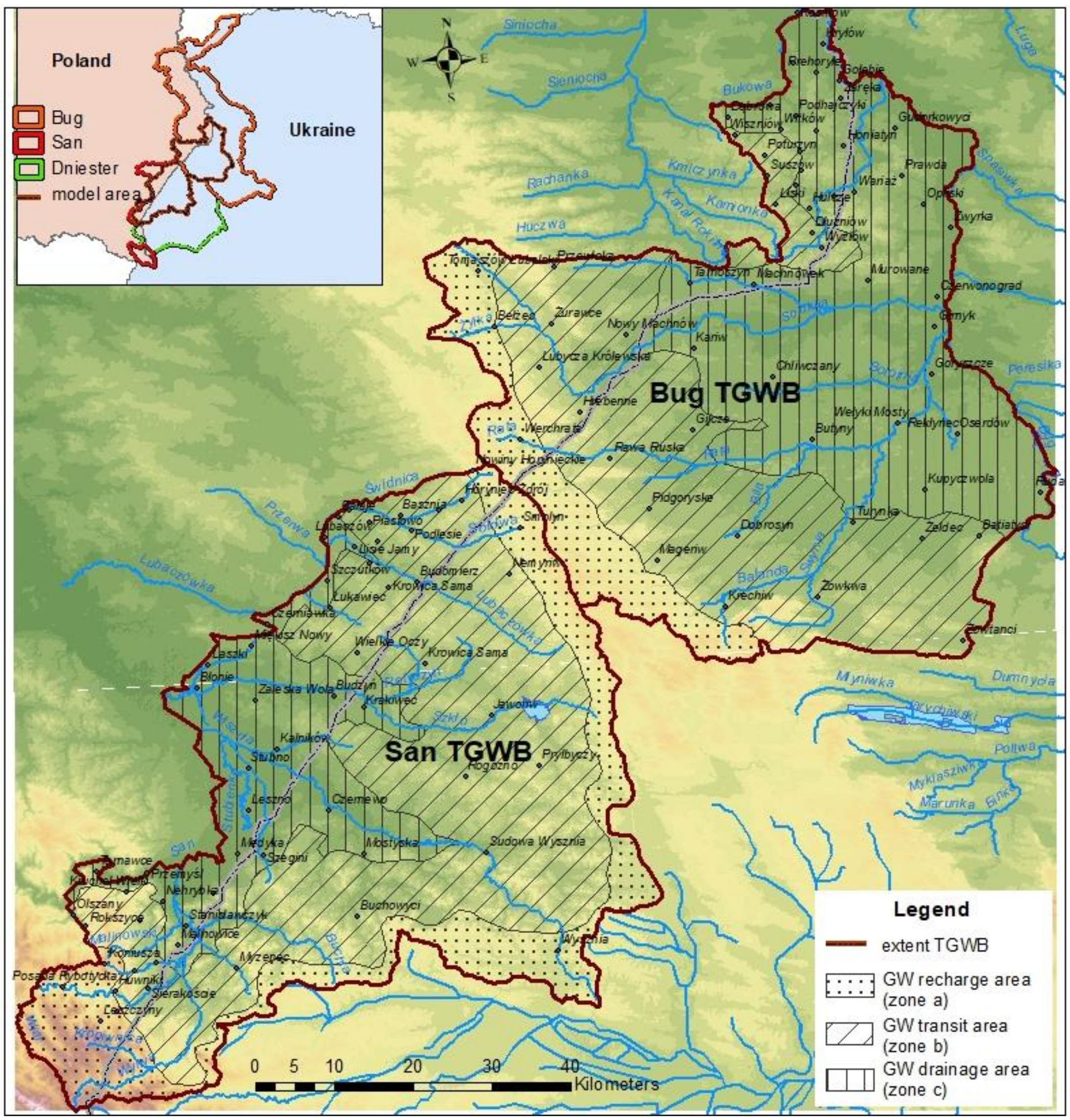

Figure 15. Range proposal of Polish–Ukrainian transboundary groundwater bodies.

plays a secondary role in the valleys of cross-border rivers.

In San TGWB, it should be considered that almost half of the area is devoid of the aquifer. Its presence is confirmed in the northern part of the TGWB within the Roztocze highlands and in larger river valleys. In Roztocze, the main aquifer is the Miocene aquifer isolated from the surface. On the other hand, alluvial Quaternary aquifer should be considered in the valleys of cross-border rivers.

The structure of the aquifer adopted in the model allows the vertical structure of the TGWB to be determined and the simulation allows the determination of the relationship between the aquifer and water-dependent ecosystems and surface waters. For both TGWBs in the valleys of the above-mentioned rivers, the two-layer vertical structure of the TGWB should be considered. In other areas, a single layer or no useable layers should be considered.

Numerical simulations have proven that the extensive wetlands in the Bug TGWB are dependent on groundwater and are particularly related to the alluvial Quaternary aquifer, which should be considered when allocating resources among users. In turn, in both TGWBs it was found that the connection with surface waters, apart from the drainage character, can locally be of infiltration character. Therefore, exploitation of groundwater significantly increases the infiltration of the river and can result in possible decreased river flow.

5.5. Implications for Transboundary Monitoring Network

The simulation of the regional groundwater system allows for the design of an effective monitoring network to control the transboundary impacts on the state of groundwater. Based on the model, certain criteria can be formulated:

- the location of groundwater and surface water monitoring points, as well as groundwater-dependent ecosystem observation points, which will capture the transboundary impact of intake exploitation;
- the design of a research well (point) to ensure its functionality at the predicted depression level in the water table;
- the assessment of the representativeness of the groundwater monitoring point by identifying the area of groundwater inflow to this point; and
- the optimization of the sampling frequency in relation to the water flow velocity in a given area.

6. Conclusions

Numerical modeling of groundwater flow is one of the most important tools in assessing transboundary water exchange. Simulations provide information about the size, speed, and direction of the flow depending on the input data and constraints and they can be useful for the protection of these valuable natural resources. Despite the presence of TBAs on the Polish-Ukrainian border, to date, no common hydrodynamic models have been developed and no harmonization of hydrogeological data has been carried out. This study is the first attempt to determine the quantity and spatial extent of the regional system of cross-border flows between Poland and Ukraine. The results show that the transboundary groundwater flow takes place on a limited section of the interstate border — from where the Bug River ceases to be a border river and turns eastward to where the border enters the mountainous region of the Outer Carpathians, through the San catchment. This flow occurs in four main transboundary layers: 1) a porous alluvial (alQ) aquifer, 2) a fractured Upper Cretaceous (K_2) aquifer, 3) a fractured/porous Lower Neogene (N_1) aquifer, and 4) a porous Quaternary fluvioglacial (fgQ) aquifer. The amount of flow from Poland to Ukraine is over 1.5 times higher than that in the opposite direction. The current level of groundwater exploitation does not significantly change the natural conditions. On the other hand, when the maximum permissible amounts of groundwater abstraction are reached, the calculations show a reduction in groundwater runoff to transboundary rivers and the compensation effect of surface water infiltration into the aquifer. In addition, it will create cones of depression with a cross-border effect. The characterization of the water circulation regime based on the model should be the starting point when defining the spatial units for integrated management of groundwater resources, designing a transboundary monitoring network, and establishing the conditions for the sustainable exploitation of TBAs In summary, the creation of the first joint Polish-Ukrainian model of groundwater flow provides important information on (1) the structure and formation of resources of the TBAs, (2) possible quantitative changes caused by groundwater exploitation, (3) the spatial extent of transboundary impacts, and (4) the conditions necessary for the sustainable exploitation of TBAs and the monitoring of transboundary impacts. It should be emphasized here that this is only the first, preliminary stage of model research and that the next steps should include a detailed analysis of the sensitive areas and sites to examine the impact of specific scenarios on the development of the hydrodynamic situation over time.

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