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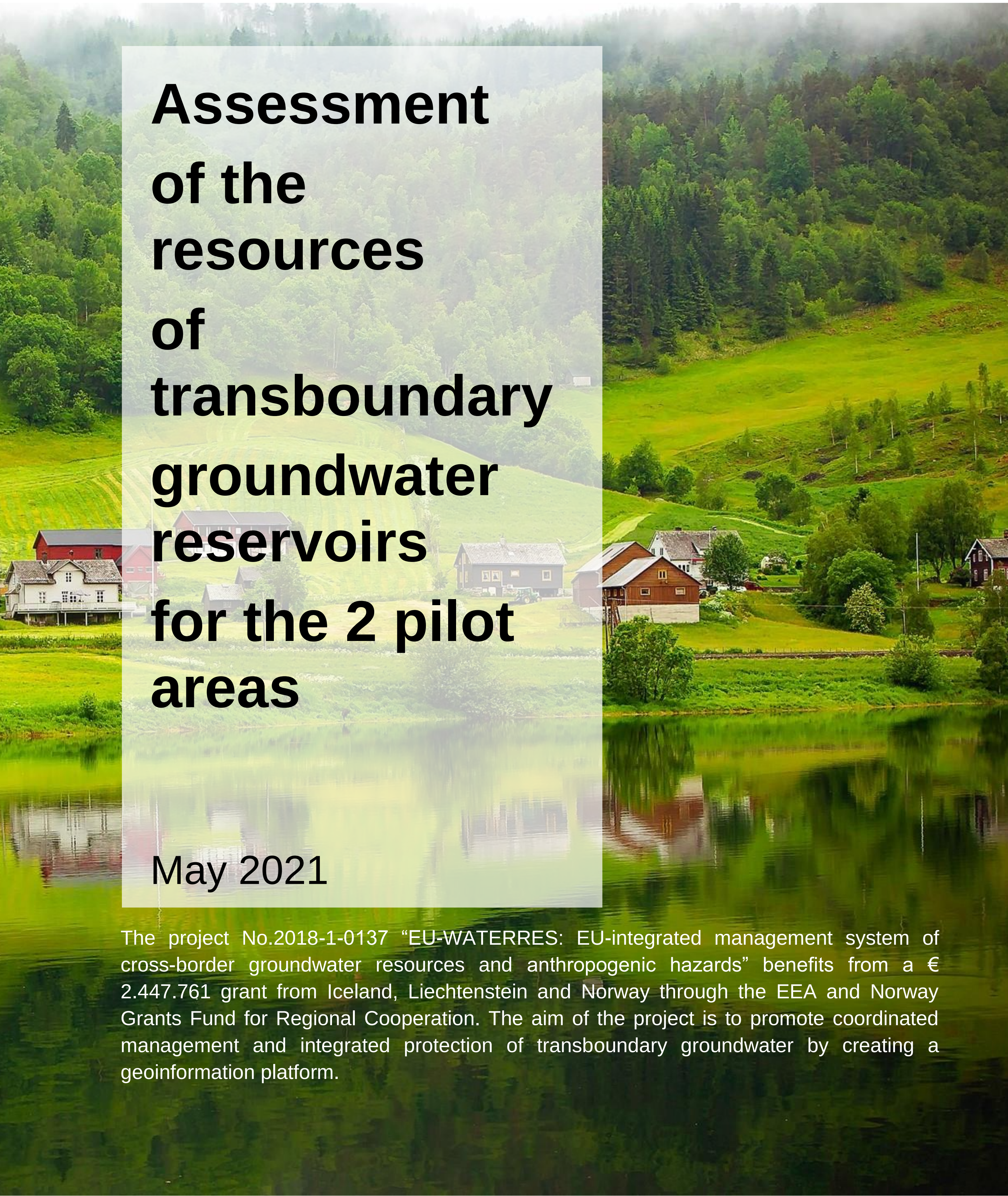

Assessment of the resources of transboundary groundwater reservoirs for the 2 pilot areas

May 2021

The project No.2018-1-0137 “EU-WATERRES: EU-integrated management system of cross-border groundwater resources and anthropogenic hazards” benefits from a € 2.447.761 grant from Iceland, Liechtenstein and Norway through the EEA and Norway Grants Fund for Regional Cooperation. The aim of the project is to promote coordinated management and integrated protection of transboundary groundwater by creating a geoinformation platform.

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Document summary

The aim of the document is to create a conceptual understanding of the hydrogeological processes and flow dynamics across the national borders in two different pilot territories - Polish-Ukrainian and Latvian-Estonian border area. Within the framework of this report, assessment of transboundary groundwater resources, as well as the determination of groundwater flow volumes across the state borders has been carried out. The report has been developed by seven project partners: Polish Geological Institute - National Research Institute, Latvian Environment, Geology and Meteorology Centre, University of Latvia, State Enterprise "Ukrainian Geological Company", Geological Survey of Estonia, The Institute of Geology and Geochemistry of Combustible Minerals of National Academy of Sciences of Ukraine and DC of NJSC "NADRA UKRAJYNY" "Zahidukrgeologiya".

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Abbreviations

BAB – Baltic Artesian Basin

DEM – Digital elevation model

EEA - European Economic Area

EU – European Union

GWB – Groundwater Body

IGRAC – International Groundwater Resources Assessment Center

IHF – International Hydrological Programme

INPIRE – Infrastructure for spatial information in Europe

ISARM – Internationally Aquifer Resources Management

RBD – River basin district

RBMP – River basin management plans

TBA – Transboundary aquifer

TGR – Transboundary Groundwater Reservoirs

UNECE – United Nations Economic Commission for Europe

UNESCO – United Nations Educational, Scientific and Cultural Organization

UN/FAO – The Food and Agriculture Organization of the United Nations

WFD – Water Framework Directive (2000/60/EC)

Preface

This report has been prepared as part of the EU-WATERRES (EU-integrated management system of cross-border groundwater resources and anthropogenic hazards; www.eu-waterres.eu) project, funded by the EEA and Norway Grants Fund for Regional Cooperation. The project aims to increase the capacity of public institutions to manage transboundary groundwater resources by creating an integrated information platform, introducing new data analysis tools and solutions for coordinated management and integrated groundwater protection. The recommendations are aimed at a wide range of target groups - geological institutes and surveys, water management authorities, geological sector companies, regional and local authorities - concerned with environmental protection.

EU-WATERRES project promotes international harmonized data collection, monitoring and assessment of TBAs. A thorough and comprehensive assessment of groundwater resources in these layers will let to avoid possible international disputes and maximize the rational and justified use of common TBAs.

This report synthesizes the knowledge of international law in the management of TBAs and bilateral agreements between neighboring countries for two pilot regions representing: the Baltic and Eastern Europe, i.e. the Latvian-Estonian border and the Polish-Ukrainian border. As part of the assessment of the resources of transboundary groundwater reservoirs, an analysis of hydrogeological conditions in the entire border section was presented on the basis of integrated data between neighboring countries. As a result, target areas of detailed modeling studies with significant transboundary flow in usable aquifers were identified and the first conceptual hydrogeological model of TBAs was developed. This concept of the TBAs structure was the basis for the creation of a numerical hydrodynamic model and the assessment of transboundary flows on its basis. In addition, this model in further work will be necessary to simulate the transboundary effects of groundwater abstraction and other anthropogenic factors on the quantitative and qualitative state of TBAs.

As part of the assessment of transboundary groundwater flows, the extent of the area particularly sensitive to transboundary impacts on groundwater was presented. The structure of TBAs and the spatial distribution of its basic hydrogeological parameters were visualized - the coefficient of filtration, alimentation, piezometric surfaces. The developed maps, calculation and simulation results will ultimately be used to solve problems related to the ownership, use, access and protection of transboundary groundwater resources in the pilot border areas.

May 2021,

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Introduction

Coordinated management of TBAs is increasingly desirable around the world to minimize adverse transboundary impacts. In addition, due to the increasing global trend of groundwater consumption, the exceeding of sustainable groundwater abstraction in many parts of the world, and to avoid future international disputes and maximize the rational and equitable use of common TBAs, there is a need for an accurate and comprehensive assessment of the development potential of groundwater resources in these layers.

The global identification of TBAs began in 2000 under the coordination of the ISARM Committee under the UNESCO-IHP. According to the results of this assessment, presented by IGRAC, it is estimated that there is a total of 591 TBAs in the world, including 72 in Africa, 73 in the Americas, 129 in Asia and Oceania and 317 in Europe (in including 226 Transboundary GWB as defined in the WFD. The conducted project aroused wide interest of the international community in the issues of managing the TBAs. As a result of the active activities of a team of experts from three international organizations: ISARM, UN/FAO, and the International Association of Hydrogeologists (IAH), work was initiated on the development of the main principles of international water law in the field of TBAs. In international law, this issue was formalized in 2008 by the United Nations International Law Commission in the form of draft Articles on the law on transboundary aquifers (Resolution, 2008).

Within the framework of the EU-WATERRES project, the assessment of transboundary groundwater resources was performed in two pilot areas - Polish-Ukrainian and Latvian-Estonian borderland. Both territories are different from natural conditions (terrain, geological and hydrogeological conditions) and from a socio-economic point of view (land use, perspective, water management, etc.), thus achieving project goals is even more challenging and requires for close cooperation between countries. However, sustainable transboundary groundwater management, to ensure good quality and quantity status of groundwater resources for future generations is of great importance in both areas.

In the Polish-Ukrainian borderland, only the transboundary groundwater reservoir within the Bug river basin has been qualified to the world list of TBAs (IGRAC, 2015). On the other hand, scientific publications present the premises allowing to justify the hypothesis of the existence of transboundary flows within other catchments apart from the Bug River. With this in mind and the problems related to the intensive intake of groundwater in the Polish-Ukrainian border zone as a result of mining drainage in the region of Lublin and the Lviv-Volyn Coal Basin, as part of the international EU-WATERRES project, the development of the concept of coordinated management and harmonized monitoring of TBAs was initiated. The first stage of the work, presented in this report, is to assess the transboundary groundwater flows and identify the areas of TBAs with significant potential for groundwater exchange between Poland and Ukraine. A reliable calculation in this respect was possible only with the use of numerical hydrodynamic models. The basis of these numerical models was a conceptual hydrogeological model as a description of the structure and natural and anthropogenic factors that shape the groundwater circulation system.

The conducted research has been focused on characterizing the hydrogeological conditions in the entire border section on the basis of integrated data between Poland and Ukraine, with the aim of identifying the target area where there is significant transboundary flow in the usable aquifers. The created numerical hydrodynamic model for this area will provide the most detailed assessment of TBAs resources between Poland and Ukraine so far, and will estimate the transboundary groundwater flows. It will also show where the TBAs are supplied and drained, and how groundwater abstraction will affect flows.

A great challenge in this project was the consolidation of hydrogeological data between Poland and Ukraine, including the continuity of the TBAs. The key to success was not only integrating scientific assumptions, but also connecting people.

The hydrodynamic model and the assessment of cross-border flows on its basis should lead to more effective joint management of TBAs between Poland and Ukraine. It can also help lay the foundations for a formal international agreement between two countries on the rational and fair use of joint TBAs under the Agreement on Cooperation in the field of water management in border waters (Agreement, 1996).

Similar to the Polish-Ukrainian case, the assessment of transboundary groundwater resources was also performed in the second pilot area - on the Latvian-Estonian borderland. Already at the initial stage of the assessment of the two pilot areas, it became clear that the two pilot areas are very different in nature. In contrast to the Polish-Ukrainian border, where there is a mountainous relief, significant anthropogenic impact due to groundwater extraction and mining, the Latvian-Estonian border is relatively flat, sparsely populated, there are no significant water abstraction and anthropogenic pressures.

So far, no common transboundary groundwater bodies have been delineated on the Latvian-Estonian border area. According to the World List of Transboundary Aquifers (ISARM, 2015), several groundwater bodies on the Latvian-Estonian border on the Latvian side have been identified as transboundary, however, on the Estonian side, transboundary aquifers with Latvia have not been officially delineated before. This situation clearly demonstrates the need for cooperation between the two countries in the assessment and management of transboundary groundwater, which is directly implemented within the framework of the EU-WATERRES project.

A bilateral agreement on co-operation in transboundary water management was concluded between Latvia and Estonia in 2003, however, no real actions for the assessment of transboundary groundwater were implemented. Only in 2018, cooperation between the two countries in the field of transboundary groundwater management was launched through the GroundECO project. Within this framework, groundwater resources were assessed in the common international river basin - Gauja river basin district, which includes the Gauja (Latvia) and Koiva (Estonia) river basins.

The pilot area selected within the framework of the EU-WATERRES project includes the entire Latvian-Estonian land border in order to be able to more fully assess the common groundwater resources. Initially, both countries exchanged information data, followed by a harmonization process. Combining the available information and existing knowledge, a conceptual picture of the pilot area was created. The hydrogeological model was used to determine the geological, hydrogeological conditions and groundwater flow directions. A semi-analytical method was also developed to identify significant transboundary groundwater flows and to quantify transboundary overflows.

The performed assessment of groundwater resources will serve as a basis for future transboundary project activities - identification of representative transboundary monitoring points, as well as assessment of anthropogenic impact on groundwater.

Basic concepts and definitions

For the identification and assessment of transboundary groundwater resources, it is important to have a common understanding of the hydrogeological terms and definitions used to achieve the project outputs. At the beginning of the project, a database of basic terms and definitions used by project partners was developed, where a list of the most commonly used basic hydrogeological terms and definitions for transboundary groundwater characterization was created. The definitions of terms used in the national legislation and practice of each country were summarized.

From the compiled definitions, it can be concluded that groundwater terminology (especially for transboundary groundwater) in countries is poorly defined in national legislation and most of the terminology for practical use has been taken over from available literature, binding guidelines and directives.

In Latvia, Estonia and Ukraine, only the definitions of the aquifer and groundwater body have been covered by national legislation and all other terms are interpreted from relevant guidelines and directives. In Poland, terms are mainly derived from two publications: 1) Instructions for sharing, updating, verifying and developing the Hydrogeological Map of Poland (Instructions, 2004); 2) The Hydrogeological Dictionary (Dowgiałło et al. 2002). In the case of Norway, the definitions are applied from the INSPIRE feature concept dictionary.

Nevertheless, the common understanding of the terms among the participating countries is quite similar and there are no conceptual differences.

Conclusions on concepts between partners: (1) list of terms which are similar: *Aquifer, Aquitard, Unconfined aquifer, Confined aquifer, Transboundary aquifer, Groundwater level, Groundwater table, Groundwater body; (2*) there are no terms that differ significantly, only a few that are not practically used on in countries; (3) terms covered by legislation: *Aquifer* and *Groundwater body*.

The definitions provided by the partner countries correspond to the glossary compiled by the IGRAC and INSPIRE which provides definitions for groundwater-related terms. According to previously mentioned, the glossary of this report is mainly based on IGRAC and INSPIRE definitions. Also, there are some additional terms, like *groundwater reservoir, subsurface waters, main useful aquifers, available groundwater resources*, which are used in Poland. As these terms are included in the content of the report, they are also added to the glossary.

Aquifer – (water bearing horizon) - a hydraulically continuous body of relatively permeable unconsolidated porous sediments or porous or fissured rocks containing groundwater. It is capable of yielding exploitable quantities of groundwater (IGRAC, n.d.);

Aquitard – groundwater-filled body of poorly permeable formations, through which still significant volumes of groundwater may move, although at low flow rates (IGRAC, n.d.);

Aquiclude – groundwater-filled bodies of poorly permeable formations, through which no or almost no flow of groundwater passes (IGRAC, n.d.);

Artesian aquifer – An aquifer containing water between two relatively impermeable boundaries. The water level in a well tapping a confined aquifer stands above the top of the confined aquifer and can be higher or lower than the water table that may be present in the material above. The water level rises above the ground surface, yielding a flowing well (INSPIRE, 2014);

Available Groundwater Resources (AGR) – the multiannual average amount of the total supply of a defined groundwater body, reduced by the multiannual average amount of the flow required to achieve the ecological quality objectives set for surface waters, so as not to allow a significant deterioration of the ecological status of such waters and to avoid any significant damage to associated terrestrial ecosystems (Zasady, 2005);

Confined aquifer – fully saturated aquifer (i.e. pressure everywhere greater than atmospheric pressure) directly overlain by an impermeable or almost impermeable formation (confining bed). The confining bed prevents the aquifer from interacting directly with the atmosphere and with surface water bodies (except for surface water bodies that intersect the aquifer) (IGRAC, n.d.);

First Water Bearing Horizon (FWBH) – the first aquifer or group of aquifers from the surface having good hydraulic contact with each other (Instructions, 2004);

Groundwater body – distinct volume of groundwater within an aquifer or aquifers (INSPIRE, 2014);

Groundwater level – elevation to which groundwater will or does rise in a piezometer connected to a point in the groundwater domain. It is a time-dependent variable, varies from point to point within the groundwater domain, and indicates the potential energy of groundwater in any point considered (in meters of water column relative to a selected topographic reference level) (IGRAC, n.d.);

Groundwater Reservoir (GR) – complex of permeable aquifers of utility importance, the boundaries of which are determined by hydrogeological parameters or hydrodynamic conditions and the conditions of formation of groundwater resources (Dowgiałło et al. 2002);

Groundwater table – surface defined by the phreatic levels in an aquifer (i.e. surface of atmospheric pressure within an unconfined aquifer) (IGRAC, n.d.);

Hydrogeological unit – a part of the lithosphere with distinctive parameters for water storage and conduction (INSPIRE, 2014);

Main Useful Aquifer (MUA) – the first usable aquifer or usable level from the ground surface, constituting the main source of supply with a predominant range and abundance in the area of a separate hydrogeological unit (Instructions, 2004);

Subsurface Waters (SW) – waters of the aeration zone occurring above the groundwater table, also known as suspended waters: bound waters, capillary waters (some of them are soil waters), as well as free gravitational waters moving/flowing through the aeration zone to the groundwater table, to reach the free groundwater. The near-surface waters also include suspended groundwater levels and very shallow groundwater (low-thickness aeration zone) (Instructions, 2004);

Transboundary aquifer – an aquifer that spans two or more political entities, separated by political boundaries (IGRAC, n.d.);

Transboundary groundwater flow – groundwater flow over two or more political entities, separated by political boundaries;

Unconfined aquifer – an aquifer containing water that is not under pressure. The water level in a well is the same as the water table outside the well (INSPIRE, 2014);

Useful aquifer – a layer or set of aquifers showing good hydraulic contact, with the parameters of the quantity and quality of water qualifying for municipal use: thickness of aquifers over 5 m, water conductivity over 50 m^2/24 hours, potential well over 5 m^3/hour (Instructions, 2004).

PART I. Assessment of the resources of transboundary groundwater reservoirs for the Polish-Ukrainian borderland

Summary

The research carried out in the Polish-Ukrainian borderland has shown the usefulness of the numerical hydrodynamic model in the assessment of TBAs resources and transboundary groundwater flows. In the computational process, it was necessary to create a cross-border conceptual model of the structure of the aquifer TBAs. The merging of hydrogeological data between Poland and Ukraine has contributed to the continuity of the TBAs. The assumption was made that the model area will be limited to the area where the cross-border connectivity of the main usable aquifers is not disturbed by tight barriers to the flow of groundwater, such as drainage rivers. The area identified this way covers the area of approximately 7,150 km^2 and in the catchment division it includes fragments of the catchment areas of the San and Bug rivers in their upper parts. The transboundary groundwater flow occurs in the following layers: 1) Quaternary with an unconfined groundwater table - in alluvia in the valleys of large rivers and in fluvioglacial sands - on postglacial plains, 2) Upper Cretaceous with a partially confined groundwater table - in Polesie and the Volyn Uplands, 3) Neogene with a confined groundwater table in Roztocze and Przedkarpackie Foredeep. The analysis of the individual parameters of the model results showed that more than 1.5 times more groundwater flows from the main usable layer from Poland to Ukraine than from Ukraine to Poland. From the territory of Poland to Ukraine, groundwater outflow is 42,350 m^3 / 24h, and broken down into the catchment areas of the Bug and San - 32,981 m^3/24h and 9,369 m^3/24h, respectively. On the other hand, only 27,924 m^3/24h is transported to Poland from Ukraine (broken down into the catchment areas of the Bug and San - 11,632 m^3/24h and 16,292 m^3/24h, respectively).

In the Bug basin, the transboundary groundwater flow is directed mainly to Ukraine, while in the San basin - to Poland. Therefore, it can be reasonably assumed that in the identified area particularly sensitive to transboundary impacts on groundwater in the Bug catchment basin, Ukraine is at a disadvantage as the "Recipient" party. On the other hand, in the San catchment area, Poland is in a similar situation.

The system of piezometric surfaces defined in this report also proves that in Poland the area of special attention due to the possible negative transboundary impact on underground waters of Ukraine is located in the Bug catchment area and has an area of approx. 936 km^2, including Uniform Parts of Surface Waters numbered: RW20000626714189, RW200006267141718, RW20000626714163, RW2000062671414839, RW2000062671414591, RW20000626714125.

In Ukraine, the relevant area is in the San catchment area and covers an area of approximately 2,334 km^2, including the Uniform Parts of Surface Waters with the numbers: RW200009225645, RW200011225699, RW200009225629, RW200011225499, RW2000092254529, RW200009225249, RW2000092252329, RW200011225299, RW200010225269, RW20000622499.

1 Legal systematics of transboundary groundwater reservoirs

1.1 Transboundary groundwater reservoirs in international law

In the legislation of the EU on the protection and management of groundwater, the problem of transboundary groundwater resources is poorly addressed, despite their high socio-economic importance. The term "transboundary groundwater bodies" appeared in 2005 as part of the publication on guidelines for the identification of Groundwater Units. Transboundary Groundwater Units - these are groundwater reservoirs that are shared by two or more countries. An aquifer that crosses the administrative boundaries of countries and thus has the potential to exchange groundwater between neighboring countries is defined as transboundary.

In international law, the development of this issue can be traced back to 2008, when the main principles of international water law on transboundary aquifers were developed by the United Nations International Law Commission in the form of draft Articles on the law on transboundary aquifers (Resolution, 2008; Resolution, 2011). The proposals developed by a team of experts from three international organizations: UNESCO-IHP ISARM, UN/FAO, and the International Association of Hydrogeologists (IAH) had the greatest impact on the scope of the Articles project. Moreover, ISARM was the first to gain international community interest in the management of transboundary aquifers. In 2001-2010, the organization initiated research on a global scale for the identification and mapping of transboundary aquifers. In this way, ISARM created a set of unified data that accelerated international cooperation and was the basis for generating guidelines essential for the development of international water law. Overall, ISARM has made a significant contribution to the international management of transboundary aquifers.

The draft Articles were discussed four times by the United Nations General Assembly (UNGA) Committee over the next 12 years. The last discussion took place on October 22, 2019, followed by a three-year break for another discussion on this topic and in this format. The 2019 debate showed a certain degree of agreement on the legal nature of the draft Articles. This document was considered an optional legal framework and is treated as legally non-binding guidance that can be adapted to the specific circumstances of countries when developing bilateral agreements or interstate arrangements for the management and conservation of transboundary aquifers. The overarching goal of the Articles project is to support effective transboundary cooperation in the field of groundwater and to strengthen integrated management of transboundary groundwater resources.

Currently, 366 transboundary aquifers and 226 transboundary Groundwater Units (IGRAC and UNESCO-IHP2015) have been identified around the world according to uniform criteria. In addition to the hydrogeological conditions of the transboundary groundwater bodies, social, institutional, legal and economic aspects were also defined, with the most progress being made in the ISARM-Americas group (UNESCO-IHP) in the Northern Hemisphere. A team of ISARM-Americas experts developed the "Regional Strategy for the Assessment and Management of Transboundary Aquifer Systems in the Americas" (Rivera, 2015). The overarching goal of this strategy is to achieve, sustainably manage and protect transboundary aquifers through:

1. Generating knowledge about the condition, protection and use of TGR resources.
2. Development of guidelines for the management of transboundary aquifers, including the assessment of the aquifer's sensitivity to pollution and hydraulic connectivity with surface waters in transboundary catchments.
3. Promoting the exchange of information and scientific knowledge, cooperation between countries using transboundary aquifers.

4. Development of common standards, methodologies and procedures for assessment, as well as of hydrodynamic models for the management of the TGR.
5. Development and establishment of *ad hoc* legal and institutional frameworks related to the management of the TGR with the use of international legal instruments.

There is a large disproportion between the number of Transboundary Aquifers and Transboundary Uniform Waters in the world and the number of ratified international treaties that have been signed. According to data from Burshi (Burshi, 2018), only seven transboundary groundwater agreements have been signed at the international level and several other transboundary agreements, including:

1. Agreement on transboundary groundwater between France and Switzerland (1977 and 2007).
2. Agreement on the Strategic Action Program for a Transboundary Aquifer between Chad, Egypt, Libya and Sudan (1992 and 2000).
3. Agreement on transboundary groundwater between Argentina, Brazil, Paraguay and Uruguay (2010).
4. Agreement on Transboundary Groundwater between Jordan and Saudi Arabia (2015).
5. Agreement on the Transboundary Groundwater of the North-West Sahara between Algeria, Libya and Tunisia (2002, 2008).
6. Agreement on transboundary groundwater between Mali, Niger and Nigeria (2009).

The agreement between France and Switzerland should be seen as a positive example of cross-border water cooperation between an EU Member State (France) and a non-EU country (Switzerland). It also sets a precedent that the agreement can be concluded successfully without full EU status and can be used as a model for cooperation between Poland and Ukraine.

The main principles of international water law regarding transboundary aquifers contained in the draft Articles document are:

1. Countries recognize the need for joint management of a transboundary aquifer and are interested in identifying relevant international rules and practices that can shed light on how the aquifer can be used and protected in a mutually beneficial way.
2. Countries sharing or exerting an anthropogenic impact on transboundary groundwater shall take all appropriate measures to prevent and limit any adverse transboundary impact.
3. Countries declare the use of transboundary groundwater in a sustainable manner in order to increase the resulting long-term benefits and to protect groundwater-dependent ecosystems. To this end, Countries should take into account all the functions of transboundary groundwater resources, their size and quality, and the rate of renewal, with a view to avoiding their decline to a critical level.
4. Countries collaborate to identify, parameterize and characterize transboundary groundwater. They are also working to develop conceptual models whose level of detail depends on the complexity and impact of the hydrogeological system.
5. Countries shall develop a program of joint monitoring and assessment of the quantitative and qualitative status of transboundary groundwater. For this purpose, countries, inter alia:
    a) use common or agreed standards and methods;
    b) agree on evaluation criteria and key parameters to be monitored, taking into account the specificities of transboundary groundwater occurrence;
    c) design a groundwater monitoring network combined with the monitoring of surface water, where appropriate;

    d) develop integrated hydrogeological maps, including groundwater vulnerability maps and, where appropriate, hydrodynamic numerical models.

6. Countries work together for the integrated management of transboundary groundwater resources. Countries will take appropriate measures to prevent, limit and reduce pollution of transboundary groundwater, in particular usable aquifers. Therefore, they follow the precautionary principle due to the vulnerability of groundwater to pollution, especially in the case of poorly identified transboundary aquifers. Such measures include, but are not limited to:
    a) the establishment of protection zones, particularly in the most sensitive parts of the groundwater recharge area;
    b) taking measures to prevent or limit the migration of pollutants into groundwater;
    c) implementation of agri-environmental programs and protection of groundwater against pollution by nitrates and plant protection products;
    d) establishing appropriate types of groundwater quality indicators and agreeing on their criteria values.
7. Countries shall undertake activities to exchange information and data on the state of transboundary groundwater and the volume of its exploitation and other types of anthropogenic impacts.
8. Countries shall develop and implement a joint or agreed program for the integrated management of transboundary groundwater resources. This program includes, but is not limited to:
    a) the sharing of transboundary groundwater resources among users, including groundwater-dependent ecosystems;
    b) fixing of abstraction permits for transboundary groundwater;
    c) setting limits to the total annual abstraction of transboundary groundwater, its distribution among users and establishing criteria for the location of new intakes;
    d) develop a program to protect and restore good quality and adequate quantity of groundwater.
9. Planned activities that may have a significant negative impact on transboundary groundwater, and thus have a detrimental effect on another Party, shall be subject to the procedure of transboundary environmental impact assessment.
10. Countries take measures to raise public awareness and ensure access to information on the state of transboundary groundwater.
11. For the implementation of international rules and practices in the field of transboundary groundwater and for the coordination of cooperation, the Countries shall establish a joint body.

In conclusion, the main thrust of the transboundary groundwater management strategy governed by international law is to achieve "good status" of transboundary groundwater through its sustainable use while ensuring strict control of the qualitative and quantitative status of groundwater. To this end, a system of joint monitoring of the status of transboundary groundwater should be implemented.

On January 24, 1994, the Government of the Republic of Poland and the Government of Ukraine signed an agreement on cooperation in the field of environmental protection, solving ecological problems and rational use of natural resources in accordance with the concept of sustainable development (Agreement, 1994). The agreement was concluded on, *inter alia*:

- treaty between the Republic of Poland and Ukraine on good neighborhood, friendly relations and cooperation (Treaty between the Republic of Poland and Ukraine, 1992);
- the Rio Declaration on Environment and Development;

- "Agenda 21";
- Convention on Climate Protection,
- Convention on the Protection of Biological Diversity,

which were adopted and signed at the United Nations Conference on Environment and Development in Rio de Janeiro in 1992.

The aim of the cooperation is to improve the condition of the environment and increase ecological safety in both countries and to prevent environmental pollution, *inter alia* by (Agreement, 1994):

- strengthening the control of sources of transboundary pollution and taking the necessary steps to reduce them continuously, and
- increasing the effectiveness of water, atmosphere and earth surface protection.

The subject of cooperation is primarily the following environmental protection issues (Agreement, 1994):

- exchange of experience in the field of improving management and legal regulations in the field of environmental protection,
- protection of surface and underground inland waters against pollution,
- creating a system of rational use of natural resources, including at the regional level,
- environmental monitoring, primarily in border areas.

Basing on the provisions of the Article 5, in order to implement the agreement, parties have established a Joint Commission for cooperation in the field of environmental protection.

Two years after signing the agreement on cooperation in the field of environmental protection (…), on October 10th, 1996 in Kiev both parties signed an agreement on cooperation in the field of water management in border waters (Agreement, 1996). As a strategic goal of the cooperation, the parties indicated ensuring rational management of border waters and improvement of their quality, as well as ensuring the preservation of ecosystems. In concluding the Agreement, the parties were convinced that the protection and use of border waters and protection against damage caused by border waters are important tasks, the effective solution of which can only be ensured through close cooperation in the field of water management. In the Agreement, the parties referred to the Treaty between the Republic of Poland and Ukraine (1992).

Within the meaning of the Polish-Ukrainian Agreement, border waters mean rivers and other surface waters along the border, as well as surface and underground waters crossed by the state border. Polish-Ukrainian cooperation covers a significant part of the cross-border catchment area of the Bug and San, rivers that are part of the international Vistula river basin. The Bug is approx. 772 km long, and its catchment area is located in Poland, Ukraine and Belarus. The sources of the Bug are in Ukraine, and the estuary to the Narew River, on the territory of Poland. The average flow in the lower course is 154 m^3/s, which makes the Bug the fourth largest river in Poland. The San is a right-bank tributary of the Vistula River, its sources are in Ukraine. The length of the river is 457.76 km. According to the border documentation, the water section of the Polish-Ukrainian border is 287.97 km in total and runs along the rivers: Bug - 227.77 km, San - 59.21 km and the Zawadówka Canal - 0.99 km. The rivers Wiar, Wisznia, Szkło and Lubaczówka, which cross the state border, also have a cross-border character.

The cooperation platform is the Polish-Ukrainian Commission for Border Waters (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko---ukrainska). The Committee is composed of Delegations of the Parties composed of Government Plenipotentiaries, their Deputies, Secretaries, Members and Working Group Managers, who are selected from among the relevant water management bodies. The function of the Government Plenipotentiary for

Cooperation with Ukraine is performed by a representative in the rank of Deputy Minister responsible for water management. The functions of the Deputy and Secretary are also performed by representatives of the ministry responsible for water management. The members of the Polish delegation are representatives of the State Water Holding "Polish Waters", including the Regional Water Management Boards in Lublin and Rzeszów, the Management of the Basin in Przemyśl, the Institute of Meteorology and Water Management - National Research Institute, the Chief Inspectorate for Environmental Protection and the Border Guard Headquarters. The plenipotentiary of the Council of Ministers of Ukraine for cooperation with Poland is a representative of the State Agency for Water Resources of Ukraine in the rank of president or his deputy. The task of the Plenipotentiaries and their Deputies is to care for the fulfillment of the parties' obligations under the Agreement. They contact directly, appoint experts as needed and convene meetings. The secretaries are responsible for drawing up protocols and other cooperation documents. Once a year, a Commission meeting is held to assess the implementation of the work, hear the reports of the working groups and approve the work plans.

The cooperation is divided into four areas and is carried out throughout the year within the Polish-Ukrainian Working Groups, which operate on the basis of the statute of the Commission, mandates and regulations, and work plans approved during the meetings of the Commission (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko---ukrainska).

- The HH group conducts research, observations and data exchange in the field of hydrometeorology and hydrogeology of boundary waters.

On the Polish side, the tasks of the HH Group are the responsibility of the Institute of Meteorology and Water Management - National Research Institute with its seat in Warsaw. The Hydrological and Meteorological Station in Lublin-Radawiec and the Polish Geological Institute - National Research Institute PGI-NRI, Carpathian Division also cooperate within the HH Group. On the Ukrainian side, the Ukrainian Hydrological and Meteorological Center is responsible for cooperation with the help of the Regional Hydrological and Meteorological Center in Lviv and the Regional Hydrological and Meteorological Center of the Volyn Oblast in Lutsk (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko---ukrainska).

As part of the work of the HH group, daily exchange of operational hydrological and meteorological data for the preparation of hydrological forecasts takes place. Hydrometeorological and hydrogeological data for the needs of water balances are exchanged on a quarterly basis. The parties also perform joint flow measurements and joint geodetic cross-sections in selected Bug profiles. On the basis of agreed data, annual hydrological characteristics of the established profiles are compiled.

Current information from water gauges and rainfall stations enables the assessment of the hydrological and meteorological situation in the Ukrainian part of the Bug catchment area. Forecasts for the daily hydrological cover are also analyzed on an ongoing basis. Forecasts from the meteorological model are obtained three days in advance and contain data on the daily sum of precipitation and the average daily air temperature. The results of these forecasts are entered into a hydrological model that calculates the ratio of rainfall / thaw to runoff, then transferred to the hydrological forecasting offices and used to formulate hydrometeorological messages and warnings.

- OW Working Group for the protection of border waters against pollution

The tasks of the OW Group include monitoring of the state of border waters. On the Polish side, the tasks of the group are the responsibility of the Chief Inspectorate of Environmental Protection - Regional Environmental Monitoring Departments in Lublin and Rzeszów. The analysis of the samples is the responsibility of the Central Research Laboratories of the Chief Inspectorate of Environmental Protection, branches in Lublin and Rzeszów. On the Ukrainian side, the Department of Water Resources in Lviv, subordinated to the State Agency for Water Resources of Ukraine, the Regional Office of Water Resources of the Volyn Oblast, the Lviv Regional Center of Hydrometeorology and the Volyn District Hydrometeorology Center are responsible for cooperation (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko---ukrainska).

The regular tasks of the OW Group include testing the quality of water in the Bug and San catchments. In the Bug catchment area, each side has four measurement and control points, the Polish side: Kryłów, Zosin, Horodło, Dorohusk, the Ukrainian side: Litowież, Ambuków, Uściług, Zabuże. In the San catchment area, measurement and control points are located on the Wisznia and Szkło rivers. On the Polish side: on Wisznia in Gaje, on the Szkło in Budzyń, on the Ukrainian side: on the Vishnia in Czerwoniewo, on the Szkło in Krakowiec. The analysis of 9 indicators is performed from the collected samples, i.e.: total suspended solids, BOD5, dissolved oxygen, ammonium nitrogen, nitrite nitrogen, phosphates, chlorides and sulphates. Samples are taken 6 times a year. The quality and comparability of research is ensured by experts in the field of analysis quality, who develop measurement programs and standardize research methods. A joint sampling is carried out once a year by both parties at the same time. On the Bug, the sampling takes place at the measurement and control point located at the border crossing Zosin-Uściług, in the catchment of the San river, the sampling takes place at the measurement and control points in Wisznia and Szkło, simultaneously on both sides of the border. Joint sampling allows the verification of the measurement methods used on both sides. The results of tests and observations are used to prepare the annual assessment of the quality of border waters. This assessment concerns the waters of the Bug and rivers in the San catchment area. The OW Group also deals with the identification of potential sources of contamination of border waters.

Moreover, the OW Group undertakes actions in the event of extraordinary contamination of border waters. These activities include the exchange of information and warnings as well as the elimination of the consequences of an accident. Crisis management is the responsibility of the competent authorities of both parties. On the Polish side, the National Center for Rescue Coordination and Population Protection of the Main State Fire Service, Provincial Environmental Protection Inspectorates, provincial offices, marshal offices and the State Center for Crisis Management are notified. On the Ukrainian side, the Ministry of Environment and Natural Resources, the State Agency for Water Resources, the State Service for Emergency Situations and the State Inspectorate for Environmental Protection cooperate at the state level.

- PL Working Group for Border Water Planning

The PL group is responsible for planning the management of border waters in terms of their use for utility purposes and the implementation of EU water regulations in the Bug and San river basins. On the Polish side, the tasks of the group are the responsibility of the State Water Management Authority (Polish Waters), in particular the Regional Water Management Boards in Rzeszów and Lublin. The Marshal's Office of the Lubelskie Voivodeship and the Regional Directorate for Environmental Protection in Lublin also cooperate. On the Ukrainian side, the Catchment Water Resource Authority in Lviv, which is subordinated to the State Agency for Water Resources of Ukraine, is responsible for cooperation. The newly established river basin boards also cooperate (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko---ukrainska).

The role of the PL Group is to exchange information on the directions of water policy, planning and management of water resources, as well as to inform each other about changes in the regulations and institutional structure. Equally important is the group's role in implementing EU water directives. Ukraine currently has the status of an associated country with the EU and is undergoing an administrative reform in the field of water resources management. In the context of the above, the parties exchange data for the purposes of developing water management plans and other planning documents resulting from the provisions of the WFD. The water resource management plans that the parties have carried out in the cooperation so far are helpful in the implementation of this task. As regards the economic planning of border waters, the parties carry out an analysis and exchange of information on water abstraction and wastewater discharge in the catchments of the Bug and San rivers. With this task, an inventory of water supply and sewage networks as well as sewage treatment plants in the border area is carried out (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko---ukrainska).

The PL group coordinates the cooperation with the other working groups within the Commission as well with local government administration and bodies managing water resources. To this end, the group monitors Polish-Ukrainian-Belarusian water management projects implemented in the Bug catchment area, as well as bilateral cooperation between regional water management units. On the basis of a cooperation agreement in the Bug catchment area, the regional boards of the parties exchange information on the water and meteorological situation. A constant analysis of water levels and consumption is carried out for the purposes of flood forecasting and water quality assessment on the border section of the Bug. These activities support the state protection system against the risk of flooding and extraordinary pollution.

- OP Working Group on flood protection, regulation and drainage

The main task of the OP Group is to maintain the patency of watercourses and secure border areas in order to protect them against flooding. On the Polish side, the tasks of the group are the responsibility of the State Water Management of Polish Waters, in particular the Regional Water Management Boards in Lublin and Rzeszów. On the Ukrainian side, the Catchment Water Resource Authority in Lviv, which is subordinate to the State Agency for Water Resources of Ukraine, is responsible for cooperation, and the newly established boards of river basins cooperate (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko---ukrainska).

The OP Group makes detours of border waters, during which problems are identified and necessary maintenance works within the border waters and water facilities are located. Smaller works, which do not require a lot of time and money, are performed by the field team on their own. Larger repairs and renovations requiring investments are carried out according to the schedule or reported to the relevant water authorities. The catalog of works and works of the OP group includes: repair and restoration correction of the bed and strengthening of eroded banks, cleaning the lumen of openings under bridges from contaminants deposited by water, maintenance of hydrotechnical structures, mowing of bushes and grasses on the banks of rivers, liquidation of illegal landfills and others (https://www.gov.pl/web/infrastruktura/wspolpraca-polsko---ukrainska).

1.2 Transboundary groundwater reservoirs in Poland's water/geological law and their status of recognition

Water management, use and protection issues have been regulated by the Water Act dated on July 20th, 2017. The Act regulates water management in accordance with the principle of sustainable development, in particular - shaping and protection of water resources, the use of reservoirs and management of water resources. The Act, in terms of its regulation, implements (Prawo wodne, 2017):

- Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment;
- Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources;

- Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy;
- Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 concerning the management of bathing water quality and repealing Directive 76/160/EEC;
- Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration;
- Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks;
- Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive);
- Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council.

The Water Act, together with the Geological Law and other environmental acts regulate all environmental and economic issues of water management in the country.

Chapter 1 of the Act defines the general rules and issues to which the Act does not apply like water services in the field of storage, treatment or distribution of surface water and groundwater, and sewage collection.

Article 13, point 1 defines the river basin districts including parts of international river basins located on the territory of the Republic of Poland. The river basins are as follows:

1. The area of the Vistula river basin, including – apart from the Vistula river basin – the basins of Słupia, Łupawa, Łeba, Reda and other rivers flowing directly into the Balti Sea and the Vistula Lagoon.
2. The Odra river basin, including – apart from the part of the Odra river basin located in Poland – the basins of Rega, Parsęta, Wieprz, Ücker and other rivers flowing directly into the Baltic Sea west of the mouth of Słupia and also to the Szczecińska Lagoon.
3. River basins of: (a) the Dniester, (b) the Danube, (c) Banówka, (d) the Łaba, (e) the Nemunas, (f) Pregoła, (g) Świeża – covering parts of international river basins located on the territory of the Republic of Poland.

In Section I (General Rules), chapter 2 - Explanation of statutory terms, article 16, point 67 defines the term “border waters” as waters through which the state border runs, or waters in places where they are crossed by the state border.

Section II - Use of water has been divided into two chapters: Chapter 1 defines the issues connected with water use and water services while Chapter 2 defines issues connected to water used for recreation.

Section III - Water protection – has been divided into seven sections dedicated to principles of protection, treatment of wastes, protection against pollution from agricultural sources, listing of contaminants, protection of water intakes and inland waters, protection of marine waters and flood risk management and counteracting of drought.

Section IV – Flood risk management – defines the scope of responsibility of public administration for preparation of flood hazard maps. Article 171 defines the State Water Holding “Polish Waters” as being responsible for the task.

Section IV – Flood risk management and counteracting the effects of drought, specifies in article 171, point 6 that the preparation of flood hazard maps and flood risk maps for the areas located in river basin districts, parts of which are located on the territory of other Member States of the EU, shall be preceded by activities aimed at the exchange of information with the competent authorities of these countries. The following point (no. 7) defines that in case of the areas located in river basin districts, parts of which are located on the territory of countries outside the EU preparation of flood hazard maps and flood risk maps is preceded by actions aimed at establishing cooperation with the competent authorities of these countries in this respect.

In Article 173, point 10 of the Article, defines that for the river basin district, part of which is located on the territory of other Member States of the EU, the minister responsible for water management shall cooperate with the competent authorities of these countries in order to prepare for the international river basin district one international flood risk management plan or a set of flood risk management plans coordinated at the level of international river basin district or ensuring coordination to the greatest extent possible at the international river basin district level of a flood risk management plan covering the river basin district within the territory of the Republic of Poland.

Point 11 of the Article states that for the river basin district, part of which is located on the territory of countries outside the EU, the minister responsible for water management takes steps to establish cooperation with the competent authorities of these countries in order to prepare one international flood risk management plan or a set of plans for the international river basin district. flood risk management coordinated at the international river basin district level or ensuring coordination as far as possible at the international river basin district level of a flood risk management plan covering the river basin district within the territory of the Republic of Poland.

In order to supplement the flood risk management plans in the international river basin districts, more detailed flood risk management plans coordinated at the level of the international catchment, part of which is located in other countries, the minister competent for water management may cooperate with the competent authorities of these countries. For this purpose, the minister responsible for water management may use the existing structures resulting from international agreements.

Actions aimed at achieving the objectives of flood risk management included in the flood risk management plans may not significantly increase the flood risk in the territory of other countries, except for cases in which these actions have been agreed in the framework of the cooperation.

In Section VII – Water management, Chapter 1 – Planning, Article 320 specifies that for a river basin district, part of which is located on the territory of other Member States of the EU, the minister responsible for water management shall cooperate with the competent authorities of these countries in order to prepare a single international water management plan or to ensure coordination, as far as possible, at the level of the international river basin district management plan. For this purpose, the minister responsible for water management may use the existing structures resulting from international agreements.

Point 3. of the Article 320 stresses that for the river basin district, part of which is located on the territory of countries outside the borders of the EU, the minister responsible for water management takes steps to establish cooperation with the competent authorities of these countries in order to prepare one international water management plan or to ensure coordination, to the greatest extent, at the international level, of the river basin district located on the territory of the Republic of Poland, in particular in scope of the activities in this river basin district aimed at achieving the environmental objectives. If the development of the plan referred to in this point, or ensuring the coordination, is not possible, the provisions of paragraphs 1 and 2 shall apply to the part of the international territory belonging to the territory of the EU.

In order to supplement the water management plans in the international river basin, more detailed water management plans coordinated at the level of the international catchment, part of which is located on the territory of other countries, the minister competent for water management may cooperate with the competent authorities of these countries.

Based on point 5 of the Article 320, complementary measures may also be adopted to ensure additional protection or improvement of water status or for the implementation of international agreements aimed at water protection, including protection and prevention against the pollution of the marine environment.

Article 335 defines the State Water Holding “Polish Waters” and Directors of Maritime Offices as the entities responsible for the control of water management. In case of transboundary waters, the control is performed in cooperation with the Border Guards.

In Section VIII – Water Management Authorities, Chapter I - The minister competent for water management, Article 353, states that the minister responsible for water management is the supreme government administration body responsible for water management.

The Minister submits to the Sejm of the Republic of Poland every 2 years, not later than by August 31, information on water management regarding, among others, water management regarding international cooperation in border waters and the performance of contracts in this regard.

Article 354 defines that the minister competent for water management coordinates the implementation of public tasks in water management, in particular performs the obligations arising from international agreements regarding water management to which the Republic of Poland is a party.

In Section VIII – Water Authorities – Chapter I – Minister responsible for water management, Article 354 specifies that the minister responsible for water management performs information and reporting obligations towards the European Commission in the scope specified in the provisions of the Act. Moreover, the minister responsible for water management shall perform the duties resulting from international agreements relating to water management to which the Republic of Poland is a party.

1.3 Transboundary groundwater reservoirs in Ukraine's water/geological law and their status of recognition

Water relations in Ukraine are regulated by the Water Code, the Law of Ukraine "On Environmental Protection" and other legislation.

The Water Code, in combination with measures of organizational, legal, economic and educational impact, will contribute to the formation of water and environmental law and order and environmental safety of the population of Ukraine, as well as more efficient, scientifically sound use of water and protection from pollution, clogging and depletion.

Thus, Article 1 provides a definition of the 74 basic terms used in this Code.

Article 83 states that the use of border waters is carried out in the manner prescribed by the legislation of Ukraine and interstate agreements.

Article 112 establishes the procedure for the application of international treaties: if an international treaty in which Ukraine participates establishes norms other than those provided for by the water legislation of Ukraine, the norms of the international treaty shall apply.

The signing of the Association Agreement between Ukraine and the EU and its Member States in 2014 obliges Ukraine to implement European standards in various spheres of public life, including the management of water resources, their protection and the fight against water pollution (Association Agreement, 2014).

The central body of executive power that ensures the formation of state policy in the field of environmental protection (including the protection of water resources) is the Ministry of Ecology and Natural Resources of Ukraine (Ministry of Environment of Ukraine). The implementation of the state policy in the field of management, use and reproduction of surface water resources is supervised by the State Agency of Water Resources of Ukraine (State Water Agency of Ukraine).

The signing of the Association Agreement between Ukraine and the EU and its Member States in 2014 obliges Ukraine to implement European standards in various spheres of public life, including the management of water resources, their protection and combating water pollution, in particular to synchronize in accordance with Directive 2000/60 / EC of the European Parliament and of the Council on the establishment of a Community framework for water policy of 23 October 2000 (Association Agreement, 2014).

With the adoption of the Law of Ukraine "On Amendments to Certain Legislative Acts of Ukraine on the Implementation of Integrated Approaches to Water Resources Management on the Basin Principle", (adopted by the Verkhovna Rada of Ukraine on October 4, 2016, № 1641-VIII), the implementation of the provisions of the WFD in the Water Code of Ukraine and, in general, in the practice of water resources management in Ukraine has begun.

Schedule of achieving the goals in Ukraine on the WFD (since the signing of the Association Agreement (2014)):

1. 3 years - for the adoption of national legislation and the definition of the authorized body, the consolidation at the legislative level of the unit of hydrographic zoning of the country, the development of regulations on basin management with the assignment of relevant functions.
2. 6 years - to determine the areas of river basins and create mechanisms for managing international rivers, lakes and coastal waters, analysis of the characteristics of river basin districts, introduction of water quality monitoring programs.
3. 10 years - to prepare river basin management plans, hold public consultations and publish these plans.

In addition to the WFD, Ukraine has ratified two more main documents in the field of international law on transboundary surface waters.

The use of transboundary watercourses is regulated in accordance with the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, adopted on 17 March 1992, in Helsinki, Finland. The Convention aims to strengthen national measures for the protection and Ukraine acceded to the Convention on July 1, 1999, and its provisions came into force on January 6, 2000. The Convention aims to strengthen national measures for the protection and environmentally sound management of transboundary surface and groundwater.

On 17 June 1999, the Protocol on Water and Health to the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, London, United Kingdom, was adopted (Protocol on Water and Health, 1999). Ukraine acceded to this Protocol on July 9, 2003, and entered into force in Ukraine on August 4, 2005. The purpose of the Protocol is to promote, at all relevant levels, both nationally and in transboundary and international contexts, the health and well-being of people on an individual and collective basis in accordance with the principles of sustainable development by improving water management, including protection of aquatic ecosystems, as well as by preventing, controlling and reducing the spread of water-related diseases (Protocol on Water and Health, 1999).

In addition to being a party to a number of international global and regional environmental agreements, Ukraine has concluded a number of bilateral agreements with other countries. Such agreements are framework or special, concluded at the governmental or ministerial level.

The largest group consists of agreements concluded at the intergovernmental level and have a framework character - agreements on cooperation in the field of environmental protection. Intergovernmental agreements define the main areas of cooperation between the parties. Sometimes, depending on the geographical location of the country with which the agreement is signed or the interest in a common issue, the agreement may contain specific areas of cooperation, such as mutual information, impact assessment and coordination of measures that could potentially have a negative impact on the environment. on the territory of another state (Agreement, 1994).

Intergovernmental agreements determine the agencies responsible for implementing the agreement. On the Ukrainian side, it is the Ministry of Environmental Protection of Ukraine. For example, in pursuance of intergovernmental agreements, an Agreement was signed between the Ministry of Environmental Protection of Ukraine and the Ministry of Environmental Protection, Natural Resources and Forestry of the Republic of Poland on cooperation in the field of environmental protection.

2 Criteria for the identification of hydrogeological units of a transboundary character

The results of the research on the transboundary groundwater reservoirs of the Polish-Ukrainian borderland to date are related to the identification of the TGR carried out by IGRAC and UNESCO-IHP (2015) on a global scale. In the Polish-Ukrainian borderland, one transboundary groundwater reservoir was identified, limited by the watershed of the Bug river basin. In Ukraine, the river Bug is defined as Western Bug. Using the numerical terrain model in a given project, the line of the Bug River catchment basin was determined (Figure 1).

In addition, in the Polish-Ukrainian borderland, two more transboundary groundwater reservoirs catchments were identified in the project - the San and Dniester (Figure 1).

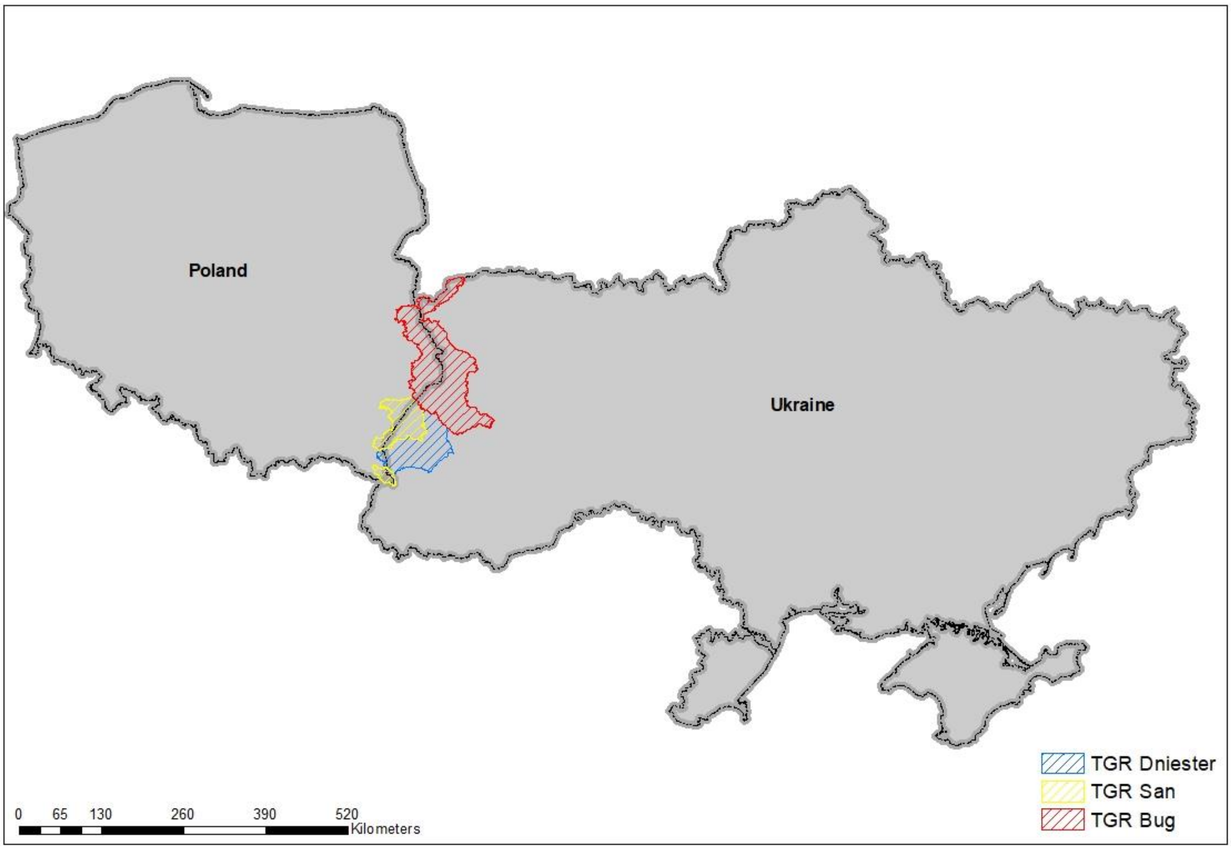


Figure 1 Polish-Ukrainian transboundary groundwater reservoirs within the Bug, San and Dniester River catchment areas

According to our data, the area of the TGR "Bug" is 15,575 km^2. Within the boundaries of the TGR "Bug", on the Polish side, Uniform Groundwater Body (UGB) No. 91 and 121 and partially No. 67 were located. Currently, there is no division into UGB on the Ukrainian side.

The area of the TGR "San" is 4,569 km^2. Within the boundaries of the "San" TGR, on the Polish side, there are partially UGB No. 136, 154 and 168.

The area of the TGR "Dniester" is 5.929 km^2. Within the boundaries of the TGR "Dniester" on the Polish side, GWB No. 169 was located in its entirety.

The approach to separating hydrogeological units in Poland and Ukraine is similar and consists of zoning the first usable aquifer. Therefore, uniform rules for the separation of hydrogeological units within the TGR with regard to the first usable aquifer have been developed.

In order to distinguish the main hydrogeostructural forms of FUA occurrence within the TGR Bug, San and Dniester the criteria used in the schematization of hydrogeological conditions were recognized for the need to develop a Hydrogeological Map of Poland in the scale 1: 50,000. Consequently, it is assumed that the FUA meeting the following criteria will be identified on the unified hydrogeological map of the TGR Bug, San and Dniester:

- achieves water conductivity over 50 $m^2/24h$;
- total thickness $M \geq 5m$ (with an average state of retention);
- shows continuity of occurrence (with the accuracy of hydrogeological schematization appropriate for a map in the scale of 1: 50,000) in the area $A > 20\ km^2$ (in conditions of good identification and clear spatial differentiation of hydrogeological conditions, $A > 5\ km^2$ is allowed);
- enable the execution of a drilled well with a recharge of over 5 m^3/h.

Carrying out hydrogeological identification and defining transboundary aquifers begins with harmonization of hydrogeological spatial data between neighboring countries. The key data are the spatial diversification of the development and hydrogeological properties of the usable aquifers, the mapping of the hydroisohypses surface and the thickness of the aquifers with an accuracy at least appropriate for a 1: 50,000 scale maps. Creation of integrated maps of the distribution of the above hydrogeological characteristics and maps supporting the analysis - lithostratigraphic, hydrographic geomorphology is the basis for identifying transboundary aquifers. The definition of the transboundary nature of an aquifer is carried out on the basis of the criterion of the potential for groundwater exchange between neighboring countries. In this regard, it is proposed to consider the division of the groundwater exchange potential determined based on the water conductivity parameter of the aquifer into:

- significant - water conductivity $\geq 50\ m^2/24h$;
- average - water conductivity $\geq 20\ m^2/24h$;
- negligible - water conductivity $<20\ m^2/24h$.

Lack of groundwater exchange is stated in the case of identifying a "tight" boundary for the groundwater flow, which is formed by the watercourses draining a specific aquifer and watersheds.

Stages of identification of the conditions of the occurrence of transboundary aquifers constituting the basis for the implementation of hydrogeological regionalization are:

1. Determining the type and extent of basic geomorphological forms (hydrodynamic zones) within the areas of transboundary aquifers.
2. Elucidation of the main hydrological parameters of catchment basins.
3. Identification of common large tectonic structures of the transboundary territory.
4. Stratigraphic and lithological identification of transboundary geological formations.
5. Identification of useful transboundary aquifers that meet the criterion of significant and average potential for groundwater exchange between neighboring countries.
6. Investigation of spatial (lateral and vertical) characteristics of aquifers.
7. Initial studies of hydrodynamic and hydrochemical parameters of these useful aquifers.
8. Determining the boundaries of transboundary aquifers.

3 Geological and hydrogeological conditions of the PL-UA borderland

The region of the Polish-Ukrainian borderland is located in the south-eastern part of Poland and the north-western part of Ukraine. Its geographical coordinates are:

- Longitude from 22°25'N to 25°09'N;
- Latitude from 51°54′E to 48°59′E.

According to the physical and geographical division, the research area is located on the border of two megaregions - the East European Lowlands and the Carpathian Region.

3.1 Geological and hydrogeological conditions of the TGR Bug

TGR Bug is located in the East European Lowlands. In the northern part of the TGR Bug, which is within Western Polessye, denudation or accumulation plains with a slight slope dominate here. There are many peat bogs, wetlands and lakes here. The southern part of the TGR Bug is located in the area of the Volyn Upland, in Ukraine – Volyn-Podillia Upland (Figure 2). Its characteristic feature is the alternating occurrence of elevated areas and extensive depressions and valleys. The largest geomorphological structure in the TGR Bug region is the upper and middle part of the Bug river valley, up to 4 km wide and 20-30 m deep with distinct terraced levels. Annual precipitation sums in the last forty years ranged from 500 mm in Polessye to 600-700 mm in the area of the Volyn Uplands. In this period, field evaporation ranged from 450 mm/year to 470 mm/year.

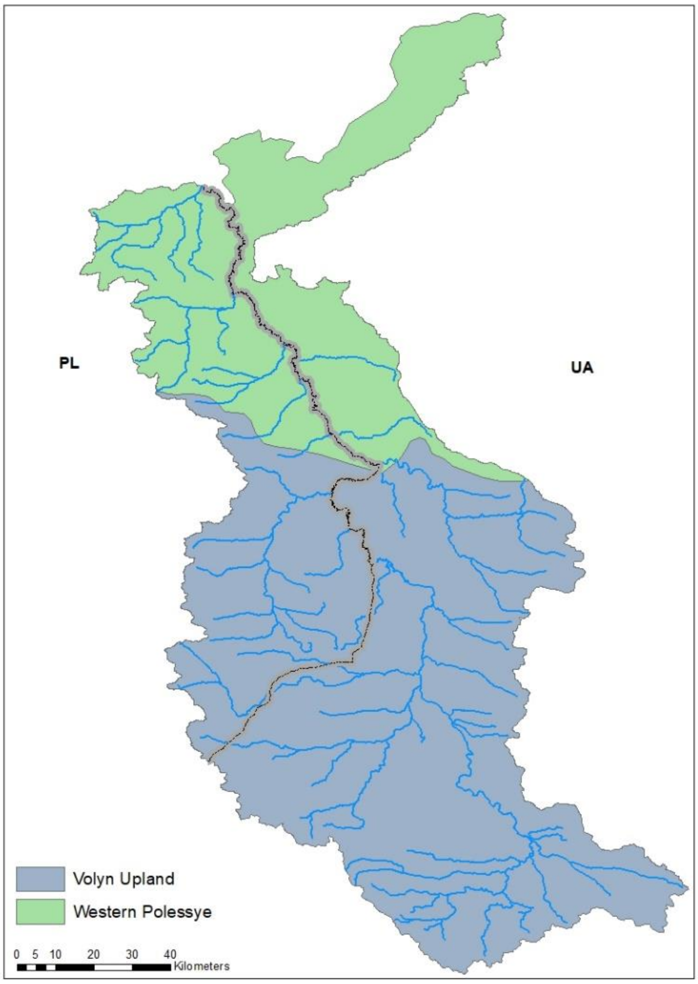


Figure 2 Physical environment map of TGR Bug

The TGR Bug area lies within the East European Platform and is characterized by a significant diversity of the Paleozoic tectonics. The lowland part of Polessye falls within the Kumów elevation, while the upland part - into the Włodawa-Lviv basin. Within the elevation, on the Proterozoic rocks there are Jurassic and Cretaceous rocks and a thin Cenozoic cover. In the depression part, the platform cover is formed by Ediacaran, Cambrian, Silurian and Devonian deposits, on which the Carboniferous deposits lie inconsistently. They are covered with Jurassic and Upper Cretaceous sediments, and on them Neogene and Paleogene in the form of patches of varying thickness are locally deposited. The Upper Cretaceous formations on the surface are usually exposed on hills and are formed of carbonate (writing chalk and marl) and carbonate-silica-clay formations of the Upper Maastrichtian. The thickness of the Upper Cretaceous carbonate complex reaches 500-700 m. In most of the TGR Bug area, there is a Quaternary cover on the surface. In the drainage depressions, it is formed of organic formations, in watershed areas, glacial sediments as well as limnic and limnoglacial glacial muds dominate, in river valleys - sands, gravel, and flooding silts. The thickness of the Quaternary cover is usually 2-10 m, only in the valleys of larger rivers the series of limnic and fluvioglacial sediments reaches 30 m (Figure 3).

In the area of the TGR Bug, the usable aquifer is mainly associated with Upper Cretaceous formations. The aquifer consists mainly of cracked marls and writing chalk. Circulation of groundwater is carried out by a system of interconnected fractures. The fractures network is relatively regular and, together with the almost horizontal gaps between the aquifer, forms the most common fractures in the massif, which determine its water capacity. Bundles of vertical fractures of increased width and large extent are much less common, creating strongly water-bearing zones of tectonic loosening of the massif.

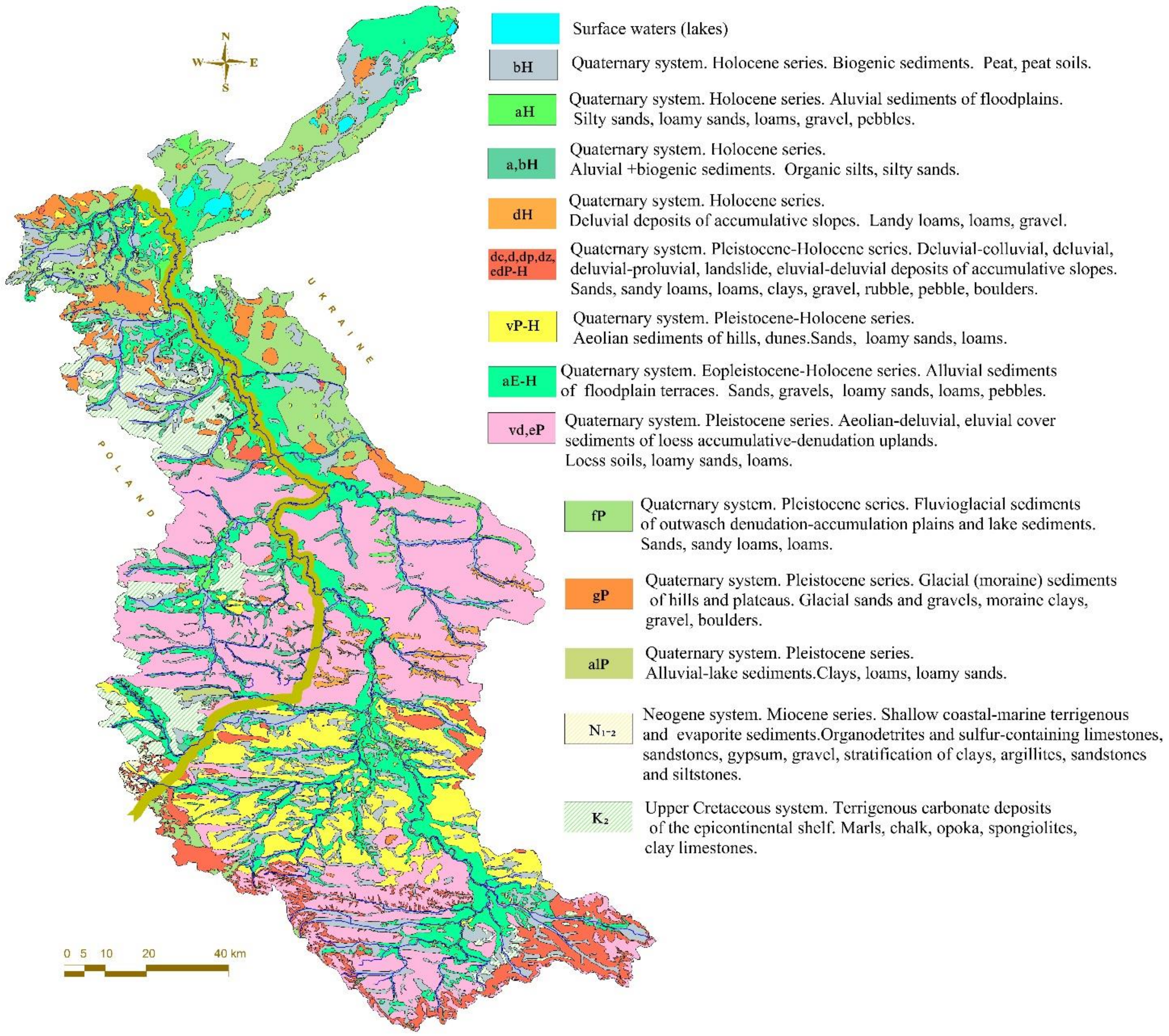


Figure 3 Geological map of TGR Bug

The best hydrogeological conditions are found within tectonic zones constituting routes of concentrated, underground horizontal flow, and near river valleys, buried valleys and valley edge zones. The thickness of the Cretaceous formations may be up to several hundred meters, however, the depth of the active exchange zone, due to the increasing pressure of the rock mass, decreases with depth, and is estimated at 100 to 150 m from the surface.

In most of the area, the Upper Cretaceous formations are covered with loess and clay loam, and partly covered with silt and clay formations. The thickness of this cover of poorly permeable formations varies - from a couple to several or even several dozen meters. Sometimes, Upper Cretaceous aquifer occurs from the ground surface.

The Upper Cretaceous aquifer is recharged by direct infiltration of surface waters. The recharge takes place especially in the elevated areas of Upper Cretaceous sediments outcrops. The main drainage base is the Bug River and its tributaries.

The preliminary hydrogeological studies in Ukraine have shown the possibility of water inflows into the Upper Cretaceous aquifer from the lower aquifers by tectonic faults. Such areas are characterized by local halos of increased total dissolved solid in waters and specific geochemical features. Excessive water pumping at water intakes can lead to the mixtures of such waters reaching consumers. One of the tasks of this project will be to confirm or refute this theory.

Within Poland, the aquifer is usually unconfined, although when covered with low-permeable Quaternary formations, there are also areas with a confined water table. However, in Ukraine the Upper Cretaceous aquifer has mainly confined water table. The depth of the groundwater table is set at 1.5-10 m in river valleys, up to 20-40 m - in watersheds. The discharge of the intakes ranges from 0.09 to 11 dm^3/s.

Most often, in river valleys, there is one shallow, 15-20 m thick, Quaternary aquifer with an unconfined groundwater table. This reservoir is characterized by high groundwater resources. Waters of this aquifer usually remain in a hydraulic contact with the Upper Cretaceous aquifer. In the Polessye part of the Bug River Basin, in the watershed area, the subsurface aquifer is formed by fluvioglacial sandy formations with a thickness of 5-10 m. The water table is unconfined, the depth of occurrence is 0-15 m. The Quaternary aquifer is characterized by a very high variability of hydrogeological parameters. The water conductivity is usually in the range of 10-100 m^2/day, although locally it is 500 m^2/day.

3.2 Geological and hydrogeological conditions of the TGR San

TGR San is located in Roztochia in the northern part and in the vast majority of the Carpathian Region - the central and southern parts (Figure 4).

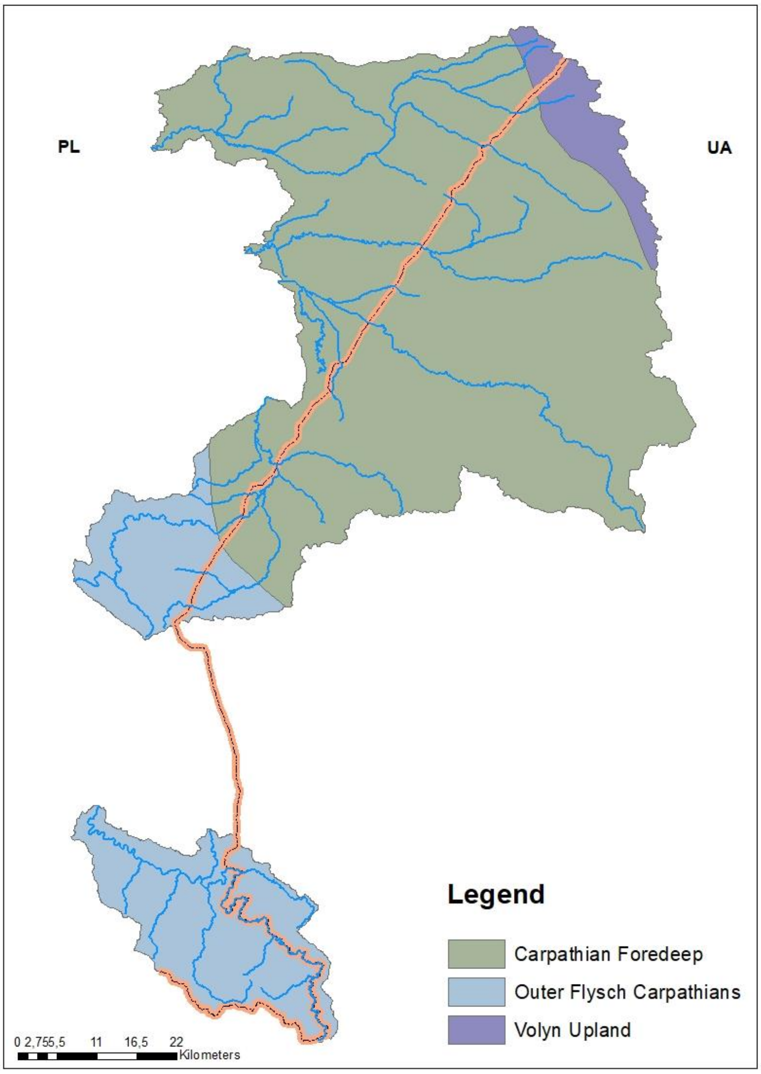


Figure 4 Physical environment map of TGR San

It is an area belonging to three geological and tectonic units. The Roztochia part of the TGR San belongs to the margin basin, the Podkarpacie region - to the Carpathian basin, and only the southern part - the Eastern Beskids is associated with the Outer Flysch Carpathians. This fact is reflected in the geological structure (Figure 5).

The Badenian sediments of the Roztochia hills are formed by quartz sands and limestones. Detritic limestones are most widespread in the study area.

In the area of the Carpathian Foredeep, the Miocene limestone sediments are of other geological origin and are thrown down by faults to a considerable depth. A thick layer of Sarmatian deposits in the form of the so-called "Kraków loams" is composed of loams, silts and fine-grained sands. In the near-edge zone, they also include sandstones, mudstones and marls. The thickness of the Sarmatian deposits is varied and reaches up to 3,000 m. On the surface, the Kraków loams are exposed only on the hills.

The southern part of the TGR San belonging to the Outer Carpathians is characterized by its distribution of flysch deposits on the surface. These formations are formed as alternately deposited Cretaceous and Tertiary sandstones and shales, which has a significant influence on the hydrogeological conditions. The ratio of schist to sandstone varies. Krosno layers have the largest share of schist in the structure of flysch, therefore the worst hydrogeological features.

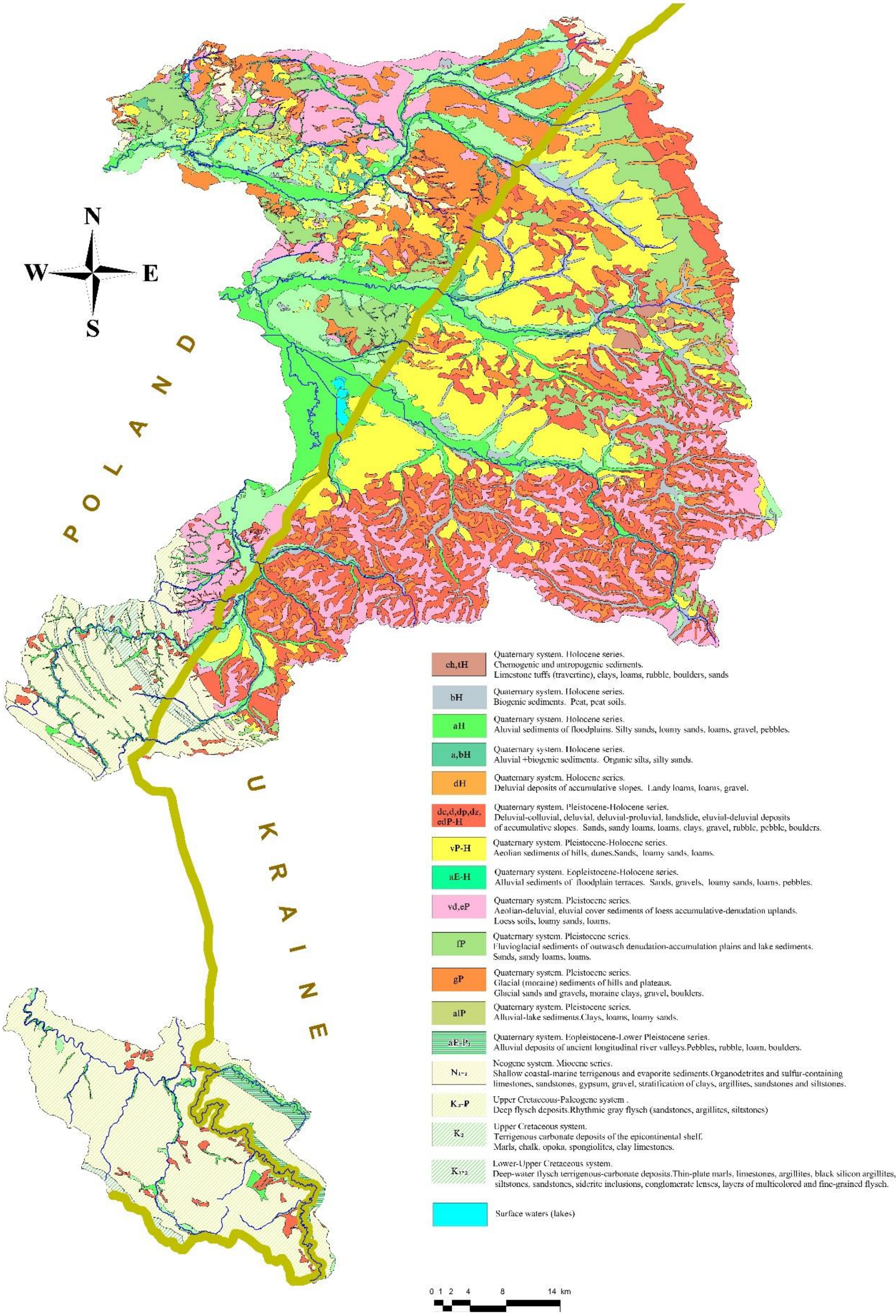


Figure 5 Geological map of TGR San

The vast majority of the TGR San area (over 90%) is covered by Quaternary sediments. These are sediments of variable thickness (up to several dozen meters in the buried valleys) and of various types of development. River valleys are filled with alluvial sediments - sand, gravel, pebbles. These sediments are generally well permeable, and the thickness of the aquifer is varied, usually not exceeding 5 m. Apart from the river valleys in Roztochia and the Carpathian Foredeep, the Quaternary formations are represented by glacial residues, limnoglacial hydro-glacial silts and aeolian sediments. In the Carpathians flysch, Quaternary formations are represented by weathered clays with a relatively small thickness, usually up to several meters.

In the area of the TGR San, there are aquifers in the Cretaceous, Neogene and Quaternary formations.

The useable Upper Cretaceous aquifer in Roztochia is mainly in the Polish part of the area. It is associated primarily with the carbonate formations of the Upper Cretaceous. Thus, it is a fractured reservoir, most often with a unconfined or lightly confined water table. The average thickness of waterlogged deposits is 100 m. The averaged filtration coefficient is 3.7 m/d. The water conductivity of the aquifer ranges from <100 to 1500 m^2/d, and the potential intake discharge from <10 to 120 m^3/h.

Within the Polish part, the Neogene aquifer is of local importance, because most of the basin is filled with thick series of Kraków clays. Within the Ukrainian part, this aquifer is useful. It is the main aquifer of the western water intakes of Lviv.

The Neogene aquifer is common in sandy sediments, sandstones, gypsum and calcareous-lithotamous formations.

The average thickness of these sediments is up to 30.0 m. These formations lie at a depth of 16.0 – 21.0 m and sink towards the south-west. The Neogene 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. The discharge of the wells ranges from 13.3 to 45.7 m^3/h. This aquifer is also associated with the presence of sulphate medicinal waters. The Neogene aquifer recharges in the Roztochia region and discharges in the San River. The waters of the Neogene and Cretaceous aquifers are often in hydraulic contact.

The useful aquifer in the Quaternary alluvial formations is widely spread in the area of the TGR San. Actually, it does not occur only in places where there are tills covers directly on the Miocene loams. The quaternary aquifer is built of river sediments of the San valley and its tributaries, as well as hydro-glacial formations and sediments of old buried structures (e.g. the San and Lubaczówka proglacial valleys). They are made of gravel and sand. The thickness of the Quaternary formations in the San valley is up to 20.0 meters. Outside this region, the thickness of the Quaternary formations usually does not exceed several meters. The best conditions for infiltration occur within the Holocene terraces of San, Szkło and Lubaczówka, i.e. where there are deposits with high permeability. The aquifer is generally up to 1-5 m below the ground level. The Quaternary aquifer is unconfined (usually in river valleys) or pressurized. The pressure may be up to 20 m. The filtration coefficient is usually in the range of 10 - 30 m/d. The capacity of wells is 30 m^3/h on average.

Due to the presence of flysch on the surface, the southern part of the TGR San outside the river valleys was treated as a waterless area in terms of the presence of usable aquifers. However, it is believed that in areas separated as anhydrous, there may be places where even more than 5 m^3/h can be obtained from a single intake. These places are conditioned by the occurrence of fractures in the sandstone.

3.3 Geological and hydrogeological conditions of the TGR Dniester

TGR Dniester is mostly located in Ukraine. It is an area belonging to three geological and tectonic units (Figure 6):

1. Northern part - the Roztochia - belongs to the Volyn-Podillia Upland.
2. Central parts - the Podkarpacie region - to the Carpathian Foredeep.
3. Southern part - the Eastern Beskids is associated with the Outer Flysch Carpathians.

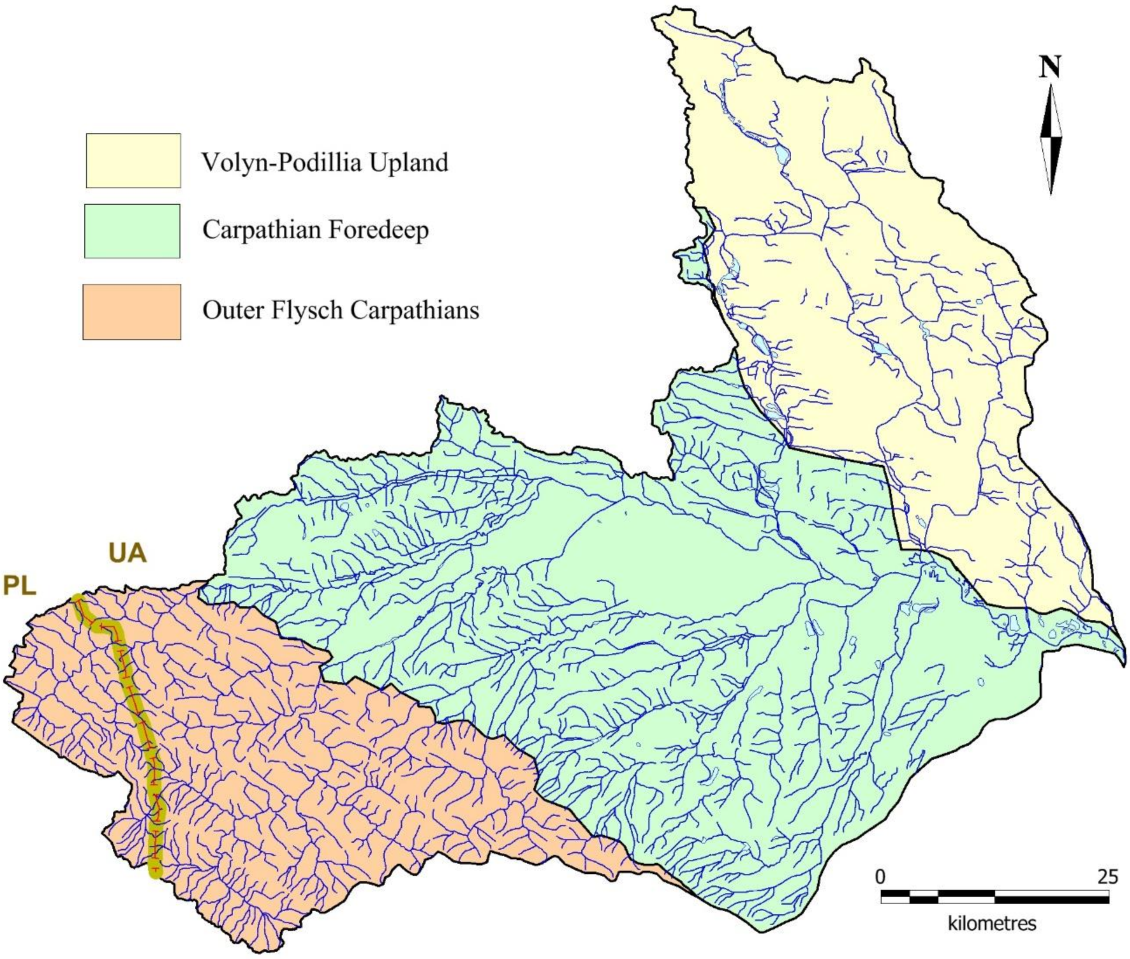


Figure 6 Physical environment map of TGR Dniester

In the Roztochia Miocene limestone is the most widespread. In the Carpathian Foredeep, the Miocene limestone sediments are thrown down by faults to a considerable depth. Here they appear on the surface of the ground the Sarmatian deposits in the form of the so-called "Kraków loams" is composed of loams, silts and fine-grained sands.

The southern part of the TGR San belonging to the Outer Carpathians is characterized by its distribution of flysch deposits on the surface. These formations are formed as alternately deposited Cretaceous and Tertiary sandstones and shales. Flysch formations are covered with quaternary weathered clays with an admixture of sandstone. Their thickness is generally 1–3 m.

There are two aquifers in the TGR Dniester area: Quaternary and flysch (i.e. Paleogene-Cretaceous). The flysch aquifer occurs almost in the entire area, while the Quaternary - only locally in river valleys, in a very small area in total.

The Paleogene-Cretaceous (flysch) layer represents the Upper Cretaceous, Paleogene and Lower Miocene layers. The flysch aquifer of a rift character is a near-surface zone built of fractured sandstones containing clay-marly shale inserts with a thickness of 40-80 m. The flow of groundwater in the flysch formations takes place in the cracked and fractured zone, accordingly to the morphology of the terrain towards the river valleys. The water table of this level is fragmented, not continuous and its shape cannot be reproduced in the form of hydroisohypses. On the Polish side, the Paleogene-Cretaceous horizon has a poor hydrogeological recognition based on ca. 70 wells reaching a maximum depth of 100 m (most often 30–50 m). The well discharge of flysch aquifer ranges from 0.3 to 14 m^3/h. The flysch aquifer is drained by the Strwiąż and Mszanka rivers with their tributaries, and by numerous springs of various discharges, usually not exceeding 1 dm^3/s.

The Quaternary useful aquifer occurs in gravel-sandy, partially clayey alluvial sediments of Strwiąż and Mszanka. The supply of the Quaternary aquifer takes place through direct infiltration of atmospheric precipitation, infiltration of surface waters and lateral inflow of waters from flysch formations, which is favored by full hydraulic connectivity of both aquifers. The best conditions for infiltration exist within the Holocene terraces of the Strwiąż River, i.e. where there are deposits with high permeability.

The Quaternary aquifer is drained by Strwiąż and Mszanka. The water table is generally up to 5 m below the ground level and is most often unconfined. Only in regions where the Quaternary formations are characterized by high lithological variability in the vertical profile and in horizontal spread, and where they are covered with a layer of silty and loess formations, the waters may be characterized by low pressure. Moreover, it was found that the alluvials of Strwiąż and Mszanka are often muddy. The thickness of the Quaternary formations in the Strwiąż and Mszanka valleys reaches a maximum of 7.0 meters. The filtration coefficient is usually in the range 5 - 10 m/24h. The discharge of the wells is 10 m^3/h on average.

4 Conceptual model of transboundary groundwater aquifers with significant potential of groundwater transfer between Poland and Ukraine

The conceptual hydrogeological model (conceptual model of an aquifer) is a descriptive and graphical representation of the structure and processes occurring in the hydrogeological system. The model is a set of hypotheses as to how the real hydrogeological system is structured and behaves, how it is related to the environment (supply, contact with surface water) and how it responds to recharge. These hypotheses are verified in the next, more detailed, stages of hydrogeological research (e.g. mathematical modeling).

The concept of the functioning of the hydrogeological system on the PL-UA pilot site was developed on the basis of analyzes of archival materials, including:

- observation of the position of the groundwater table in ok. 57 monitoring wells;
- 2 926 hydrogeological data and profiles of boreholes;
- hydrological measurements from 20 hydrometric sites;
- meteorological data form 10 meteorological observation sites;
- documentation of ca. 200 groundwater intakes;
- GIS databases "Detailed geological map of Poland in the scale 1: 50,000" (Geological map, 2017);
- GIS databases "Geological map of Ukraine in the scale 1: 50,000";
- GIS databases "Hydrogeological map of Poland - Main Useful Aquifer in the scale 1: 50,000";
- GIS databases "Hydrogeological map of Ukraine - Main Useful Aquifer in the scale 1: 50,000";
- GIS databases "Hydrogeological map of Poland - First Aquifer in the scale 1: 50,000";
- GIS CORINE Land Cover CLC 2018 Database - Land Cover (The Copernicus Programme, 2018);
- digital terrain model based on SRTM data;
- topographic maps in scales from 1: 10,000 to 1: 50,000 (geoportal.gov.pl);
- hydrographic data available in the MPWP information layer.

Stages of creating of a conceptual hydrodynamic model are:

- concept of the structure (structure) of the hydrogeological system;
- concept of the structural processes taking place in the hydrogeological system;
- structure of spatial variability - schematization of hydrogeological conditions.

The model structure concept defines and justifies:

- spatial extent of the layers forming the analyzed hydrogeological system,
- division of the hydrogeological system into aquifers and poorly permeable layers;
- hydrodynamic barriers to groundwater flow (rivers draining useful aquifers, watersheds, significant intakes and drainage systems);
- the amount of infiltration recharge (including evapotranspiration);
- directions and quantity of the aquifers flow.

In the assessment of the transboundary groundwater flows between Poland and Ukraine based on the numerical hydrodynamic model, an assumption was made that the modeling area would be limited to the area of the first cross-border usable aquifer with significant groundwater exchange potential. According to the indicator adopted in this regard - water conductivity of the aquifer, the selection of the relevant transboundary aquifers is carried out on the basis of the water conductivity criterion ≥ 50 m^2/24h.

Correct determination of the spatial extent of the model and preparation of a conceptual model of the aquifer system structure is not possible without a detailed analysis of the geological structure and hydrogeological conditions of the area. Hydrogeological maps and sections are the basis for determining the concept of the model structure. Already at this stage, the preliminary schematization of the aquifer is carried out. This is due to incomplete (discrete) knowledge of the geological space, which in turn makes it necessary to interpret the spread and lithology of rock layers. Reliable interpretation of geological data requires the widest possible use of the available geological information and knowledge about the possible course of processes that determine sedimentation and erosion.

The development of the conceptual model began with the preparation of five hydrogeological sections cutting the studied area parallel (section AA”) and perpendicular (sections BB”, CC”, DD”) to the Polish-Ukrainian border (Figure 7).

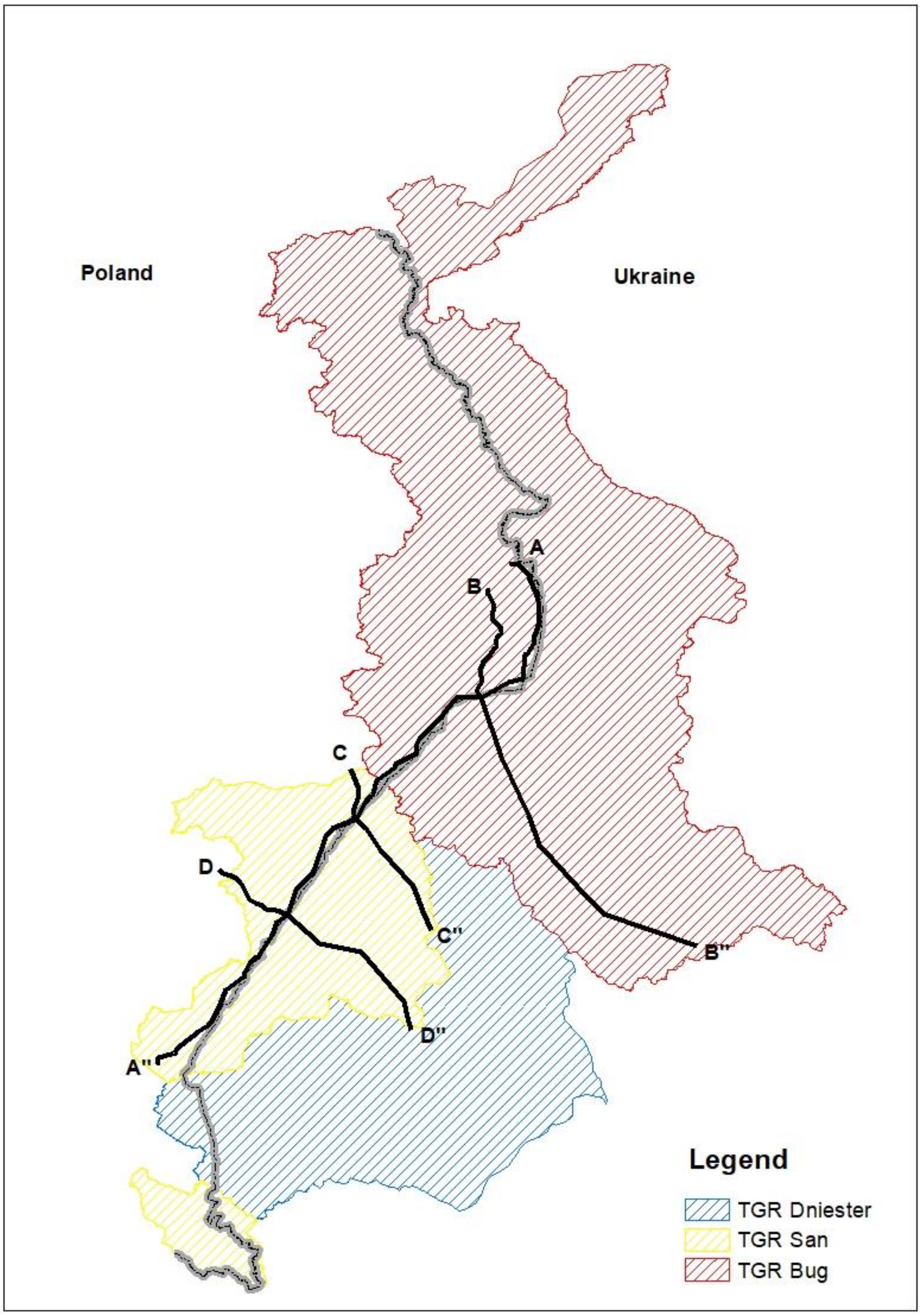
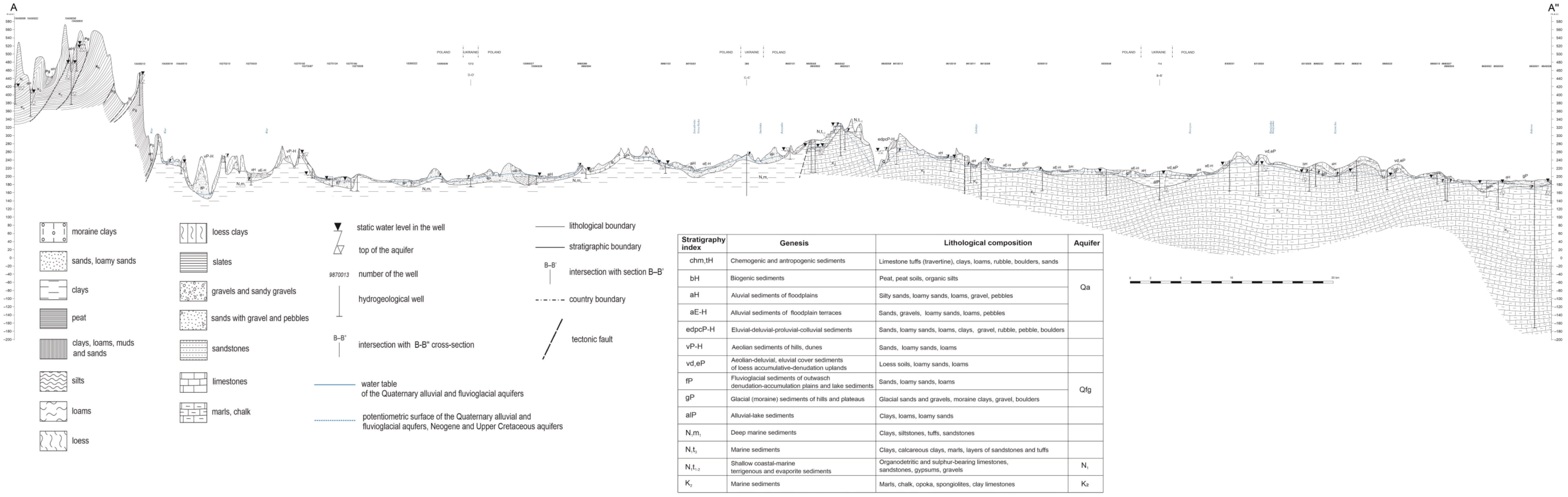


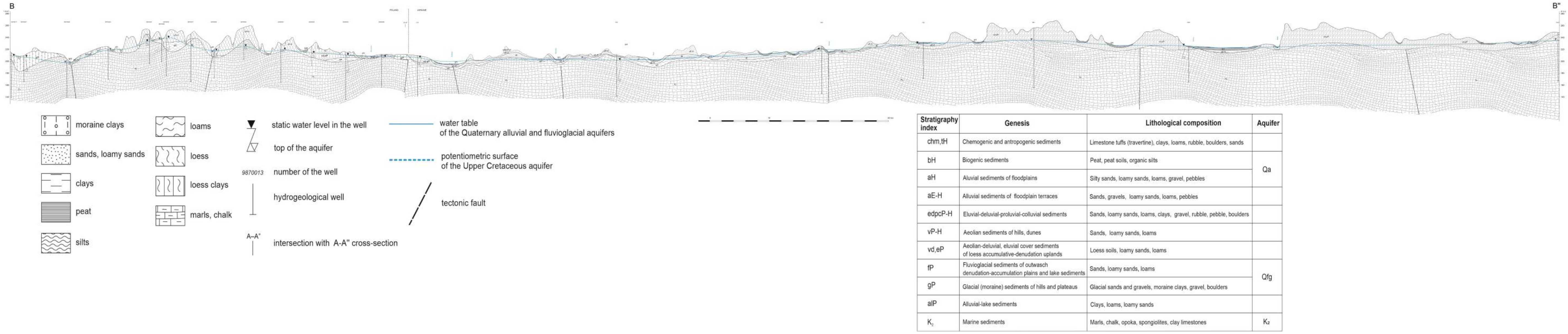
Figure 7 Lines of hydrogeological cross-sections in the Polish-Ukrainian border area

This made it possible to trace the nature and distribution of the aquifers on a regional scale and their variability. The regional approach made it possible to identify regularities that would be difficult to notice on a local scale. The profiles of exploitation and research holes were used to prepare the cross-sections. Additionally, data from the Geological Map of Poland and Ukraine in the scale 1: 50,000 were used. The cross-sections provide information on the lateral and vertical distribution of successive aquifers and impermeable layers (Figures 8-11). The levels of groundwater tables and potentiometric surfaces of individual wells was also marked, which, combined with the image of the hydroisohypses taken from the hydrogeological map, allowed for the interpretation of the directions of groundwater flow and the directions of infiltration through hardly permeable layers.



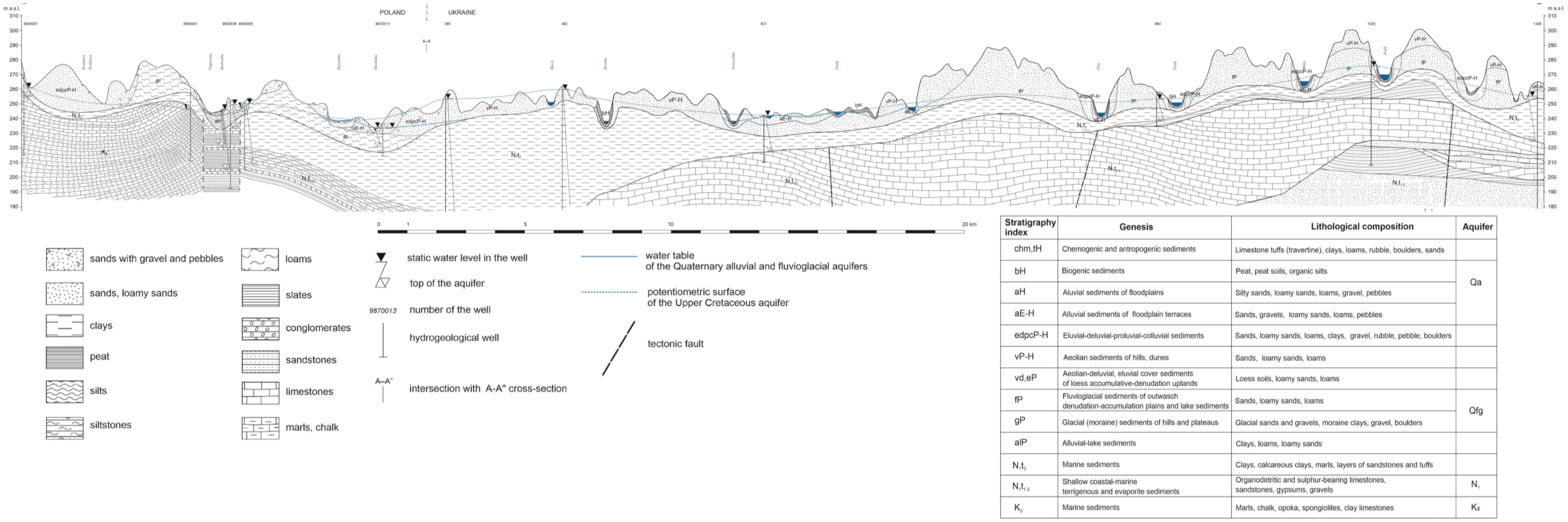
Stratigraphy index	Genesis	Lithological composition	Aquifer
chm,tH	Chemogenic and antropogenic sediments	Limestone tuffs (travertine), clays, loams, rubble, boulders, sands	
bH	Biogenic sediments	Peat, peat soils, organic silts	Qa
aH	Aluvial sediments of floodplains	Silty sands, loamy sands, loams, gravel, pebbles	
aE-H	Alluvial sediments of floodplain terraces	Sands, gravels, loamy sands, loams, pebbles	
edpcP-H	Eluvial-deluvial-proluvial-colluvial sediments	Sands, loamy sands, loams, clays, gravel, rubble, pebble, boulders	
vP-H	Aeolian sediments of hills, dunes	Sands, loamy sands, loams	
vd,eP	Aeolian-deluvial, eluvial cover sediments of loess accumulative-denudation uplands	Loess soils, loamy sands, loams	
fP	Fluvioglacial sediments of outwasch denudation-accumulation plains and lake sediments	Sands, loamy sands, loams	Qfg
gP	Glacial (moraine) sediments of hills and plateaus	Glacial sands and gravels, moraine clays, gravel, boulders	
alP	Alluvial-lake sediments	Clays, loams, loamy sands	
N_1m_1	Deep marine sediments	Clays, siltstones, tuffs, sandstones	
N_1t_3	Marine sediments	Clays, calcareous clays, marls, layers of sandstones and tuffs	
N_1t_{1-2}	Shallow coastal-marine terrigenous and evaporite sediments	Organodetritic and sulphur-bearing limestones, sandstones, gypsums, gravels	N_1
K_2	Marine sediments	Marls, chalk, opoka, spongiolites, clay limestones	K_2

Figure 8 Hydrogeological section of AA''



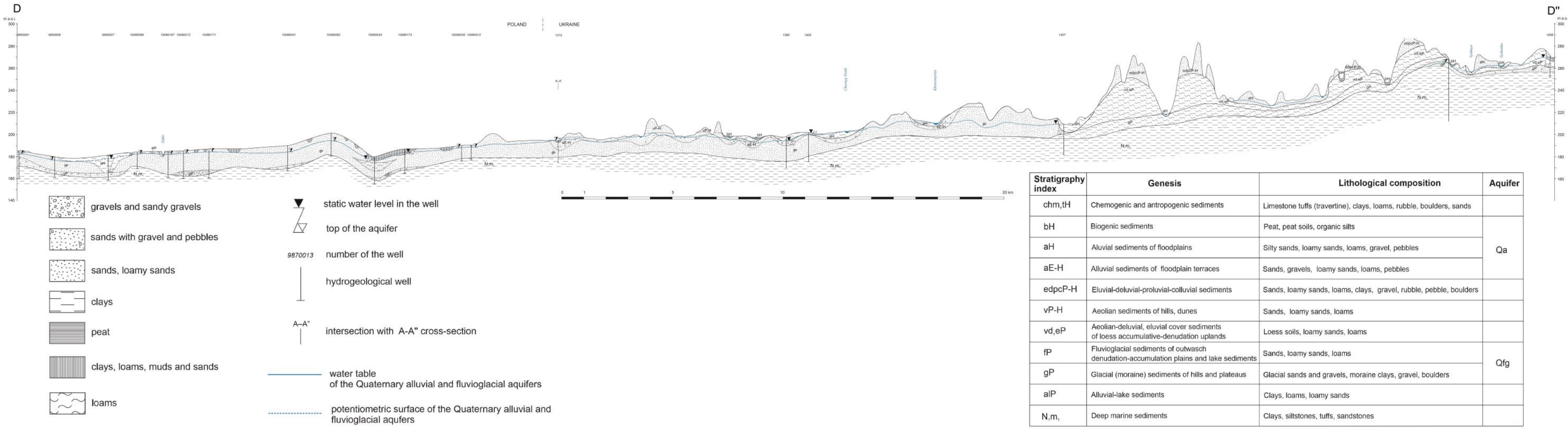
Stratigraphy index	Genesis	Lithological composition	Aquifer
chm,tH	Chemogenic and antropogenic sediments	Limestone tuffs (travertine), clays, loams, rubble, boulders, sands	
bH	Biogenic sediments	Peat, peat soils, organic silts	Qa
aH	Aluvial sediments of floodplains	Silty sands, loamy sands, loams, gravel, pebbles	
aE-H	Alluvial sediments of floodplain terraces	Sands, gravels, loamy sands, loams, pebbles	
edpcP-H	Eluvial-deluvial-proluvial-colluvial sediments	Sands, loamy sands, loams, clays, gravel, rubble, pebble, boulders	
vP-H	Aeolian sediments of hills, dunes	Sands, loamy sands, loams	
vd,eP	Aeolian-deluvial, eluvial cover sediments of loess accumulative-denudation uplands	Loess soils, loamy sands, loams	
fP	Fluvioglacial sediments of outwasch denudation-accumulation plains and lake sediments	Sands, loamy sands, loams	Qfg
gP	Glacial (moraine) sediments of hills and plateaus	Glacial sands and gravels, moraine clays, gravel, boulders	
alP	Alluvial-lake sediments	Clays, loams, loamy sands	
K_2	Marine sediments	Marls, chalk, opoka, spongiolites, clay limestones	K_2

Figure 9 Hydrogeological section of BB''



Stratigraphy index	Genesis	Lithological composition	Aquifer
chm,tH	Chemogenic and antropogenic sediments	Limestone tuffs (travertine), clays, loams, rubble, boulders, sands	
bH	Biogenic sediments	Peat, peat soils, organic silts	Qa
aH	Aluvial sediments of floodplains	Silty sands, loamy sands, loams, gravel, pebbles	
aE-H	Alluvial sediments of floodplain terraces	Sands, gravels, loamy sands, loams, pebbles	
edpcP-H	Eluvial-deluvial-proluvial-colluvial sediments	Sands, loamy sands, loams, clays, gravel, rubble, pebble, boulders	
vP-H	Aeolian sediments of hills, dunes	Sands, loamy sands, loams	
vd,eP	Aeolian-deluvial, eluvial cover sediments of loess accumulative-denudation uplands	Loess soils, loamy sands, loams	
fP	Fluvioglacial sediments of outwasch denudation-accumulation plains and lake sediments	Sands, loamy sands, loams	Qfg
gP	Glacial (moraine) sediments of hills and plateaus	Glacial sands and gravels, moraine clays, gravel, boulders	
alP	Alluvial-lake sediments	Clays, loams, loamy sands	
N_1t_3	Marine sediments	Clays, calcareous clays, marls, layers of sandstones and tuffs	
N_1t_{1-2}	Shallow coastal-marine terrigenous and evaporite sediments	Organodetritic and sulphur-bearing limestones, sandstones, gypsums, gravels	N_1
K_2	Marine sediments	Marls, chalk, opoka, spongiolites, clay limestones	K_2

Figure 10 Hydrogeological section of CC"



Stratigraphy index	Genesis	Lithological composition	Aquifer
chm,tH	Chemogenic and antropogenic sediments	Limestone tuffs (travertine), clays, loams, rubble, boulders, sands	
bH	Biogenic sediments	Peat, peat soils, organic silts	Qa
aH	Aluvial sediments of floodplains	Silty sands, loamy sands, loams, gravel, pebbles	
aE-H	Alluvial sediments of floodplain terraces	Sands, gravels, loamy sands, loams, pebbles	
edpcP-H	Eluvial-deluvial-proluvial-colluvial sediments	Sands, loamy sands, loams, clays, gravel, rubble, pebble, boulders	
vP-H	Aeolian sediments of hills, dunes	Sands, loamy sands, loams	
vd,eP	Aeolian-deluvial, eluvial cover sediments of loess accumulative-denudation uplands	Loess soils, loamy sands, loams	
fP	Fluvioglacial sediments of outwasch denudation-accumulation plains and lake sediments	Sands, loamy sands, loams	Qfg
gP	Glacial (moraine) sediments of hills and plateaus	Glacial sands and gravels, moraine clays, gravel, boulders	
alP	Alluvial-lake sediments	Clays, loams, loamy sands	
N_1m_1	Deep marine sediments	Clays, siltstones, tuffs, sandstones	

Figure 11 Hydrogeological section of DD”

Hydrogeological sections were the basis for determining the model boundaries.

In hydrogeological modeling, the most correct models are those in which the model area boundaries are surface water courses. In the developed model, in the vast majority of cases, the boundaries have been based on rivers draining the first aquifer, but also often on watersheds (Figure 12). As shown in Figure 12, the model covers only the southern part of the TGR Bug - from the place where the Bug ceases to be a border river and turns towards Ukraine, which means it ceases to be an obstacle to the transboundary flow of groundwater. Moreover, it has been decided not to include the eastern extremities of the TGR Bug - the right-bank part of the catchment area of the Bug in the model, because groundwater from these areas ends up in the Bug and does not cross the state border. According to analogous assumptions, the western extremities of the TGR San were not included. On the other hand, the exclusion from the modeling area of the TGR Dniester and the southern part of the TGR San is related to the failure to meet the criterion of significant groundwater exchange potential. In this area, the potential for cross-border groundwater exchange is below 50 m^2/24h according to water conductivity.

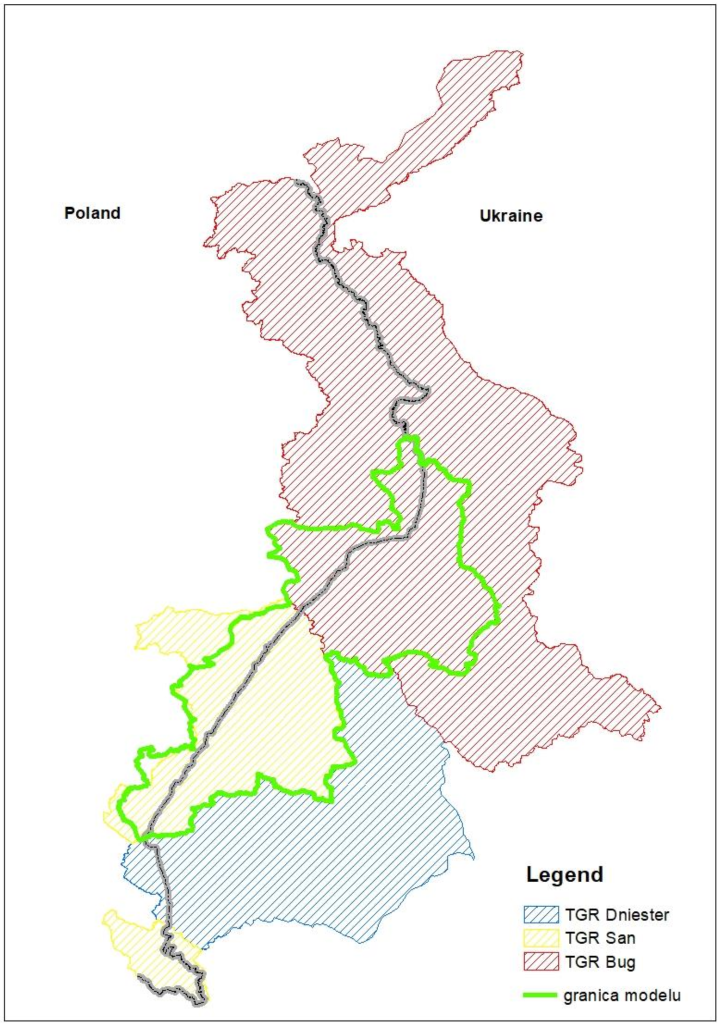


Figure 12 The spatial extent of the boundary of the hydrodynamic model

Hydrogeological sections were the basis for the development of a conceptual model diagram. This diagram provides an idea of the structure, functioning and relationship with the surroundings of the aquifer. The development of a conceptual model requires further schematization of the system. This is mainly due to incomplete (discrete) knowledge about the individual elements of the model. Thus, the image of the aquifer can be treated as a preliminary hypothesis that requires verification. The means of verification is a mathematical model of the aquifer. This means that the methodology of model development should follow the requirements of the mathematical model. It makes it necessary to apply simplifications consisting in aggregation of aquifers.

The structure of the conceptual model was developed based on the following criteria:

- the separated aggregate aquifers had to be common in the study area or at least widely distributed;
- aquifers could be aggregated only when their hydraulic connectivity was found to be common, and the separating layers were discontinuous and of limited thickness;
- when aggregating aquifers, the nature of the aquifer and its water permeability were first taken into account, and only then the stratigraphy of sediments;
- the separated isolating (separating) horizons had to be of considerable thickness and continuity.

Within the conceptual model of the research area, two layers were distinguished (Figure 13):

- 1st layer - alluvial aquifer in the valleys of large rivers;
- 2nd layer is spatially heterogeneous. In the north it is the Upper Cretaceous fissure aquifer, in the central part - the Neogene fissure-pore aquifer, and in the south - the Quaternary pore aquifer.

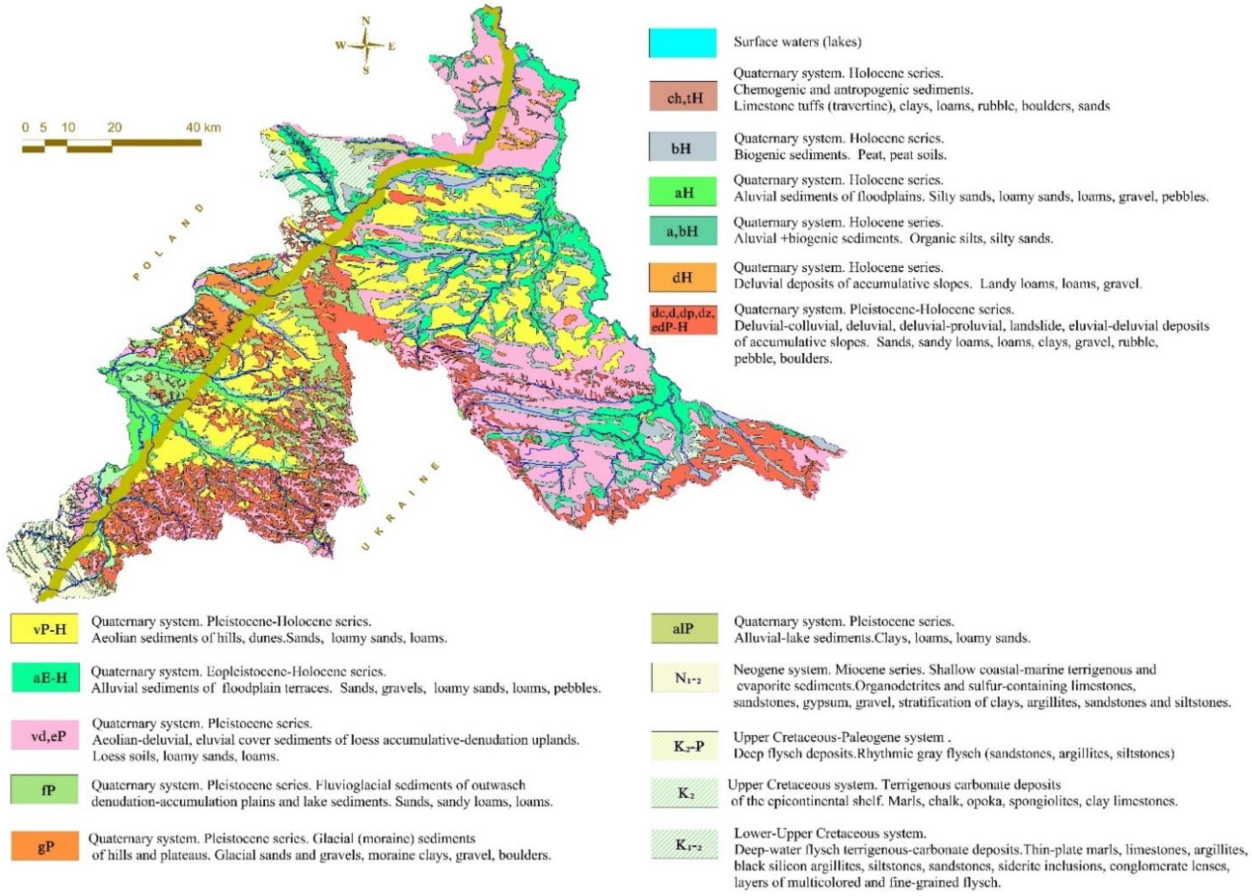


Figure 13 Geological map of the model area

1st layer - alluvial aquifer in the valleys of large rivers

It consists of various types of alluvial sands, gravel, pebbles, and therefore the layer has good permeability. As a rule, these are pieces not covered with any cover of impervious rocks, so this aquifer is unconfined. The layer occurs in the valleys of the main rivers of the study area and their larger tributaries. The thickness of the aquifer rarely exceeds 30 meters. It is recharged mainly due to precipitation.

2nd layer

- Within the Upper Cretaceous sediments of the lowland unit within the borders of the East European Platform.

This aquifer is built mainly of marls, chalk, sandy marls, marly limestones, gaize. It occurs over the entire lowland part of the model area.

Upper Cretaceous aquifer is one of the most useful aquifers of the study area. It is an aquifer of the fissure type of water-bearing rock. It is mainly confined (artesian) aquifer. The type of water is mainly HCO_3-Ca. The filtration coefficient of the aquifer is in the range of 0.01 - 1.8 m/h. The water permeability of the aquifer depends on its fracture. In the upper part of the massif, the network of tectonic fractures overlaps with airborne cracks, which facilitate the flow of groundwater. As the depth increases, the fractures are gradually tightened by the pressure of the rock mass. The conducted research has shown that the bottom of the active water exchange zone is located at a depth of 100 - 50 m, and the rocks deeper than 200 m below the surface are practically impermeable. The depth of occurrence of the base of the active exchange zone is determined by the mechanical properties of the rocks. In hard marls and limestones it is greater than in soft marls or writing chalk. Locally it may occur deeper. It takes place in dislocation zones, where the flow of groundwater through numerous fissures is facilitated. These fragmented zones of tectonic faults can be ways of penetration into the Upper Cretaceous aquifer of waters from the lower horizons.

- Within the Neogene sediments of the upland area

Despite the small distribution of the Neogene aquifer, it was decided to single out this layer because of the very large role it plays in transboundary flows. It is located in the central part of the model area within the uplands of Roztochia region.

Neogene aquifer is common in fissure-porous formations. Often water-bearing rocks are karst. It combines water-bearing layers of sandstones, limestones, gypsum. Therefore, type of water is HCO_3-Ca and SO_4-Ca. The aquifer is mostly confined, the potentiometric surface is at a depth of 5 to 50 m below ground level. The water-bearing capacity and capacity of the deep wells of this aquifer are considerable. The thickness of the connected aquifer is several dozen meters. The waters of the Neogene aquifer are often weakly isolated from the surface. The recharge is carried out by the infiltration of precipitation directly into the layers or through the permeable sands of the Quaternary aquifer.

- Within the Quaternary deposits of postglacial areas

Quaternary fluvioglacial aquifer was separated in the southern part of the modelling area within the Carpathian Foredeep.

Within the Carpathian Foredeep, only the Quaternary formations play the role of aquifer, because below the deposits of the Neogene Age are represented by a complex of practically impermeable clay. The Quaternary cover in this area is postglacial. This area, as well as the above, underwent glaciation once (southern Poland, after which there were remaining thick layers of tills), and twice during the Central and North Polish glaciations, periglacial conditions prevailed here. During the Mazovian interglacial period, the area was elevated, and strong erosion caused the cutting of the glacial sediment covers and the formation of deep valleys, which were then filled, during the Central Polish glaciation, with sand and silt sediments of large river backwaters. Aeolian sediments are among the sediments that are represented in this area and remain a remnant of the North Polish glaciation.

The Quaternary aquifer includes all fluvioglacial layers, mainly various types of sand and gravel. As a rule, these areas are not covered by any cover of impervious rocks, so aquifer is unconfined. The thickness of the aquifer rarely exceeds 20 meters. It is recharged mainly due to precipitation.

Within Ukraine, this aquifer is locally spread, mainly within river valleys. Here it is characterized by weak water saturation.

The hydrogeological characteristics of the separated aquifers are presented in Table 1.

Table 1 Hydrogeological characteristics of aquifers included in the hydrodynamic model

Aquifer		**Quaternary - alluvial**	**Cretaceous**	**Neogene**	**Quaternary - fluvioglacial**
The depth of the top of aquifer (from – to) [m]		0	0-120	10–60	2–10
The nature of the aquifer (confined / unconfined)		Unconfined	Confined, locally unconfined	Confined, locally unconfined	Unconfined
The ordinate of the water table/potentiometric surface (m above sea level)		160-220	160 - 300	250–375	220-580
Characteristics of the aquifer		pore	fissure	fissure-pore	pore
Lithology		sand, gravel, pebble	marl, chalk	sandstone, calcareous-lithotamous formations	sand, gravel
Hydrogeological parameters of the aquifer	m [m]	2–5	10-115	10-40	2-20
	k [m/h]	0.022-1.7	0.001-92.16	0,001-0,10	0.42-1.25
	T [m^2/h]	1.0-20	0.05-50	0.01-4.20	0.05-10
The nature of the contact with the underlying aquifer		Full hydraulic contact	No contact	No contact, weak contact	No contact

Apart from the aquifers, the model structure distinguishes also the separating layers that were aggregated with respect to their poor permeability and stratigraphy. The following separation layers were distinguished:

- QG - it is a discontinuous layer of tills and other sediments with poor permeability, mainly silt, which is common and constitutes interfacing in the Quaternary layer or underlying this level. In some areas, it occurs above the ground, especially in areas with no usable aquifers. The thickness of the level is varied, up to 40 m.
- Tr - a layer covering a stratigraphic range of practically impermeable Paleogene-Neogene formations, especially the Kraków loams belonging to the Miocene. It is the most common layer in the Carpathian Foredeep, whose thickness varies but reaches up to 3,000 m. Within it, there are interfaces carrying highly mineralized waters, but well insulated from the usable horizons.

5 Numerical model of the transboundary aquifer

Hydrogeological model studies of the transboundary groundwater flow in the border region of Poland and Ukraine were carried out on the basis of the conceptual model described above. Archival data and geological information, in particular, such as: profiles of hydrogeological holes, geological maps, cross-sections, numerical terrain model (SRTM) were used to construct the mathematical model. The structure of the model and the workflow were adapted to the main objective of the model study, i.e. the preparation and calibration of the model reflecting the hydrodynamic state of the groundwater flow, enabling the balance of groundwater flowing across the state border and the design of an effective monitoring network in the future.

The model study concerned the first and the main usable aquifer in the study area.

Software tools used for research

The Groundwater Vistas 6.2 program (MODFLOW, PEST counting modules) was used for mathematical modeling. ArcGIS 10.3 and QGIS 3.10 were used to manage archival hydrogeological data and conduct spatial and statistical analyzes.

In order to conduct model calculations, the research area was discretized, the model boundaries were determined, its boundary conditions were defined, the hydrogeological conditions were schematized, an appropriate calculation algorithm was selected and the model was calibrated to determine the effective values of the water-bearing filtration coefficient and conductance of the river beds.

Discretization of the area of model study

The groundwater circulation system was modeled on a two-layer hydrodynamic model (the separating layer is not a model layer). The research area was digitized with a square grid with a step of 500 m. The basic size of the discretization grid is 264 columns and 280 rows. The total area of the discretized area is 18,480 km^2. The z-axis discretization of the surface of the research area was based on dividing the space into two layers of variable thickness. Within this area, the active area of the model in layers I and II is 5,582.75 km^2. The model was made in the PUWG-1992 coordinate system. The initial model coordinates (lower left corner) are x = 745,500 y = 190000.

Model boundaries, boundary conditions

The boundaries of the model research area were defined to minimize the impact of boundary conditions on the results of the calculations in the cross-border region. The authors decided to model the area limited by the natural conditions of the 2nd type Q = 0 based on watersheds and the 3rd type - based on the course of surface watercourses. In practice, the model covers a large area of the San and Bug catchment areas limited by lower-order watersheds. The current groundwater abstraction is presented in the form of the type II condition (Q<0). Water ordinates in surface watercourses were adopted on the basis of topographic data (10k) and a numerical terrain surface model. Hydrological data (MPHP) were used to determine the parameters of the river beds. The parameters determining the hydraulic contact between groundwater and surface waters were determined by the method of solving the inverse problem in the process of taring the model.

The distribution of the boundary conditions in the model blocks is presented in the Figure 14.

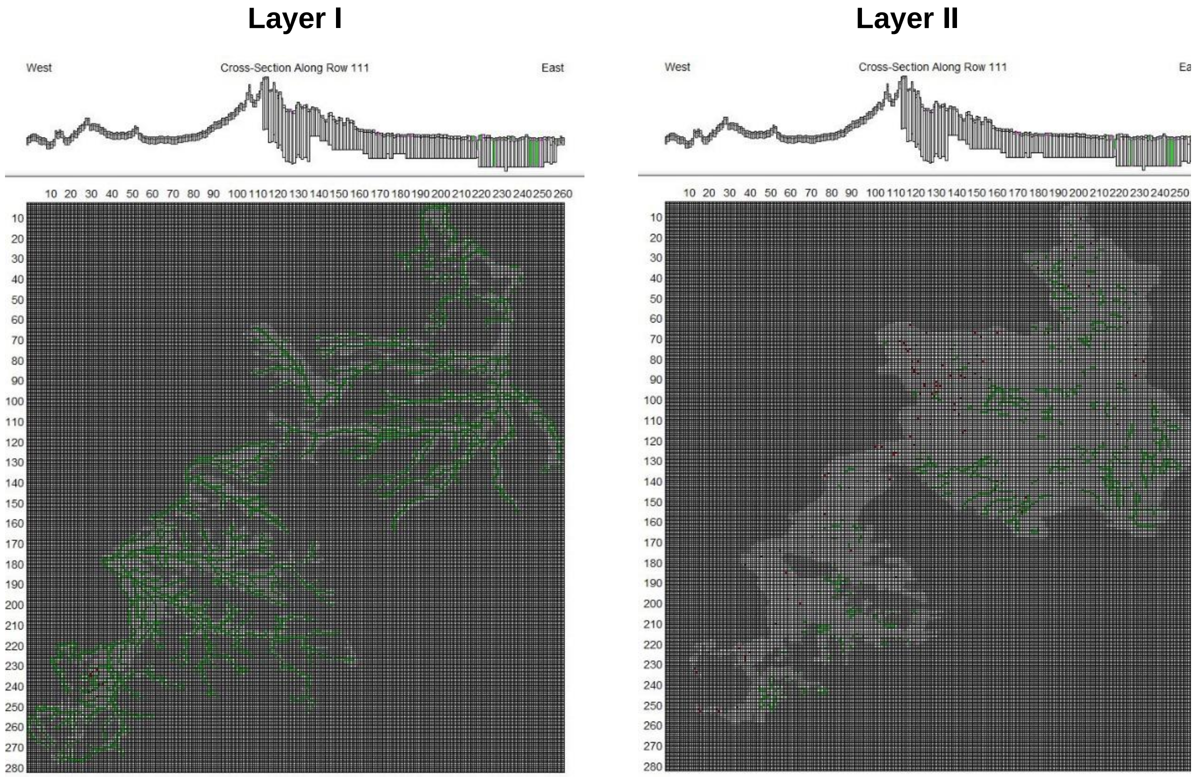


Figure 14 Model boundary conditions in the first and second modeled layers. Green color marks blocks with condition III (river) Dark gray color marks blocks with condition II (Q = 0)

Hydrogeological schematization

In the process of hydrogeological schematization, it was determined that there are two aquifers in the study area with an unconfined and confined groundwater table remaining in hydraulic contact through semi-permeable formations. The first layer from the surface is in direct contact with surface waters mapped with the 3rd type condition. In areas without layer I, layer II has hydraulic contact with surface waters. The aquifers within the model are recharged mainly by percolation, locally by infiltration of surface waters. The constructed flow model is therefore a two-layer model. Groundwater generally moves towards the San and Bug rivers, which are the main drainage base, and locally towards their more important tributaries. The so-defined hydrogeological diagram was supplemented with the following assumptions:

- aquifers are separated by a low-permeable layer, which is not a physical layer of the model, mapped by the filtration coefficient (T '= k/m, where k - separation layer filtration coefficient; m - separation layer thickness);
- bottom of the second aquifer is impermeable;
- groundwater velocity field is constant over time;
- vertical component of the groundwater flow velocity is negligible in relation to the horizontal one.

Mathematical model of water flow

The mathematical model used for the steady-state groundwater flow is the following equation:

$$\frac{\partial}{\partial x}(m(x,y)k(x,y)\frac{\partial H(x,y)}{\partial x})+\frac{\partial}{\partial y}(m(x,y)k(x,y)\frac{\partial H(x,y)}{\partial y})+Q\inf(x,y)+Qst(x,y)=0\;;$$

H(x,y) – position of the groundwater table at the point (x, y) [L]

m(x,y) – the thickness of the aquifer at the point (x, y) [L]

k(x,y) – filtration coefficient at point (x, y) [L/T]

Qinf(x,y) - infiltration intensity at point (x, y) [L^3/T]

Qst(x,y) - well discharge at point (x, y) [L^3/T]

The presented equation is solved by the finite difference method using a rectangular discretization grid with a constant step.

Model parameters

The ordinates of the top and bottom of the modeled layers were adopted on the basis of data from boreholes, cross-sections and geological cartographic studies. The spatial distribution of the filtration coefficient (Figures 15-16) in all layers in the entire domain of the model was interpreted on the basis of auto-matching values using the PEST module using the pilot points method, distributed by triangulation between points with a known value of the water table position (targets). The input values were the mean values of the filtration coefficient in the individual lithostratigraphic extracts. This is a classic example of using the inverse task method.

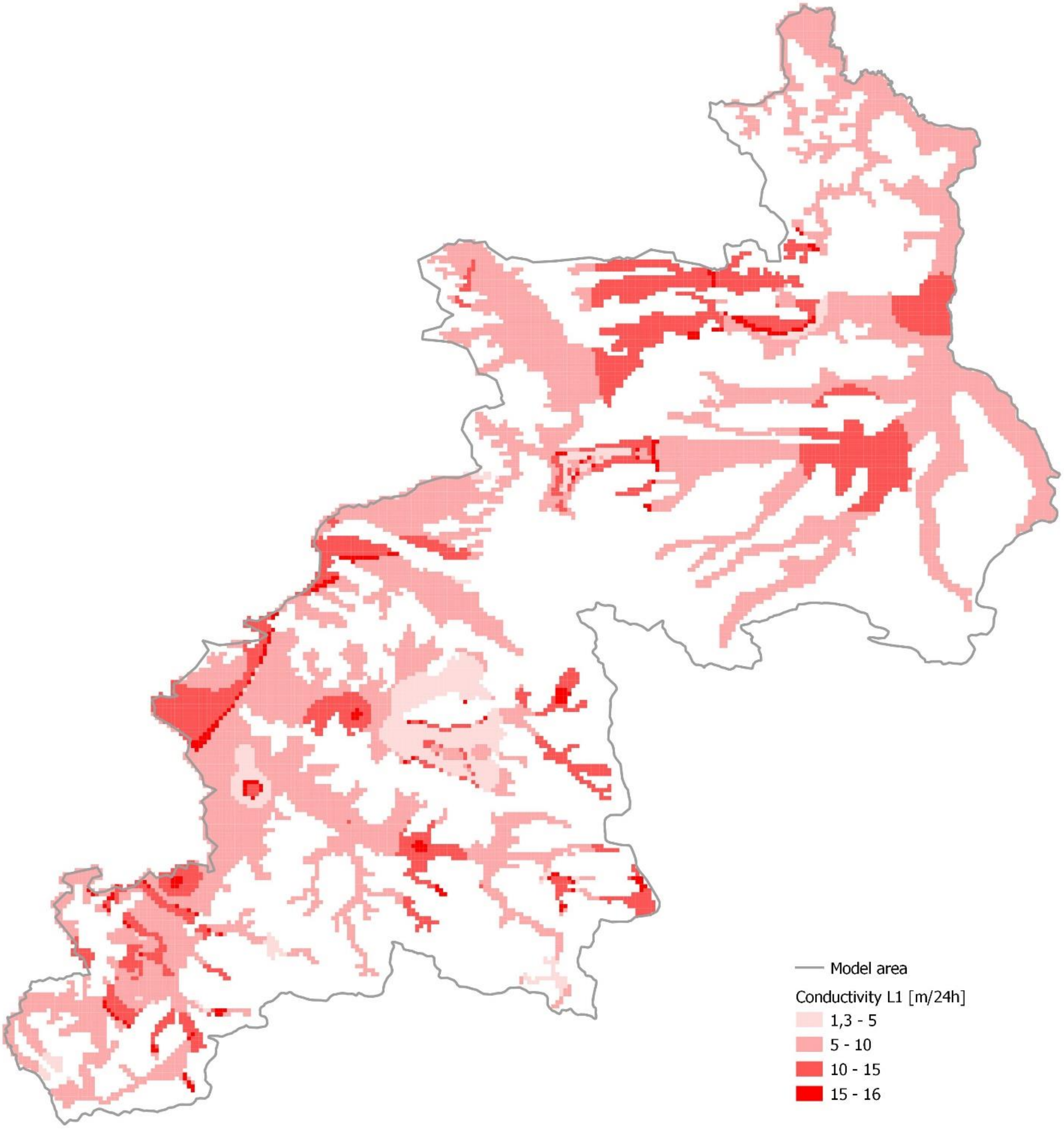


Figure 15 Filtration coefficient distribution in layer I after taring

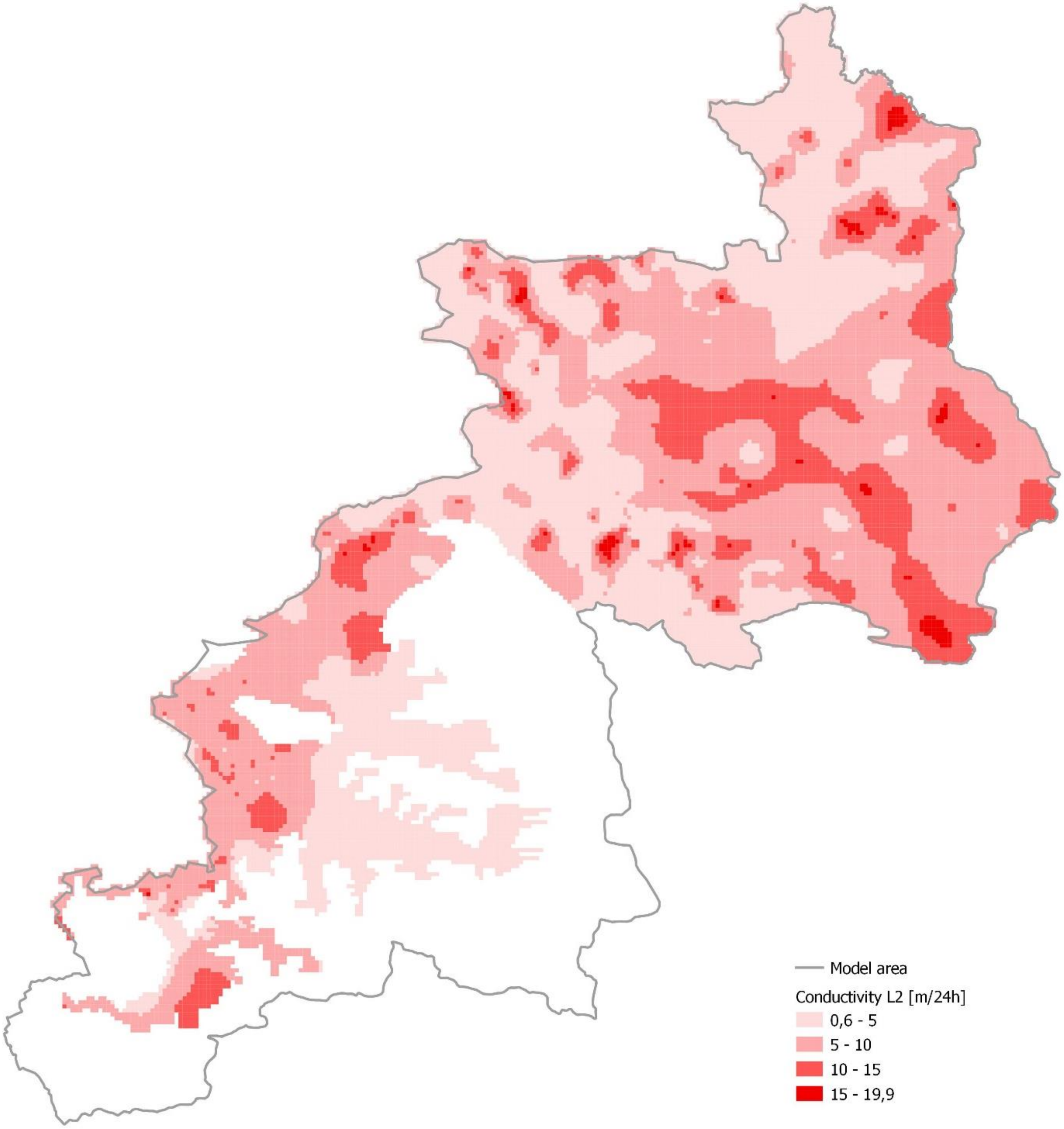


Figure 16 Filtration coefficient distribution in layer II after taring

Recharge of the model was adopted using the constant volume method. It is based on using the value of the underground runoff (Hp) to calculate the amount of infiltrating water within the catchment area (Figure 17). The long-term average value for the part of the Bug catchment area covered by the research is approx. Hp = 60 mm/year, while for the San catchment area Hp = 120 mm/year and such values were adopted as the basis for calculating the infiltration value in individual blocks. The calculated amount of infiltrating water on the model's surface was distributed on the basis of geological conditions (effective infiltration coefficient) identified with use of geological surface maps and GIS information layers showing the presence of wetlands and peatlands (evapotranspiration).

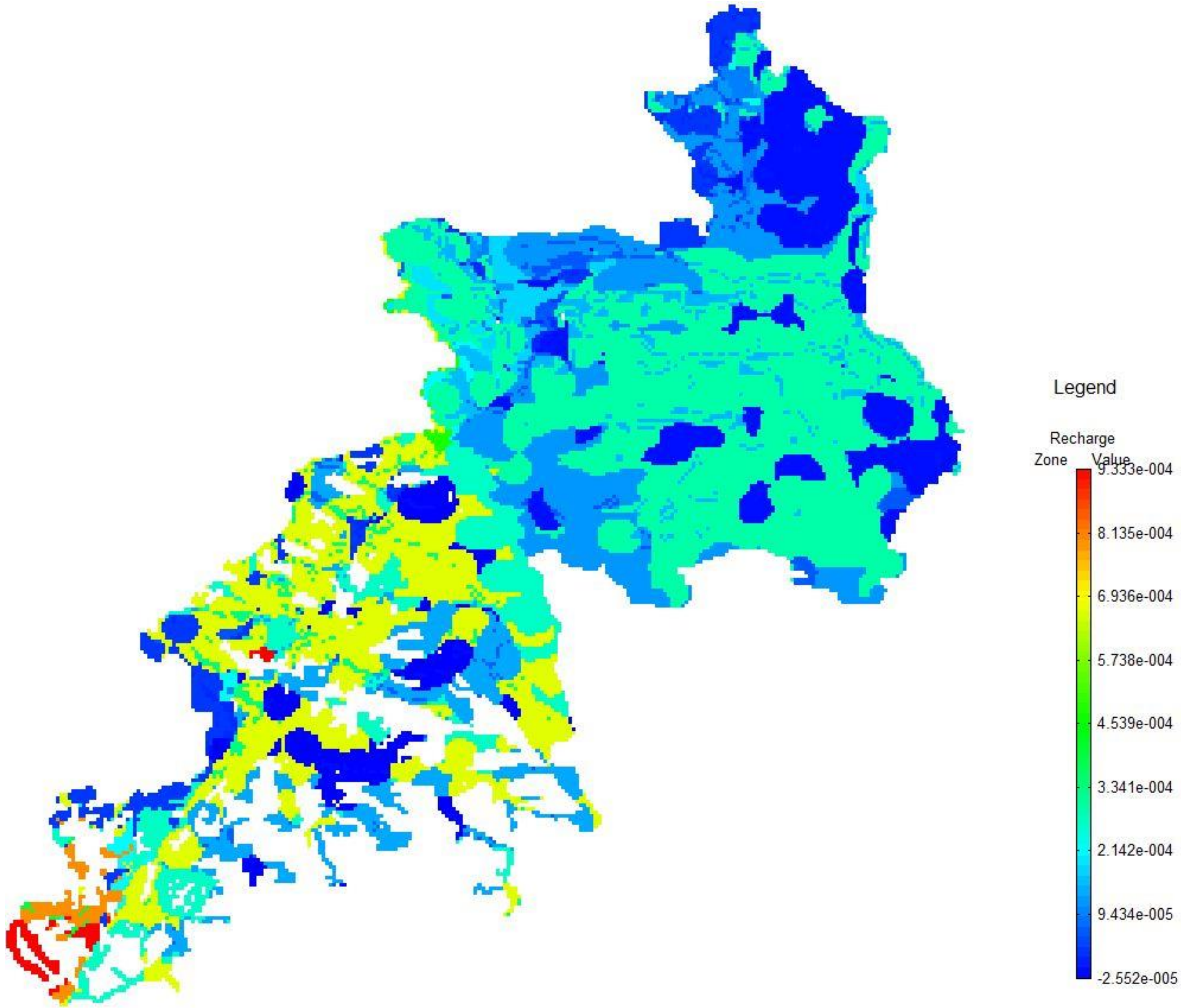


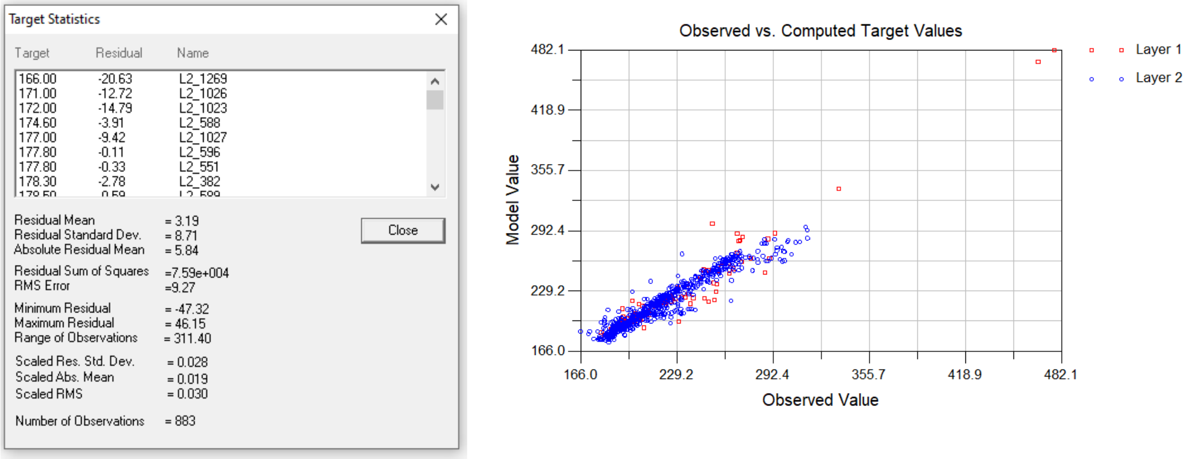
Figure 17 Spatial distribution of recharge [$m^3/24h/m^2$]

Model calibration

The basic criterion for model calibration was the compliance of the hydrodynamic state of the groundwater flow recorded during the drilling of hydrogeological wells, monitoring tests and hydroisohypses resulting from maps with the state obtained as a result of computer simulation. Both, the hydroisohypses image and the location of the groundwater table at 883 research points were analyzed, where data on the level of the groundwater table was obtained. In the model calibration procedure, the conductance of the river beds and the value of the filtration coefficient were modified. After each simulation, the calculated groundwater levels were analyzed.

After initial adjustment of the conductance of surface watercourses (by the method of successive approximations to obtain infiltration not exceeding 20% of the runoff), the values of the filtration coefficient were adjusted using the PEST module.

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 analyzed case, this value is 2.8% (Figure 18). The standard deviation is 8.7 m and the maximum deviation exceeds 40 m, which is most likely caused by incorrect determination of the water table elevation in individual wells. It should be noted here that the difference between the minimum and maximum terrain elevation in individual blocks can be as high as 125 m (average 14.5 m). This is mainly due to large differences in the mountainous area of the model. It should also be noted that for a very large range of the ordinates of the measured water table at the test points (ΔH = 311.4 m), such a deviation constitutes only about 13% of the amplitude. Based on the above data, it can therefore be concluded that the model has been calibrated to a satisfactory degree.


```
Target Statistics

Target      Residual    Name
166.00      -20.63      L2_1269
171.00      -12.72      L2_1026
172.00      -14.79      L2_1023
174.60      -3.91       L2_588
177.00      -9.42       L2_1027
177.80      -0.11       L2_596
177.80      -0.33       L2_551
178.30      -2.78       L2_382

Residual Mean               = 3.19
Residual Standard Dev.      = 8.71
Absolute Residual Mean      = 5.84

Residual Sum of Squares     =7.59e+004
RMS Error                   =9.27

Minimum Residual            = -47.32
Maximum Residual            = 46.15
Range of Observations       = 311.40

Scaled Res. Std. Dev.       = 0.028
Scaled Abs. Mean            = 0.019
Scaled RMS                  = 0.030

Number of Observations      = 883
```

Figure 18 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

Model credibility assessment

The mathematical model is always a simplification of the actual hydrogeological conditions. Therefore, the results of model simulations are burdened with a certain error, which is the result of always incomplete hydrogeological identification of the investigated aquifer and the necessary simplifications made during the schematization. In the case of the model prepared for the analysis of groundwater flows, the factors limiting the accuracy of the model forecasts and those contributing to the reliability of the results can be mentioned.

Factors limiting credibility:

- limited recognition of the structure and hydrogeological parameters of the first aquifer;
- uneven distribution of hydrogeological boreholes;
- no simultaneous hydrogeological measurements at all benchmarks;
- large terrain height differences within the model;
- a very large area covered by model studies and irregular ranges of aquifers, in particular layer I;
- significant errors in determining the ordinates in archived borehole data.

Factors increasing credibility:

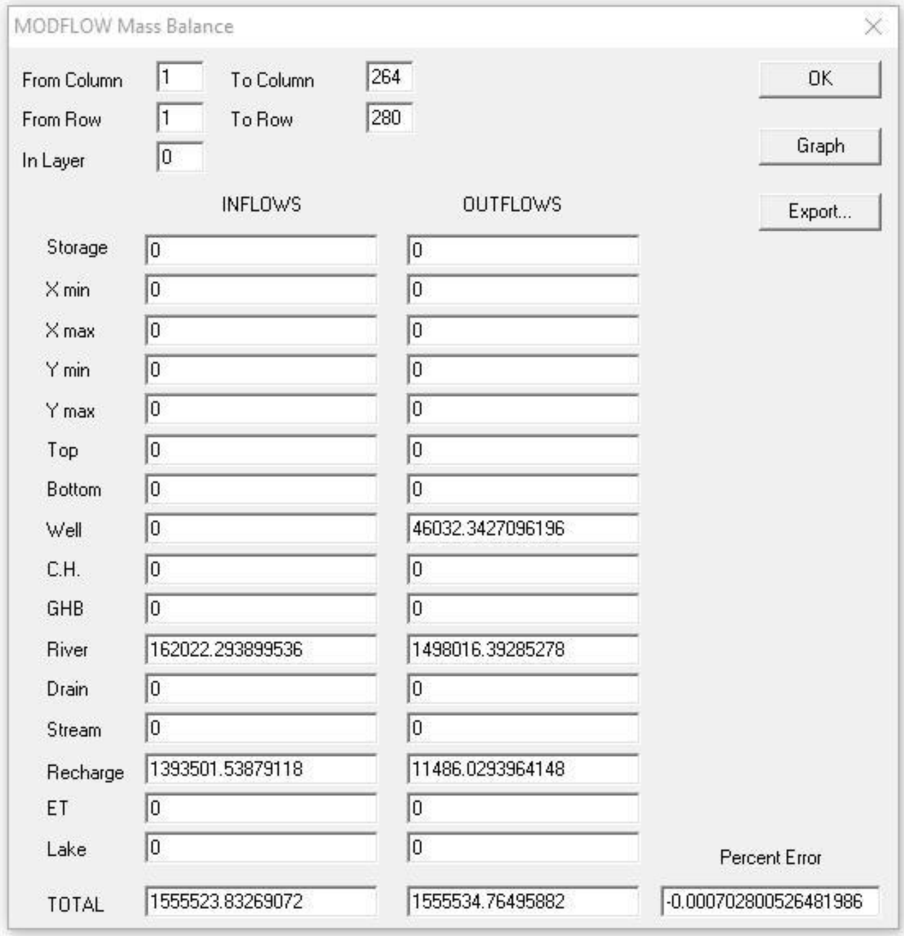
- simple geological structure and hydrogeological conditions, in particular, the presence of only two main aquifers with a regional range;

- good, regional identification of hydrogeological conditions in the second layer - the main aquifer in the study area;
- model area limited by natural boundary conditions - no participation of uncontrolled inflow/outflow from artificial boundary conditions in the balance of the model;
- no significant anthropogenic factors changing the groundwater flow regime.

Taking into account the above conditions, both those indicating deficiencies in the diagnosis and showing elements increasing the credibility, the model made can be considered sufficient to be used to assess the amount and directions of transboundary water flows. It is certainly much more reliable forecasting tool than analytical or graphical calculation methods. It should be mentioned that to assess the conditions at specific points (e.g. to be drilled for testing wells), detailed taring can be performed locally, e.g. using the results of parametric pumping of nearby groundwater intakes.

Model balance

The identification and taring of the model was performed in the conditions of the current exploitation of the intakes (average for 2018-2020). The summary balance of the model is presented below in tabular and graphic form (Figure 19).



From Column 1
To Column 264
From Row 1
To Row 280
In Layer 0

	INFLOWS	OUTFLOWS
Storage	0	0
X min	0	0
X max	0	0
Y min	0	0
Y max	0	0
Top	0	0
Bottom	0	0
Well	0	46032.3427096196
C.H.	0	0
GHB	0	0
River	162022.293899536	1498016.39285278
Drain	0	0
Stream	0	0
Recharge	1393501.53879118	11486.0293964148
ET	0	0
Lake	0	0
TOTAL	1555523.83269072	1555534.76495882

Percent Error -0.000702800526481986

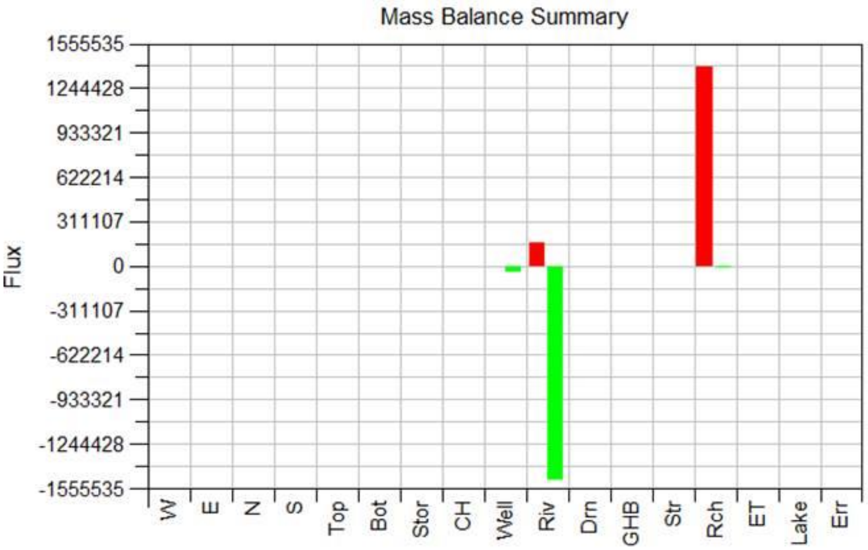


Figure 19 Model balance

The total balance includes only infiltration supply (from precipitation and river) on the positive side, and river outflow and groundwater intake on the negative side. Evapotranspiration of peatland areas was included in the infiltration supply (negative value). A good fit and a negligible percentage error indicate that the selected boundaries are tight and the area can be considered as a balanced one. It should be noted that the authors' assumption was to avoid the use of artificial boundary conditions, the impact of which on the model balance is difficult, and in the case of such an extent of the model, even impossible to control.

6 Assessment of transboundary groundwater flows by hydrodynamic modeling

The results of the modeling allowed, among others, for the determination of piezometric surfaces for both aquifers, the hydrodynamic relationship between them and the identification of the zones of transboundary groundwater flow.

Illustrative maps of the calculated hydroisohips of the groundwater table for both aquifers of the model are presented below (Figures 20-21).

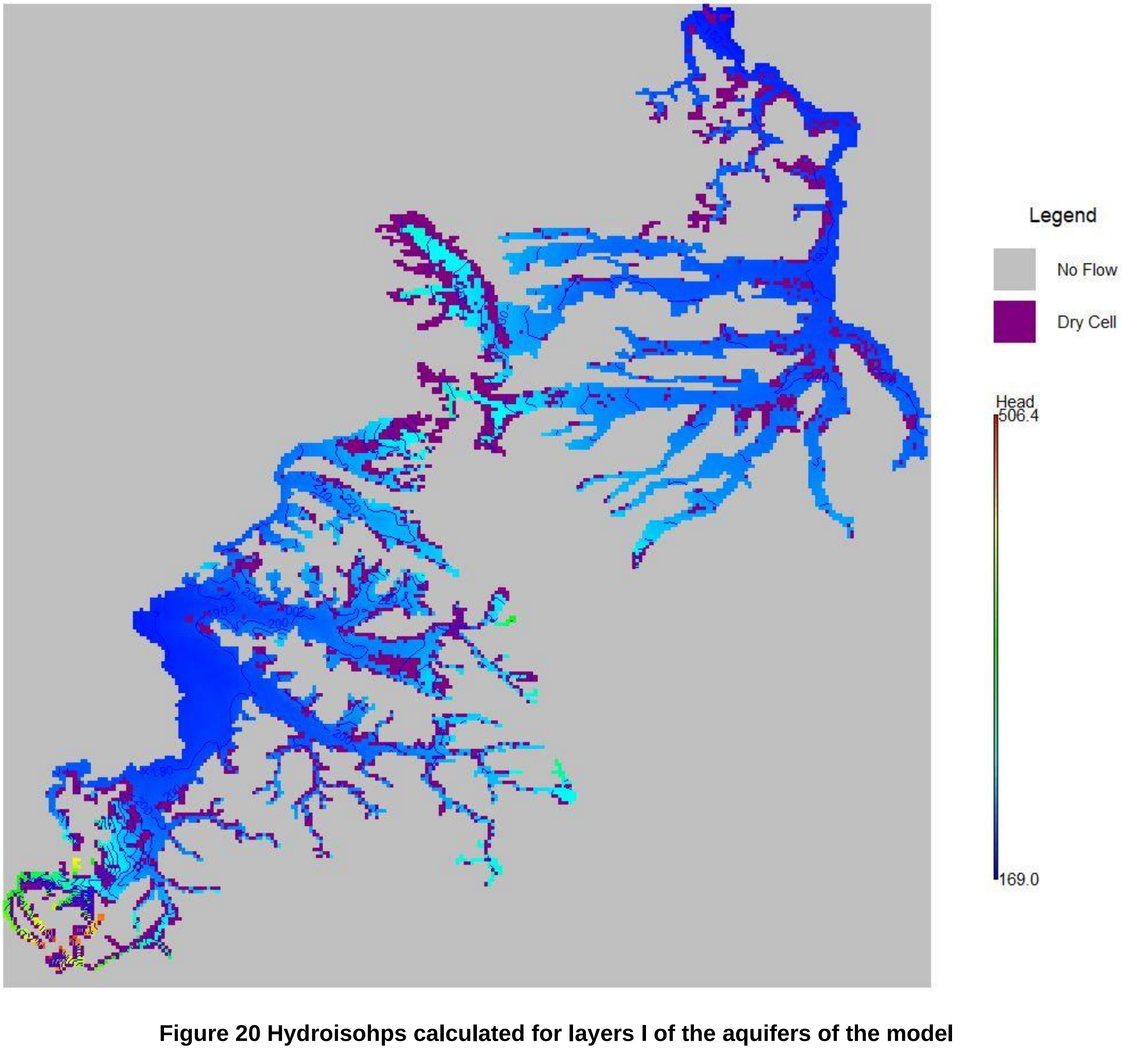


Figure 20 Hydroisohps calculated for layers I of the aquifers of the model

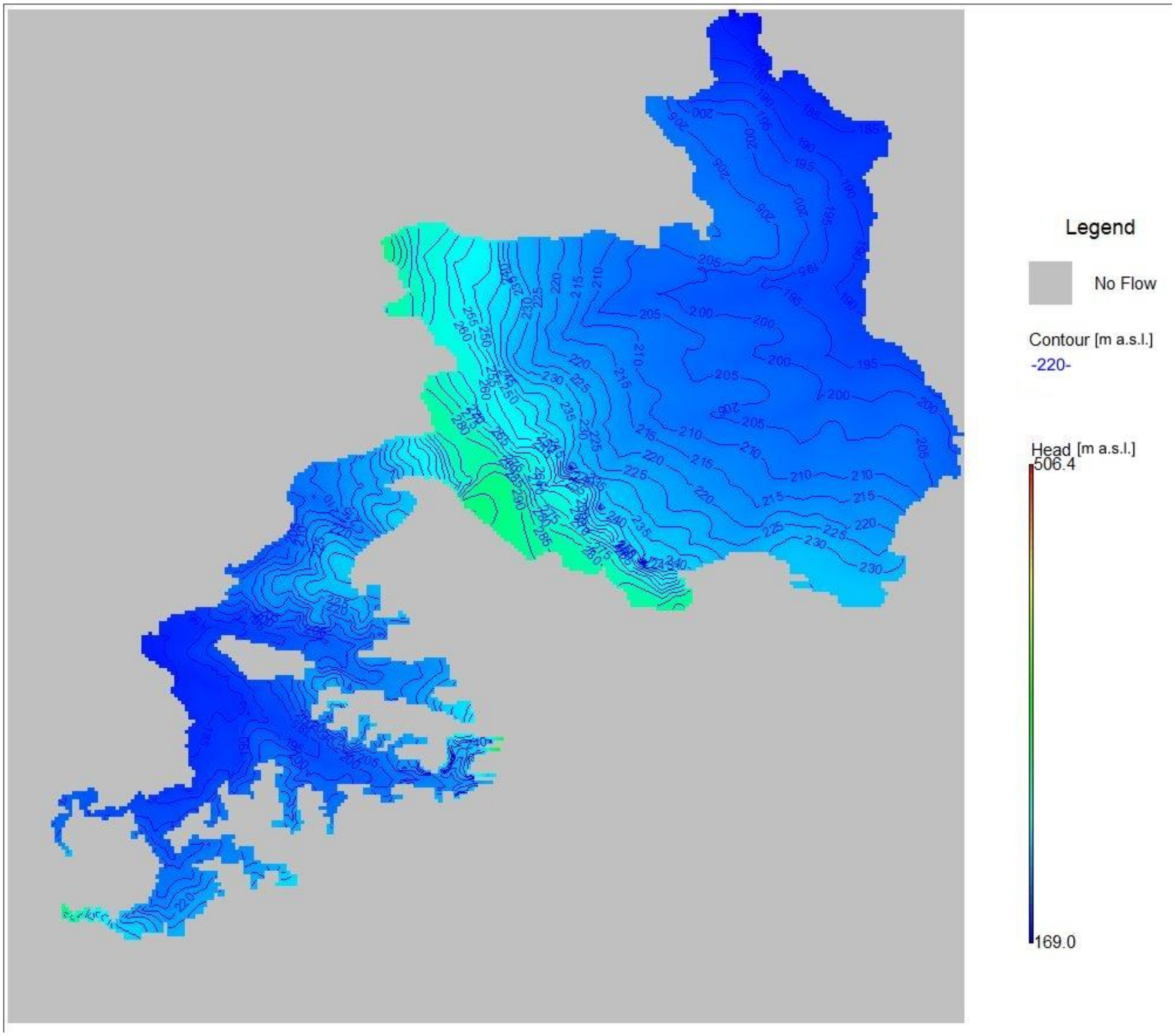


Figure 21 Hydroisohips calculated for layers II of the aquifers of the model

It should be noted that some of the blocks of layer I are dry - dark gray. This is natural because the ranges of layer I were determined on the basis of the extent of lithogenetic separations (sandy alluvial formations), often devoid of any hydrogeological recognition. The general dependence of the water table in the first layer on the morphology of the terrain and the decline of surface watercourses as well as its "mosaic" nature is visible. This is especially evident in the San catchment area.

In layer II, the hydroisohypses system confirms the regional continuity of the aquifer, despite the changing lithogenetic formation and stratigraphy of the sediments that build it.

The layout of piezometric surfaces in Figures 20 and 21 shows the groundwater circulation system in the transboundary parts of the Bug and San catchment areas. The distribution of the water table in layers I and II is determined by the river network. These figures show that the groundwater circulation system consists of a number of local systems related to the catchments of watercourses of a lower order than the Bug and San.

In the model area, the watershed zone between the basins of the Bug and San underground waters is the Roztochia region. In this area, the piezometric surface of the main usable aquifer (layer II of the model) reaches its highest elevation - 290 m a.s.l. From Roztochia, groundwater outflow takes place in two opposite directions - to the north-east in the Bug catchment area and to the west and south-west in the San catchment area. Thus, there is a general separation of the directions of cross-border flows. In the Bug basin, the transboundary groundwater flow is directed mainly to Ukraine, while from the San basin - to Poland.

For individual catchments, on the basis of calculations of the piezometric surface, the spatial extent of the main hydrodynamic zones - supply, transit and drainage - was determined (Figure 22). These figures show that the main drainage base for both model layers is Bug and San respectively. At the same time, the Sołokija and Rata rivers in the Bug basin and the Lubaczówka, Szkło, Wisznia and Wiar rivers in the San basin play a minor drainage role. The elevation of the water table in the drainage zones of the Bug and San are at the same level - 180-210 m a.s.l.

Based on the developed numerical model of the Polish-Ukrainian border zone, as a result of a detailed analysis, the values of cross-border flows were calculated for the main usable aquifer, which in larger river valleys also takes into account the alluvial aquifer. A detailed zonal balance is presented below, showing the cross-border flows divided into individual catchments (Bug and San), which was the main purpose of the research described above (Tab. 2). The zones were separated by dividing the studied catchments - San and Bug river into Polish (Zone 1 and Zone 3) and Ukrainian (Zone 2 and Zone 4) parts.

Table 2 Cross-border groundwater flow between Poland and Ukraine within the main usable aquifer

Summary of Flows for Zone	**PL_BUG**	**UA_BUG**	**PL_SAN**	**UA_SAN**	
	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**	
River Inflow	19416	64150	59143	19314	m^3/24h
River Outflow	142664	563455	456897	335000	m^3/24h
Well Outflow	5833	34884	4967	348	m^3/24h
Recharge Inflow	151309	510095	396300	335798	m^3/24h
Recharge Outflow	721	5815	880	4070	m^3/24h
Zone 1 1 Inflow	0	32981	1118	0	m^3/24h
Zone 1Outflow	0	11632	741	215	m^3/24h
Zone 2 Inflow	11632	0	0	2578	m^3/24h
Zone 2 Outflow	32981	0	0	11140	m^3/24h
Zone 3 Inflow	741	0	0	9369	m^3/24h
Zone 3 Outflow	1118	0	0	16292	m^3/24h
Zone 4 Inflow	215	11140	16292	0	m^3/24h
Zone 4 Outflow	0	2578	9369	0	m^3/24h
Total Inflow	183313	618365	472854	367059	m^3/24h
Total Outflow	183318	618364	472854	367066	m^3/24h
Error	-0,00258	0,00022	-0,00005	-0,00199	%

Figure 22 Hydrodynamic zones in the model area

In general, the transboundary groundwater flow in the main usable aquifer between Poland and Ukraine occurs not along the entire length of the border, but is concentrated on a specific section discussed in detail in the presented model study (Figure 22). The location of this section can be marked with two extreme points: starting from the place where the Bug River ceases to be a border river and turns towards Ukraine to the border point marked No. 430A on the watershed between the rivers Wyrwa and Łopuszanka.

With regard to the main usable level, the total amount of groundwater runoff from Poland to Ukraine is 42,350 m^3/24h, and broken down by the Bug and San basins - 32,981 m^3/24h and 9,369 m^3/24h, respectively. On the other hand, the inflow to Poland from Ukraine amounts to 27,924 m^3/24h, and broken down into the catchment areas of the Bug and San - 11,632 m^3/24h and 16,292 m^3/24h, respectively. The highest flow intensity is observed within the transit zone shown in Figure 22.

The amount of groundwater outflow from Ukraine to Poland is 27,924 m^3/24h, and broken down into the catchment areas of the Bug and San - 11,632 m^3/24h and 16,292 m^3/24h, respectively. On the other hand, the inflow to Ukraine from Poland amounts to 42,350 m^3/24h, and broken down into the Bug and San basins - 32,981 m^3/24h and 9,369 m^3/24h, respectively.

As a result of the balance calculations, it was unequivocally proved that the inflow of groundwater from Poland to Ukraine is more than 1.5 times greater from the main usable layer than from Ukraine to Poland. This finding is of particular importance for the further interpretation of possible transboundary impacts on a common useable aquifer.

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PART II. Assessment of the resources of transboundary groundwater reservoirs for the Latvian-Estonian borderland

Summary

The Latvian-Estonian pilot area is part of the BAB. The boundaries of the pilot area were determined taking into account the existing Latvian-Estonian border groundwater bodies along the state border, previously identified transboundary surface water bodies, Baltic sea coastline, as well as groundwater flows from the existing hydrogeological model. The defined pilot area covers an area of approximately 8000 km^2 and mainly includes Gauja-Koiva and Salaca-Salatsi transboundary river basins that are located in the territories of Gauja RBD and Daugava RBD in Latvia, as well as three RBDs in Estonia - Koiva, West Estonia and East Estonia.

Existing knowledge shared between Estonia and Latvia and the formerly developed hydrogeological model for the entire BAB were used to assess hydrogeological conditions and geological structure for the Latvian-Estonian pilot area. Also, the model was used to develop a conceptual understanding of transboundary groundwater resources dynamics.

In pilot area, for detailed characterization on transboundary area, aquifers were combined into appropriate aquifer systems. As a result, the aquifers were divided into four groups: 1) Quaternary aquifer system, 2) Pļaviņas-Ogre aquifer system, 3) Aruküla-Amata aquifer system, 4) Lower-Middle Devonian aquifer system. The deepest aquifer systems were not considered further as they were not considered aquifers according to WFD requirements.

For the assessment of transboundary groundwater flow, the project partner - University of Latvia, within the framework of the project, developed a semi-analytical method, which was used for the assessment of transboundary groundwater flow volumes across the Latvian-Estonian pilot area. The obtained results showed that the majority of transboundary groundwater flow across the Estonian-Latvian pilot area occurs in the Aruküla-Amata aquifer system with a total flow from Latvia to Estonia of 9488.5 m^3/d, a total flow from Estonia to Latvia of 5807.2 m^3/d and a total net flow of 3681.3 m^3/d that contributes to the flow from Latvia to Estonia. The majority of transboundary groundwater flow occurs in the Eastern part of the pilot territory.

1 Legal systematics of transboundary groundwater reservoirs

Even before joining the EU, international legislation in transboundary water management was incorporated into national law. In 1992, both countries signed the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE Water Convention), which was adopted in 1992 in Helsinki, Finland. It was ratified in national legislation in Estonia in 1995, and in Latvian legislation in 1996. The purpose of the Convention is to strengthen national and international action to protect transboundary waters and ensure ecological balance. The Water Convention requires Parties to prevent, control and reduce transboundary impact, use transboundary waters in a reasonable and equitable way and ensure their sustainable management. Parties bordering the same transboundary waters have to cooperate by entering into specific agreements and establishing joint bodies. As a framework agreement, the Convention does not replace bilateral and multilateral agreements for specific basins or aquifers; instead, it fosters their establishment and implementation, as well as further development. The convention also defined concepts such as “Transboundary waters” and “Transboundary impact (UNECE Water Convention, 1992).

Latvia and Estonia are two member states of the EU (since 2004), with similar historical developments in the field of groundwater management. Both countries have adopted the requirements of the WFD and incorporated it into their legislation, for the protection of groundwater, the conservation of good quality water and the sustainable use of groundwater resources.

In 2003, a bilateral agreement was signed between the Ministry of the Environment of the Republic of Latvia and the Ministry of the Environment of the Republic of Estonia on co-operation in the protection and sustainable use of transboundary watercourses. Despite the agreement, by 2018 no systematic exchange of information has taken place between both countries and no joint research has been carried out in the assessment of groundwater resources. There has been closer co-operation in transboundary surface water management.

In 2018, a joint project (GroundECO project) between Estonian and Latvian institutions was launched on the assessment of Latvian-Estonian transboundary groundwater, with the aim to promote the sustainable management of common groundwater resources and related ecosystems in the transboundary Gauja-Koiva river basin.

1.1 Transboundary groundwater reservoirs in Estonia's water/geological law and their status of recognition

To comply with WFD requirements and to coordinate the management of water resources in Estonia, the territory of Estonia is divided into 3 river basins: East-Estonia river basin, West-Estonia river basin, and Koiva river basin. RBMP for each river basin are established for six years and are then updated. County governments, local authorities, citizens located on the territory of the river basins and other interested parties will be included in the process of establishing the RBMP. The Environmental Board is responsible for the inclusion of parties. The current valid RMBPs have been drawn up from 2009 through 2015.

To reach the environmental goals of protecting the areas stated in the RMBP and areas in need of protection, a programme of measures will be developed where measures of water usage and protection shall be stated to be taken into account in establishing, reviewing and amending the general and detailed zoning plans and public water supply and sewerage system development plans of local authorities. The implementation of the programme is organised by the Commission for River Basin Management. To ensure the implementation of the programme of measures, the Environmental Board will establish an action plan for the implementation of the programme of measures for each river basin.

According to RMBP, Estonia has delineated no transboundary groundwater bodies.

1.2 Transboundary groundwater reservoirs in Latvian water/geological law and their status of recognition

In Latvia, the main legal act regulating the management and protection of water resources (including – groundwaters) is the Water Management Law, as well as the Cabinet Regulations issued on the basis of this law. Although the Water Management Law contains clear definitions of terms such as “groundwater” and “groundwater body”, so far, the law has not provided a definition of the term “transboundary groundwater body”. The law is largely based on the requirements of the EU in the field of water protection and management, including WFD.

It is worth noting, however, that Cabinet Regulation No.92 (adopted on February 17, 2004) “Requirements for the Monitoring of Surface Water, Groundwater and Protected Areas and the Development of Monitoring Programs” issued on the basis of the Water Management Law stipulate activities such as insuring monitoring network, which allows the evaluation of the direction, rate and changes in the chemical quality of transboundary groundwater flow, as well as the determination of the cause of changes; as well as performing monitoring in groundwater bodies crossing the State border of Latvia, which allow the determination of the risk of transboundary impact and the evaluation of transboundary impact.

To comply with WFD requirements and to coordinate the management of water resources in Latvia, the territory of Latvia is divided into 4 river basins: Daugava river basin, Gauja river basin, Lielupe river basin and Venta river basin. RBMP for each river basin are established for six years and are then updated. County governments, local authorities, citizens located on the territory of the river basins and other interested parties will be included in the process of establishing the RBMP. Latvian Environment, Geology and Meteorology Centre is responsible for the inclusion of parties. The current valid RMBPs have been drawn up from 2009 through 2015.

According to RBMP, Latvia has delineated transboundary groundwater bodies with Lithuania. In 2019, the project B-solution was completed, within the framework of which Latvian-Lithuanian transboundary groundwater assessment was performed. During project implementation it has been agreed that there are 14 GWBs (7 in Latvia and 7 in Lithuania). As delineation of GWBs is a matter of each Member State and accompanied with many political decisions and national level planning principles, the boundaries of GWBs have not been changed.

2 Requirements for a uniform form of parametrization of hydrogeological units

In order to get a better picture of the Estonian-Latvian transboundary territory and the common aquifers, a larger area was initially selected, based mainly on the distribution boundaries of the existing groundwater bodies (hereinafter - GWBs). All GWBs adjacent to the borders of both countries were taken into account - in the territory of Estonia they are GWBs 21, 22, 23, 24, 25, 26 and in the territory of Latvia - GWBs D6, D8, A8, A10, P. The initially selected area is shown in Figure 23.

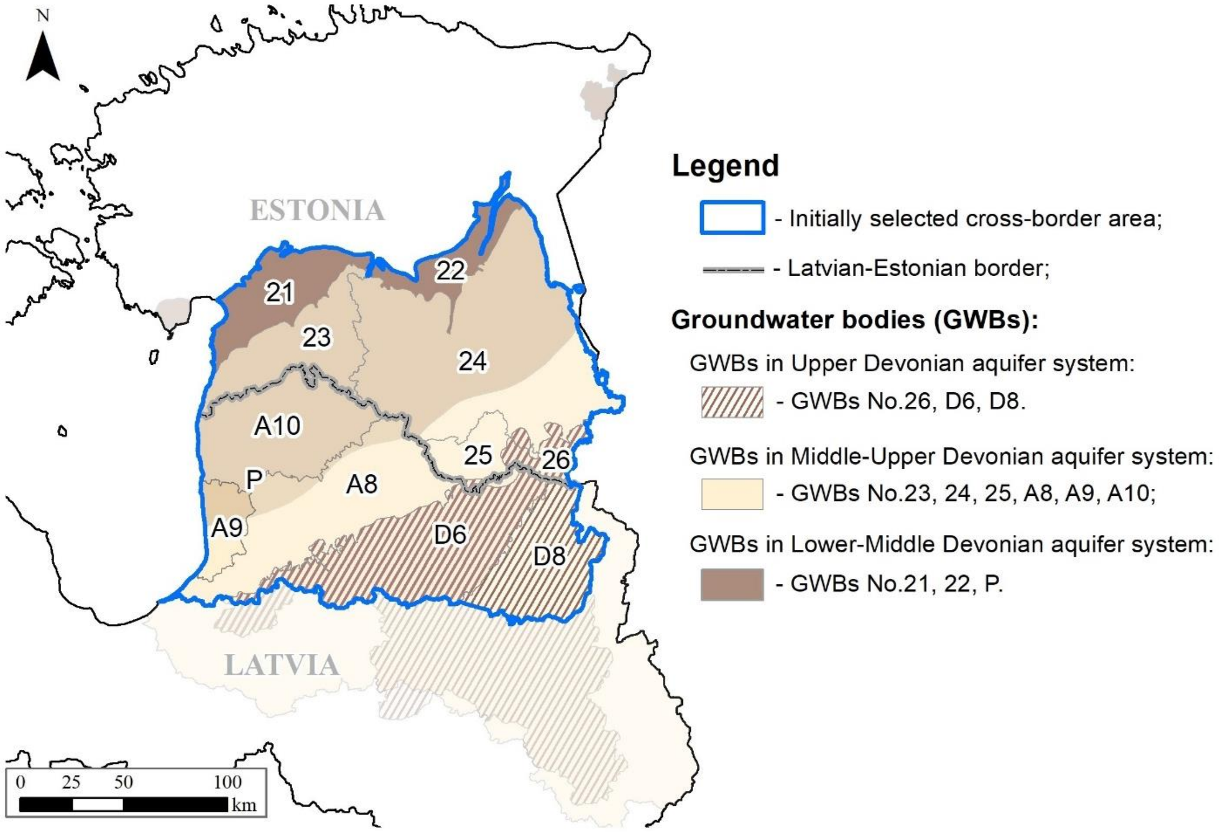


Figure 23 Initially selected cross-border territory of Latvia and Estonia

In accordance with the requirements of the WFD, GWBs in both countries (Latvia and Estonia) have been delineated mainly on the basis of the existing hydrogeological classification, and in addition to assessing the compliance of groundwater with drinking water quality requirements. As well as determining groundwater watersheds - using the existing information on groundwater levels in aquifers, which allows the identification of regional recharge and discharge areas, as well as groundwater flow directions. In Estonia, the boundary of this watershed is determined by the boundaries of the largest river basins (East-Estonian river basin and West-Estonian river basin), while in Latvia the groundwater watersheds were delineated mainly on the basis of modeled water levels in the aquifer systems.

Accordingly, the existing knowledge base was used to identify, characterize and determine the common hydrogeological parameters between the two countries:

1. On the boundaries of the distribution of aquifers and the stratification of the existing hydrogeological section (Quaternary sediment maps at the scale of 1: 200 000, pre-Quaternary sediment maps at the scale of 1: 200 000, and geological sections of existing wells).
2. On hydrogeological and geological conditions in the cross-border area, based on the results obtained from the PUMA model of the BAB.
3. On delineated GWBs in each country.
4. Regarding the compliance of the composition of groundwater with the quality requirements for drinking water (maps of the chemical composition of aquifers existing in the country, as well as data of existing water extraction and monitoring wells have been used).
5. On the volumes of groundwater abstraction, the density and number of water supply wells.

Initially, based on the available knowledge base on the lithology and permeability of sediments in the study area, water-containing and water-poor permeable layers were identified, mainly by sectioning regional aquitards (Middle Devonian Narva regional stage, Ordovician and Silurian sediments). Based on water permeability of the sediments and the lithological composition, homogeneous strata, separated from each other by weakly permeable layers, were combined in aquifers. In turn, the adjacent and hydraulically interconnected aquifers with relatively similar characteristics were combined in aquifer systems.

In addition to the above conditions, the compliance of groundwater with drinking water quality requirements was assessed, as the WFD gives priority to the protection of water that is or may be used for human consumption. After collecting the relevant data, aquifers were identified that can be used for water supply and groundwater quality meets drinking water standards (SO_4^{2-} and Cl^- concentrations do not exceed the norm - 250 mg/l, water mineralization (TDS) < 1 g/l). The role of the identified aquifers in the water supply was also taken into account when compiling data on water abstraction volumes and density of water supply wells in the identified aquifer or aquifer system. If the significance of groundwater abstraction was relatively low, then the aquifer was not identified as a separate groundwater body and a detailed data analysis for this aquifer was not performed.

Aquifers and aquifer systems where 1) water quality did not meet drinking water quality requirements and 2) there was no information on existing water supply wells or their density was low and there were no groundwater well fields, were not considered aquifers in the context of WFD. The summarized information on the determination of common hydrogeological parameters is given in Table 3, adapting it to the delineated GWBS in both countries.

For further characterization of the cross-border area, the division of aquifers into aquifer systems was mainly used. As a result, the aquifers were divided into four groups: 1) Quaternary aquifer system, 2) Pļaviņas-Stipinai aquifer system, 3) Aruküla-Amata aquifer system, 4) Lower-Middle Devonian aquifer system. The deepest aquifer systems were not considered further as they were not considered aquifers according to WFD requirements.

Table 3 Stratigraphy of hydrogeological section in the Latvian-Estonian cross-border territory

Aquifers	Geological index (LV)	Geological index (EE)	Dominant sediments	Aquifer system (GWBs)	Distribution / Aquifer in the context of the WFD
Quaternary	Q	Q	Sand, loam	Quaternary (attached to each GWB)	**Whole territory.** Considered as aquifer in the context of the WFD, as aquifer consists of freshwaters that are widely used for small household needs due to shallow occurrence and ease of access; aquifer is also crucial for groundwater dependent ecosystems and surface bodies. Quaternary aquifer is attached to the first embedded groundwater body (Upper-Middle Devonian aquifer system).
Stipinai	$\mathrm{D}_3\mathit{stp}$	-	Dolomite, marl	Pļaviņas-Stipinai (LV GWBs D6 and D8, EE GWB 26)	**In the south-eastern part.** Considered as aquifers in the context of the WFD, as the aquifer system consists mainly of freshwaters that are and can be used for drinking water supply.
Katleši-Ogre	$\mathrm{D}_3\mathit{og}$	-	Sandstone, marl		
	$\mathrm{D}_3\mathit{kt}$	-	Sandstone, marl		
Daugava	$\mathrm{D}_3\mathit{dg}$	$\mathrm{D}_3\mathit{dg}$	Dolomite		
Salaspils	$\mathrm{D}_3\mathit{slp}$	$\mathrm{D}_3\mathit{db}$	Marl, gypsum		
Pļaviņas	$\mathrm{D}_3\mathit{pl}$	$\mathrm{D}_3\mathit{pl}$	Dolomite		
Amata	$\mathrm{D}_3\mathit{am}$	$\mathrm{D}_2\mathit{am}$	Sandstone, siltstone	Aruküla-Amata (LV GWBs A8 and A10, EE GWBs 23, 24 and 25)	**Whole territory.** Considered as aquifers in the context of the WFD, as the aquifer system consists mainly of freshwaters that are and can be used for drinking water supply.
Gauja	$\mathrm{D}_3\mathit{gj}$	$\mathrm{D}_2\mathit{gj}$	Sandstone, siltstone		
Burtnieki	$\mathrm{D}_2\mathit{br}$	$\mathrm{D}_2\mathit{br}$	Sandstone, siltstone		
Aruküla	$\mathrm{D}_2\mathit{ar}$	$\mathrm{D}_2\mathit{ar}$	Sandstone, siltstone		
Narva reģional aquitard $\mathrm{D}_2\mathit{nr}$			Marl, clay		
Pärnu	$\mathrm{D}_2\mathit{pr}$	$\mathrm{D}_2\mathit{pr}$	Sandstone, siltstone	Lower-Middle Devonian (LV GWB P, EE GWBs 21 and 22)	**Whole territory.** Only in the western part of the territory were considered as aquifers in the context of WFD, in the rest of the territory they were not considered as aquifers, because saline waters that are not used as drinking water are distributed in the aquifer system.
Rēzekne	$\mathrm{D}_1\mathit{rz}$	$\mathrm{D}_1\mathit{rz}$	Marl, sandstone		
Ķemeri	$\mathrm{D}_1\mathit{km}$	$\mathrm{D}_1\mathit{km}$	Sandstone, siltstone		
Gargždai	$\mathrm{D}_1\mathit{gr}$	-	Sandstone, siltstone		
Tilžė	-	$\mathrm{D}_1\mathit{tl}$	Sandstone, siltstone		
Ordovician and Silurian regional aquitard O-S			Marl, solid limestone		
Cambrian	C	Ca	Sandstone, siltstone	Vendian-Cambrian	**Whole territory.** Were not considered as aquifers in the context of WFD, as chloride-sodium brines not used as drinking water are distributed in the aquifer system.
Vendian	V	V	Sandstone, siltstone, gravelite		
Archean and Proterozoic crystalline basement AP-PR			Gneiss, granite		

3 Criteria for the identification of hydrogeological units of a transboundary character

Transboundary area mainly includes Gauja-Koiva and Salaca-Salatsi transboundary river basins that are located in the territories of Gauja RBD in Latvia and in three RBDs in Estonia - Koiva, West Estonia and East Estonia. The Latvian side includes only the part of the Gauja river basin with direct transboundary water bodies and their tributaries, which may affect the water quality in transboundary water bodies. In addition, in order to fully view the entire transboundary area, the Estonian and Latvian sides have been supplemented with water bodies at the border that extend beyond the Gauja-Koiva and Salaca-Salatsi cross-border river basin districts. This approach would secure consideration of anthropogenic pressures in all of the Latvian-Estonian border area when devising solutions suitable for meeting the environmental objectives (Figure 24).

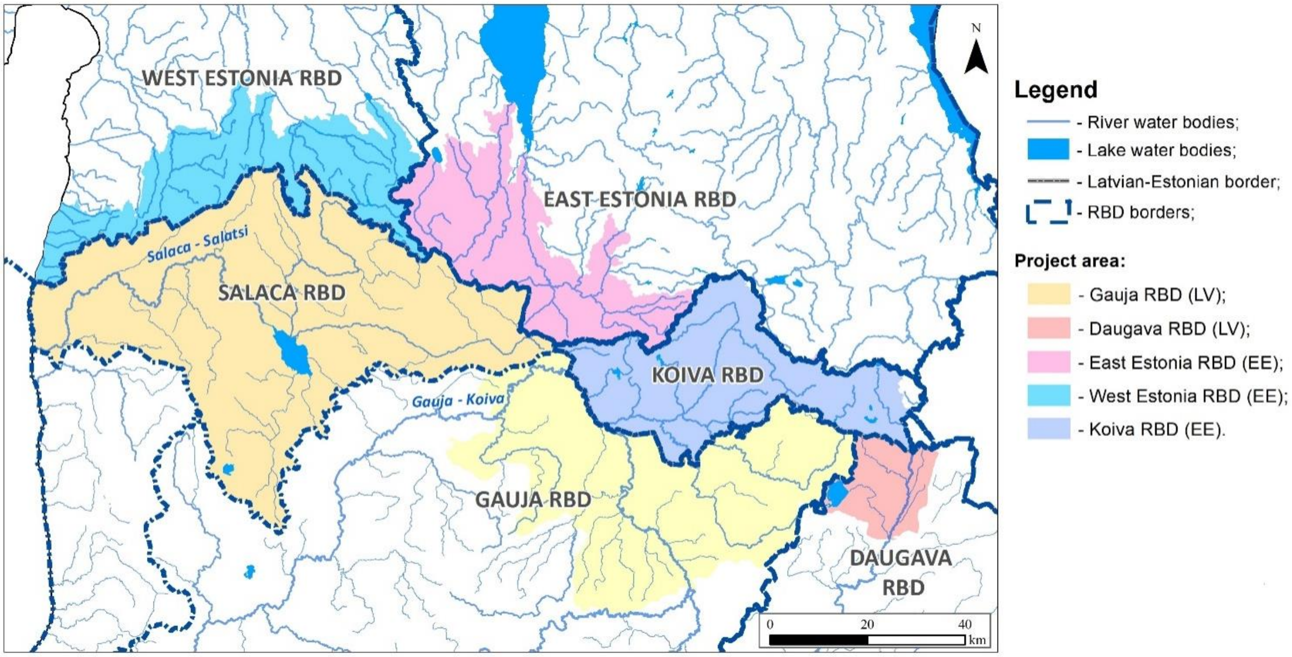


Figure 24 River Basin Districts within project area

Based on the existing knowledge base, aquifers carrying groundwater across the boundary line were identified. Figure 25 shows that groundwater flows in the Middle and Upper Devonian aquifer systems (active water exchange zone) are similar and generally follow the land surface terrain and coincide with the boundaries of river basins. The recharge of these aquifers takes place mainly in the uplands, while the valleys and the lowlands serve as discharge zones. Groundwater flow in the Lower-Middle Devonian aquifer system (slowed water exchange zone) is more homogeneous and there is no significant connection with the higher existing systems, as well as surface water catchment areas. This deepest groundwater recharge area is considered to be the south-eastern part of the territory, the groundwater flow is directed mainly in the north-western, western direction and the groundwater discharge takes place in the Baltic Sea.

The transboundary flow is mainly found in the eastern part of the territory in the upland areas, where the feeding area of all identified aquifers (except the Lower-Middle Devonian aquifer system) is detected, and in the central part, where the possible groundwater flow from Estonia to Latvia is also identified (Figure 25). In order to identify the "significance" of groundwater flow between boundaries, it is planned to determine the balance using the semi-analytical method.

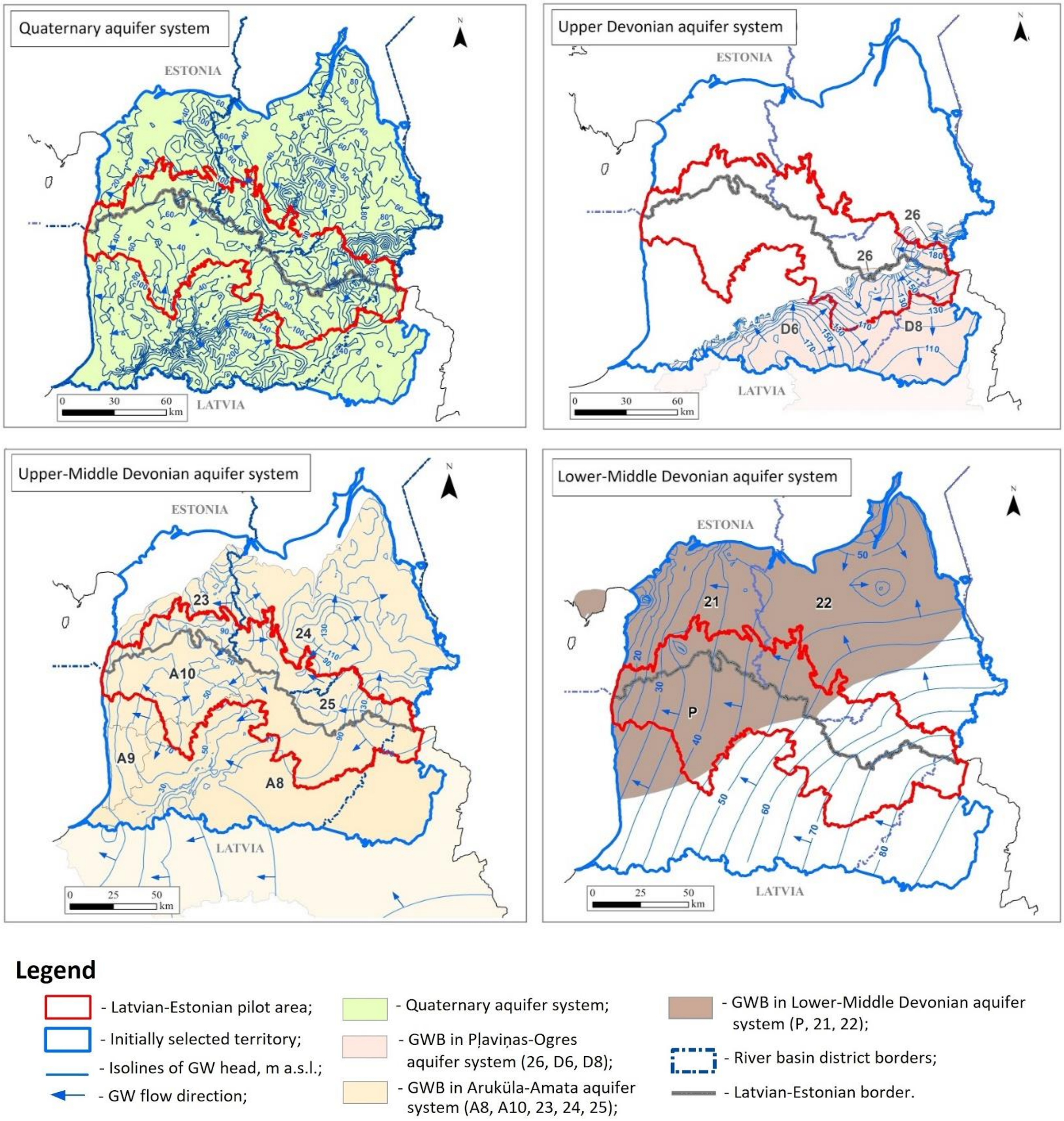
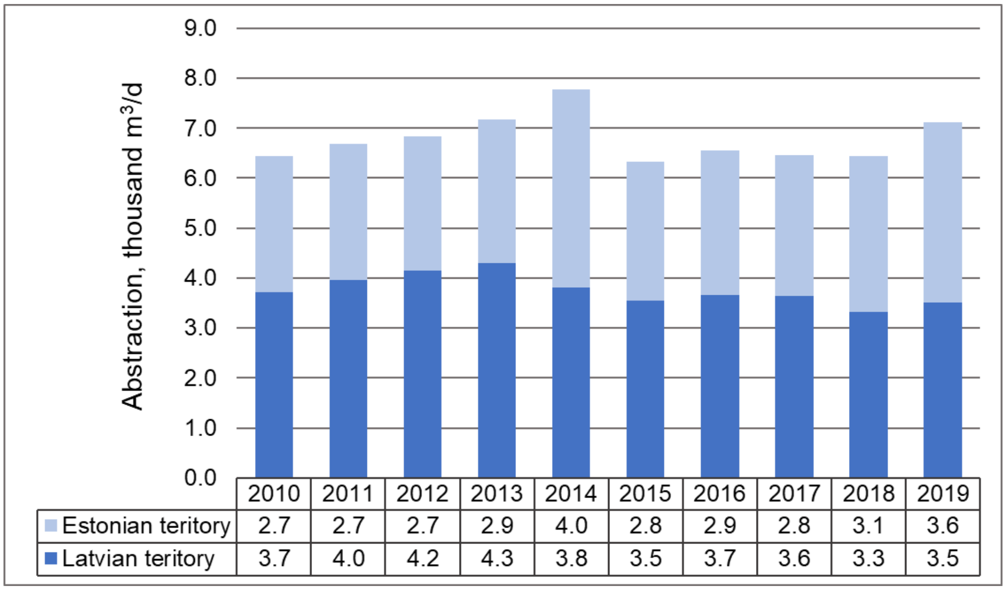


Figure 25 Groundwater flow maps

Based on the types of land use in the Latvian-Estonian pilot area (The Copernicus Programme, 2018), the largest part is covered by forest areas - 63%, followed by agricultural lands (32%) and wetlands (3%). The main pressure-causing factors that can affect the quantity of groundwater resources and influence changes in groundwater flow are water abstraction, amelioration, drainage from quarries, as well as fluctuations in groundwater levels caused by hydroelectric power plant reservoirs. It is known that drainage systems and drainage from quarries mainly significantly reduce the resources of shallow aquifers in some areas. In addition, the impact of shallow aquifers on total water resources is negligible, therefore, these factors have not been taken into account when assessing transboundary groundwater resources. In the areas affected by the reservoirs, the groundwater level is rising - i.e. the reservoir replenishes rather than decreases the groundwater resources. However, the infiltration of surface water into the groundwater in the vicinity of reservoirs increases the concentration of organic matter in groundwater, as well as slows down the exchange of groundwater. These processes can lead to the accumulation of pollutants in certain aquifers. These processes are generally poorly studied, but they are known to take place in the immediate vicinity of reservoirs and only in shallow aquifers. Therefore, similarly to the pressure caused by amelioration, the impact of water reservoirs was not taken into account when assessing transboundary groundwater resources. Thus, it was considered that in the Latvian-Estonian cross-border hydrogeological conditions, only groundwater abstraction could pose a real risk. Groundwater is abstracted mainly for the supply of drinking water.

In order to understand the water abstraction pressure and its possible impact on changes in groundwater flow, a more detailed data analysis of groundwater abstraction volumes over a longer period of time was performed in the Latvian-Estonian cross-border area identified below. The collected data show that intensive water abstraction is not marked in the cross-border area. In the period from 2010 to 2019, it mainly fluctuated from 6.3 thousand m^3/d to 7.8 thousand m^3/d, on average - 7.0 thousand m^3/d (Figure 26).



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
■ Estonian teritory	2.7	2.7	2.7	2.9	4.0	2.8	2.9	2.8	3.1	3.6
■ Latvian teritory	3.7	4.0	4.2	4.3	3.8	3.5	3.7	3.6	3.3	3.5

Figure 26 Total abstraction within Latvian-Estonian cross-border area in the period from 2010 to 2019

In the cross-border territory of Latvia, water abstraction volumes in the respective period ranged from 3.3 to 4.2 thousand m^3/d, in the last 5 years water abstraction volumes decreased, and on average did not exceed 3.5 thousand m^3/d. In turn, in the part of the cross-border territory in Estonia there is a slight increase in water extraction and in the period from 2010 to 2019 has been fluctuating from 2.7 to 3.6 thousand m^3/d. In the Latvian-Estonian cross-border area, water abstraction sites are distributed unevenly, the densest number of water abstraction wells is observed around populated areas (cities), for example, in Latvian territory around cities - Valka, Rūjiena, Salacgrīva and Ainaži, while in Estonian territory around cities - Valga, Tõrva and Karksi-Nuia. Outside populated areas, groundwater abstraction is more dispersed and groundwater is mainly extracted from individual wells (Figure 27).

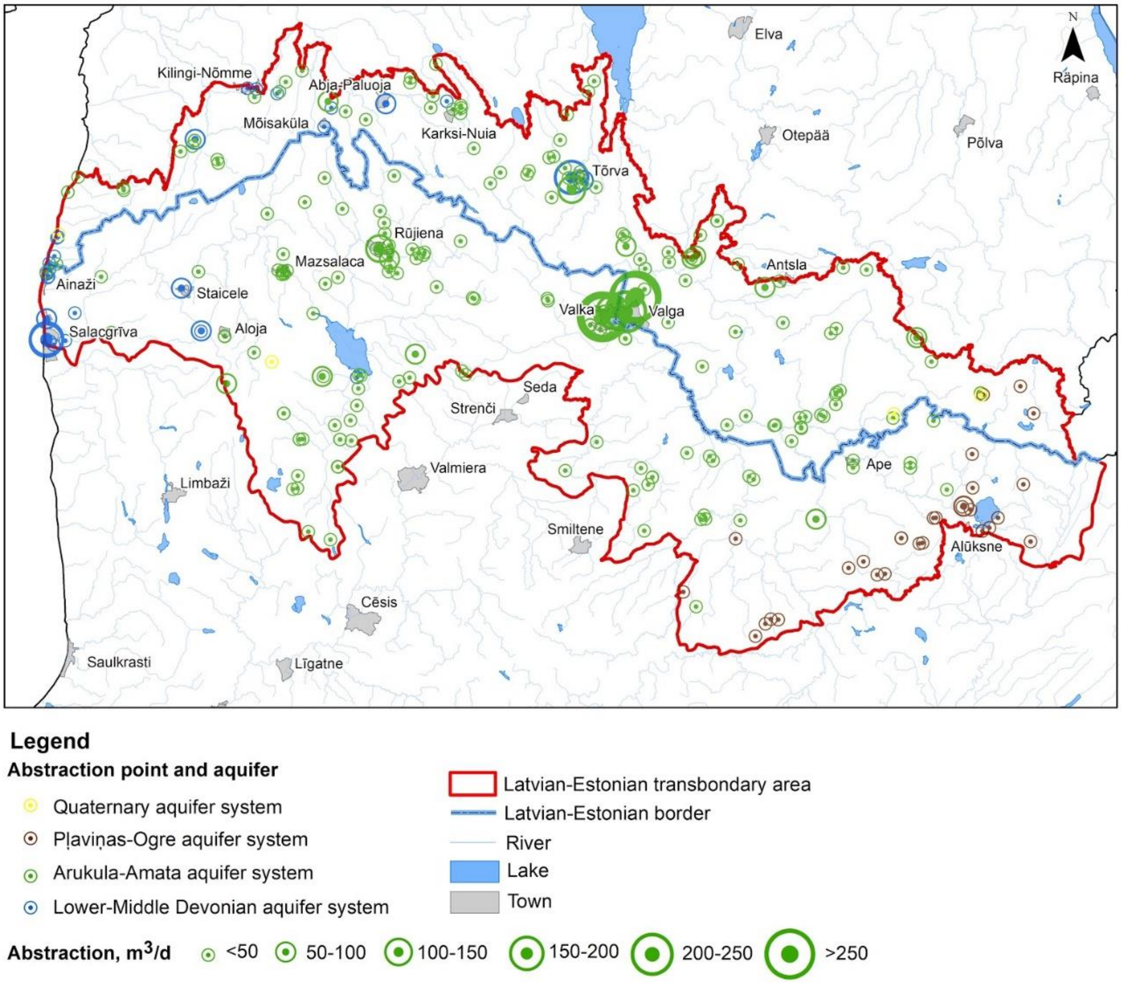
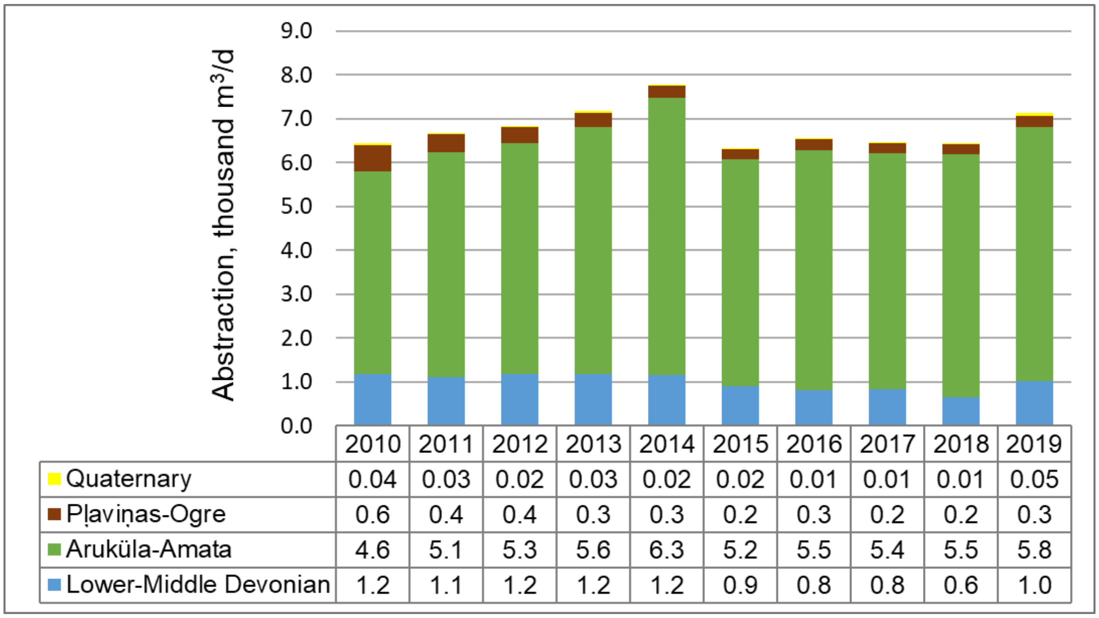


Figure 27 The distribution of abstraction sites and their average abstraction rates in the pilot area (2010-2019)

The collected data show that higher groundwater abstraction was identified from the Aruküla-Amata aquifer system, which is distributed throughout the cross-border area, water abstraction ranged from 4.6 to 6.3 thousand m^3/d during the respective period, which is on average about 80% of total water abstraction (Figure 28). Groundwater abstraction from this aquifer system mainly takes place from individual wells with abstraction volumes not exceeding 100 m^3/d (mainly ranging from 1 m^3/d to 50 m^3/d) and only in urban areas inside groundwater well fields water abstraction increases to 119-789 m^3/d. The largest groundwater abstraction in Latvian territory is marked in the groundwater well field “Valka”, which ensures the centralized water supply of the city of Valka**.** In Estonian territory, the largest abstraction sites are also in the city of Valga, which are a part of the central water supply. Large abstraction sites for centralized water supply are also in the cities of Tõrva and Karksi-Nuia.



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
🟨 Quaternary	0.04	0.03	0.02	0.03	0.02	0.02	0.01	0.01	0.01	0.05
🟫 Pļaviņas-Ogre	0.6	0.4	0.4	0.3	0.3	0.2	0.3	0.2	0.2	0.3
🟩 Aruküla-Amata	4.6	5.1	5.3	5.6	6.3	5.2	5.5	5.4	5.5	5.8
🟦 Lower-Middle Devonian	1.2	1.1	1.2	1.2	1.2	0.9	0.8	0.8	0.6	1.0

Figure 28 Groundwater abstraction from exploited aquifer systems, thousand m^3/d (2010-2019)

In the western part of the considered pilot area, insignificant groundwater abstraction from the Lower-Middle Devonian aquifer system containing freshwater in the study area is noted with a total abstraction of 1.2 thousand m^3/d (it has decreased in the last 5 years to 0.6-1.0 thousand m^3/d). Groundwater abstraction in the above-mentioned aquifer system varies up to 50 m^3/d and only in groundwater well fields it increases up to 62-377 m^3/d. Groundwater abstraction is carried out to ensure centralized water supply of cities Salacgrīva and Staicele, as well as to ensure production, technical and domestic needs of the potato starch plant (well field “Ungurpils”). The largest groundwater abstraction in Latvian territory takes place in the vicinity of the city of Salacgrīva, which is related to the centralized water supply of this city.

In the eastern part of the territory, insignificant groundwater abstraction from Pļaviņas-Ogre aquifer system is noted, with a total abstraction of 0.3 thousand m^3/d. The aquifer system is used only by individual water users with water extraction volumes from 0.2 to 25 m^3/d (in some places it increases to 48 m^3/d). In the Estonian part of the cross-border area, extraction was observed in only 2 wells in this aquifer system, because the extent and the thickness of the aquifer is limited. In Estonian side, it is only used in private households, and is not relevant in the central water supply. In turn, the Pļaviņas-Ogre aquifer system is used more in the Latvian part of the cross-border area. The abstraction from the Quaternary aquifer system in the territory was identified only in some places with abstraction not exceeding 0.03 thousand m^3/d (it is even lower).

The analysis of the above-mentioned data showed that no significant changes in the total groundwater abstraction have been observed in the Latvian-Estonian cross-border area since 2010, as well as no significant groundwater abstraction pressure has been identified in the cross-border area. The exception is the surroundings of Valka and Valga cities, where the largest groundwater abstraction from the Aruküla-Amata aquifer system has been identified (total groundwater abstraction in this area reaches up to 2.4-2.7 thousand m^3/d, which is on average about 41% of total water abstraction in Aruküla-Amata aquifer system). Based on the data analysis, it was concluded that at present in the Latvian-Estonian cross-border area attention should be paid only to the active groundwater exchange zone, which includes Quaternary, Pļaviņas-Ogres and Aruküla-Amata aquifer systems, and respectively 8 GWBs (4 Latvian GWBs - A10, A8, D6 and D8, as well as 4 Estonian

GWBs - 23, 24, 25 and 26). The deeper embedded Lower-Middle Devonian aquifer system (characterized by GWBs P, 21 and 22) was excluded from further data analysis, as no “significant” groundwater flow was found between the territories of the two countries after the initial assessment. Also, intensive groundwater abstraction in the Latvian-Estonian border area has not been noted, which may cause changes in the water flow of the above-mentioned aquifer system. However, it should be taken into account that the Lower-Middle Devonian aquifer systems in most parts of the territory are very well protected from surface water pollution, as they are embedded below 90 - 100 m thick Narva aquitard.

4 Conceptual model of a transboundary aquifer

4.1 Geological and hydrogeological conditions of the Latvian-Estonian pilot area

The pilot area is part of the **central part** of the BAB. The hydrogeological section of the basin is formed by the alternation of aquifers and low water permeability strata (Table 3). The amount of water contained in the individual layers and the water quality in them are quite different. Based on the analyzed water abstraction data, it was concluded that the main focus should be on aquifers in the active water exchange zone. For this reason, a further assessment of the geological and hydrogeological conditions of the pilot area is carried out on these aquifers, discarding deeper aquifers, which are less important for water abstraction and economics in this border area. The thickness of the active water exchange zone is gradually increasing in the east-southeast direction and its thickness in the pilot area varies from about 125 m in the western part to about 350 m in the eastern part. The maximum thickness in some places reaches up to 460 m (in Alūksne upland (Latvian) and Haanja upland (Estonia)).

The thickness of the **Quaternary sediment** cover varies from 10-20 m (sometimes also less) in the lowlands to 80-100 m in the highland areas, as well as in deep pre-Quaternary and integrative erosion depressions. In the western part of the pilot area in Estonia the thickness of the Quaternary sediment cover is between 5-10 m and even less on the alvars in Ikla region. Larger Quaternary cover thicknesses have been found in the Alūksne upland in Latvia and Haanja upland in Estonia (more than 80 m), while in the rest of the territory the thickness of Quaternary sediments does not exceed 40 m. Quaternary sediments of various genesis are widespread in the pilot area, among which glacial moraine sediments and limnoglacial clays predominate. Significantly less common are fluvioglacial sands, gravel and pebbles, as well as alluvial sediments - sand, gravel, pebbles, siltstones and loam, which are mainly distributed in river valleys. Also, sediments of bogs and lakes, as well as blown (aeolian) sediments are minimally distributed in small areas (Figure 29).

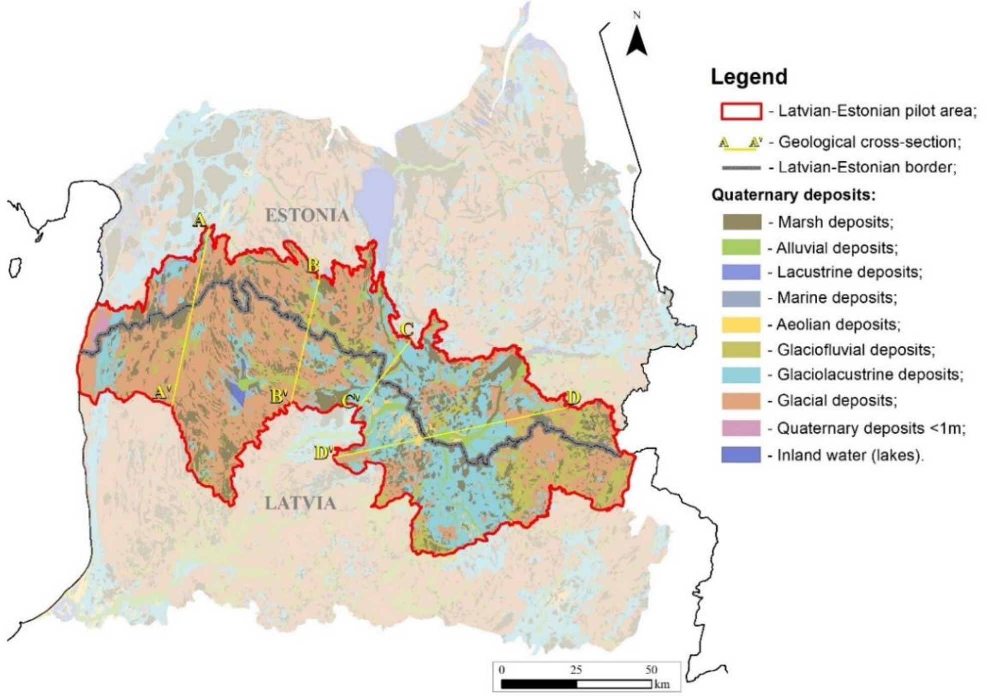


Figure 29 Quaternary deposits in Latvian-Estonian pilot territory

In general, the area is marked by poor drainage conditions, which determine difficult groundwater runoff. As a result, the thickness of the aeration zone in most parts of the territory does not exceed 1-2 m or even less; atmospheric precipitation infiltration is seasonal. There are only small areas in the Latvian-Estonian cross-border area, for example, in the Alūksne upland medium drainage conditions are marked (even well-drained areas are marked in small sections), where the thickness of the aeration zone is usually 2-5 m and even more. However, the intensity of infiltrative feeding varies. It is mainly determined by the lithological composition of the sediments lying on the surface. The smallest aeration zone is typical of clayey sediments, where the groundwater level is relatively close to the ground surface. Here, the fluctuations of the aeration zone during the year are insignificant. The maximum aeration zone thickness is observed in sandy sediments, where the groundwater level is 4-5 m and even more below ground level. These areas are characterized by significant fluctuations in the thickness of the aeration zone during the year - up to 2-3 m, where the maximum infiltration of groundwater is also observed.

Most of the Quaternary sediments are characterized by a single-layer structure, where it is represented mainly by unconfined aquifers. However, the lithological structure is not homogeneous. The Quaternary aquifer does not form a single aquifer, it is distributed sporadically in Quaternary sandy sediments, which are separated by weakly permeable moraine sediments and Quaternary clay sediments. Only in small areas a two-layer structure is marked for Quaternary sediments. In this case, sand deposits are deposited in the upper part, which are deposited on the low-permeability moraine loams and form a uniform unconfined aquifer that is distributed throughout the territory. In turn, the multilayered Quaternary sedimentary cover is mainly characteristic of the highlands. In these areas, either low water permeability moraine sediments or water permeable sediments are deposited at the top. In a multilayer structure, one or more intermoraine aquifers are formed, which are hydraulically connected to each other and form a complex aquifer system with specific formation conditions and groundwater regime.

The chemical composition of Quaternary aquifers is mainly determined by atmospheric precipitation and the lithological composition of water-permeable sediments, as well as the intensity of anthropogenic load. In the examined territory, the Quaternary aquifer mainly contains bicarbonate type freshwaters with mineralization - 150-500 mg/l. Sulphate-type waters are distributed locally, which indicates the presence of insignificant layers of gypsum in Quaternary sediments. In general, groundwater resources in Quaternary sediments are limited or small and are used mainly in individual households with dug wells, therefore not used in central water supply.

Under the Quaternary sediments in the south-eastern part of the territory embedded is the **Pļaviņas-Ogre aquifer system**, which consists of Pļaviņas, Salaspils (Dubnik), Daugava, Katleši and Ogre formations (in Estonian part only Pļaviņas and Dubnik formations are common). The aquifer system consists mainly of sediments of carbonate origin - fissured dolomites and limestones with a total thickness up to 90-110 m in Latvia, while in Estonia aquifer system consists of karstic dolomites and dolomitized limestones with a total thickness up to 17-25 m (Figure 30). In some places, the aquifer system contains a layer of gypsum, which affects the quality of groundwater. The depth of the aquifer system varies from 10-20 m to 80-100 m. The groundwater table is usually close to the ground surface in Latvia and approximately 3-8 m from the ground surface in Estonia. The filtration properties depend on the depth of the aquifer system. In areas where the aquifer system is covered by water-impermeable sediments with a thickness more than 50-100 m, the water conductivity is mainly less than 50 m^2/d. In turn, at a smaller thickness it can vary from 100 m$_2$/d to 500 m^2/d, reaching even

1000-2000 m^2/d in the karst process distribution areas. The filtration coefficient varies between 1 m/d to 50 m/d. The specific yield in the wells varies from 0.05-1 to 10-50 l/s/m. Groundwater abstraction from Pļaviņas-Ogre aquifer system in the pilot area is carried out from individual groundwater abstraction wells only.

In pilot are the Pļaviņas-Ogre aquifer system mainly contains hydrogen-bicarbonate type freshwaters with mineralization 500-600 mg/l, and increased iron content. Sulphate type waters with increased mineralization, which are formed as a result of the dissolution of gypsum, are common in some areas and are mostly distributed in gypsum-containing sediments.

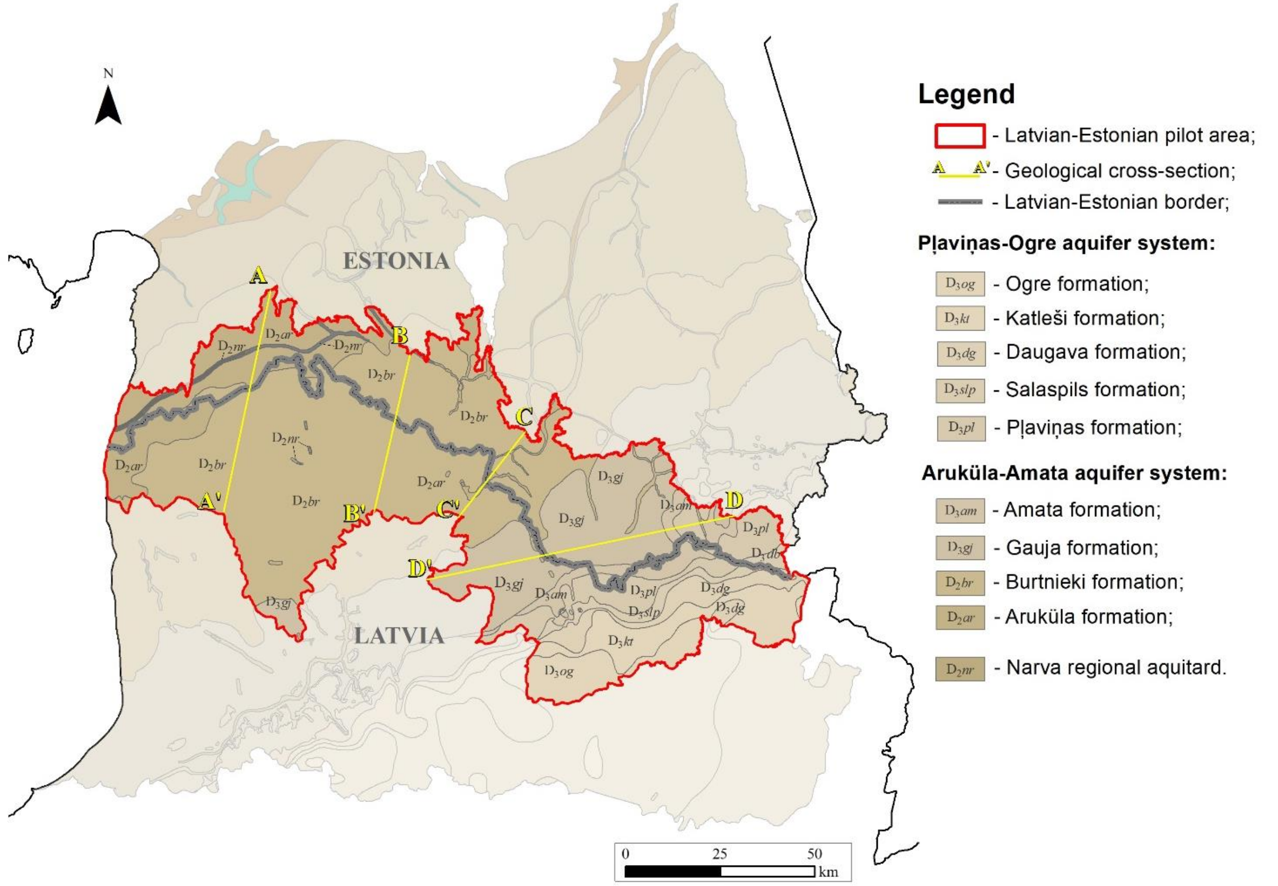


Figure 30 Pre-Quaternary deposits in Latvian-Estonian pilot territory

The **Aruküla-Amata aquifer system**, which consists of Amata, Gauja, Burtnieki and Aruküla formations, is embedded below. In this aquifer system, where the maximum thickness can reach 380 m, it is not possible to separate individual aquifers on a regional scale. Therefore, this aquifer system was considered as a single aquifer system. The aquifer system consists mainly of terrigenous sediments - sandstones with clay and siltstone interlayers in Latvia, while in Estonia third of the aquifer system consists of clayey rocks, which form local aquitards and aquifers, which have not been examined and proved.

The Aruküla-Amata aquifer system in the largest part of the pilot area is located directly below the Quaternary sediments, only in the south-eastern part of the territory it is deposited under the Pļaviņas-Ogre aquifer system. Many rivers in Estonia as well as Latvia cut through and drain this aquifer system, therefore groundwater table mainly depends on the terrain. In uplands it can rise up to 120-160 m from the ground surface, but in the northern and coastal boundaries can fluctuate from 20-50 m from the ground surface.

Water conductivity for sandstone sediments depends on the sediment effective thickness and filtration parameters (the maximum thickness of sandstones is marked in the southern part of the pilot area). The filtration coefficient mainly varies from 2 m/d to 8 m/d, and less often from 10 m/d to 15 m/d. Water conductivity can vary from 50-100 m^2/d (in Estonia) to 750-900 m^2/d (in Latvia), depending on the effective thickness. The specific flow in wells varies from 0.4 l/s/m to 1 l/s/m.

The aquifer system contains mainly freshwaters with a mineralization from 200 mg/l to 600 mg/l, and with elevated iron content (up to 3-7 mg/l). The Aruküla-Amata aquifer system differs with favorable conditions for vertical water exchange. This aquifer system has accumulated a significant part of the natural groundwater resources and groundwater abstraction from Aruküla-Amata aquifer system in the pilot area is carried out from many individual groundwater abstraction wells, as well as in groundwater well fields - well fields that provide centralized water supply to settlements and cities (Ainaži, Aloja, Mazsalaca, Rūjiena and Valka), as well as well fields, that ensures the operation of Valka cogeneration station.

Below the Aruküla-Amata aquifer system at the depth of 95-290 m on average lies the first regional aquitard - the Middle Devonian **Narva formation** marl and clay sediments with the total thickness up to 90-110 m. Throughout the pilot area, aquitard sediments safely separate the active water exchange zone (Figures 31-34) from the slow water exchange zone. The transversal filtration coefficient is 10^{-4}-10^{-5}, sometimes 10^{-6} or even less.

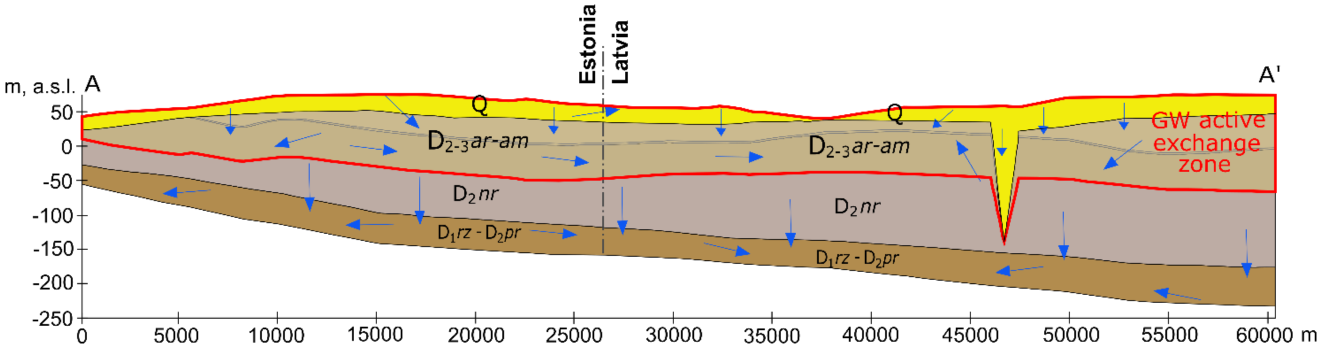


Figure 31 Geological cross-section A-A'

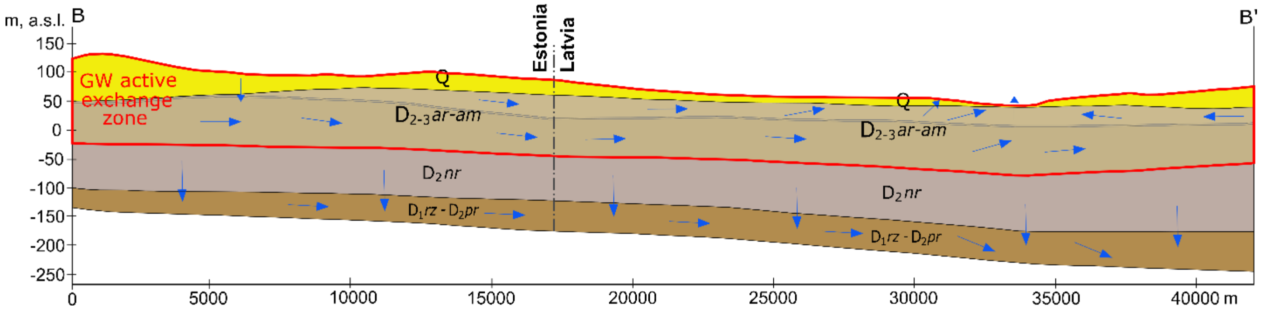


Figure 32 Geological cross-section B-B'

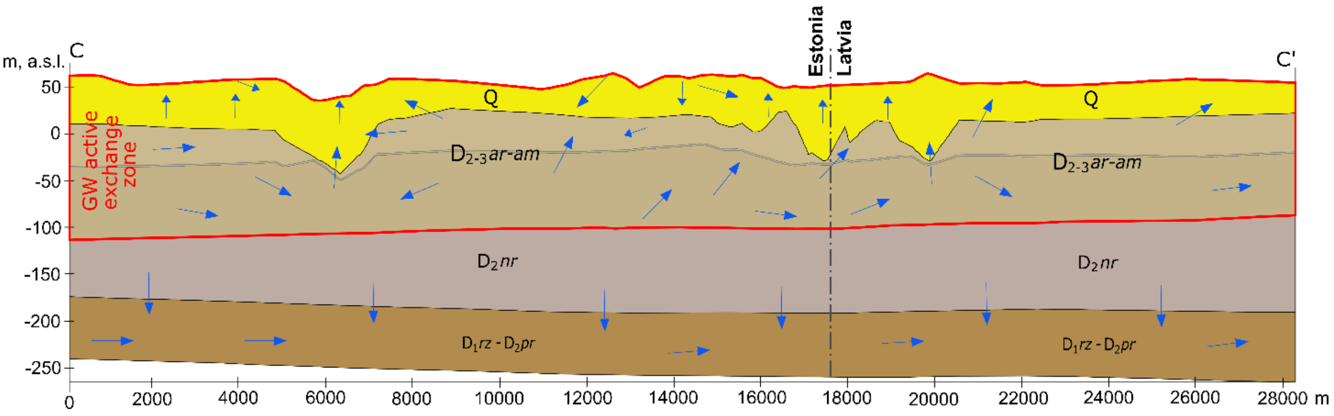


Figure 33 Geological cross-section C-C'

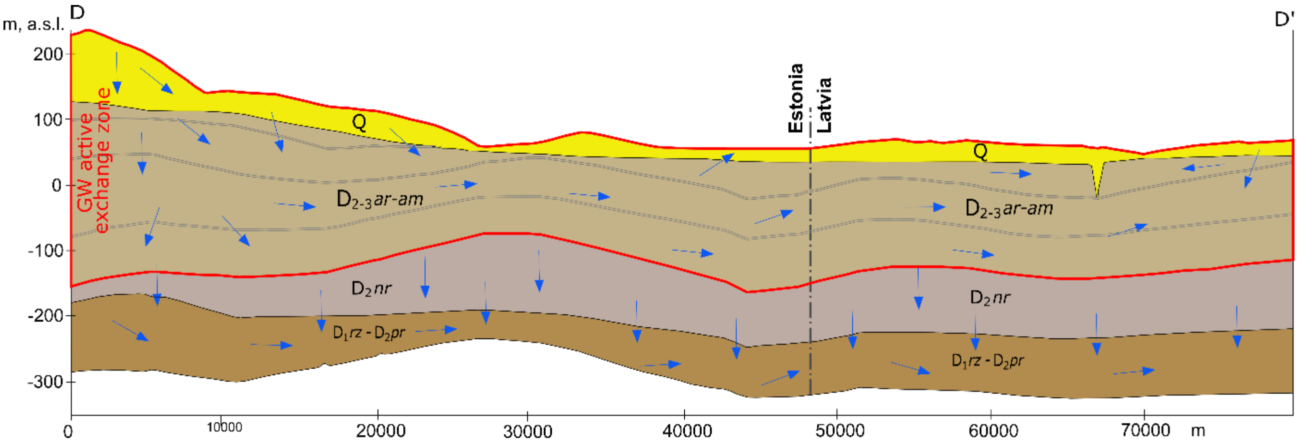


Figure 34 Geological cross-section D-D'

4.2 Conceptual model structure

In order to better describe the geological structure of the Latvian-Estonian pilot area and understand the groundwater flow system, it is useful to create a simple, conceptual representation - a conceptual model. The cross-border pilot area was identified within the project and its borders were defined.

The Latvian-Estonian pilot territory was delineated on a horizontal scale, mainly according to the boundaries of transboundary surface water bodies and their adjacent potentially influencing surface water bodies, as well as in Latvian side the directions of groundwater flows in some places were taken into account.

In the vertical scale, the conceptual model included those groundwater aquifer systems located in the active water exchange zone: 1) Quaternary aquifer system, 2) Pļaviņas-Ogre aquifer system, 3) Aruküla-Amata aquifer system. Below, the active exchange zone is delimited by Narva regional aquitard. The deepest layers in the transboundary area are not included in the conceptual assessment, as these aquifers are less used for water abstraction and the total abstraction is insignificant in the transboundary area.

In 2010, a hydrogeological model (PUMA model) was developed for the entire BAB, and the Latvian-Estonian pilot territory is part of the model territory. After the analysis of the existing data for the pilot area, it was concluded that the PUMA hydrogeological model data characterizes the existing hydrogeological conditions of the Latvian-Estonian transboundary area. In total, 1723 boreholes have been used for modeling the geological situation of the pilot area, of which 1043 are on the Latvian side and 680 on the Estonian side. The number of boreholes used in the model is sufficient and their coverage is appropriate to apply the model information for describing the pilot territory (Figure 35). The PUMA model consists of a total of 42 geological layers, 18 of which are distributed in the Latvian-Estonian pilot area and these layers are indicated in the Table 4. Quaternary aquifer system was divided into 4 separate layers so that the model can better describe the heterogeneity of Quaternary sediments.

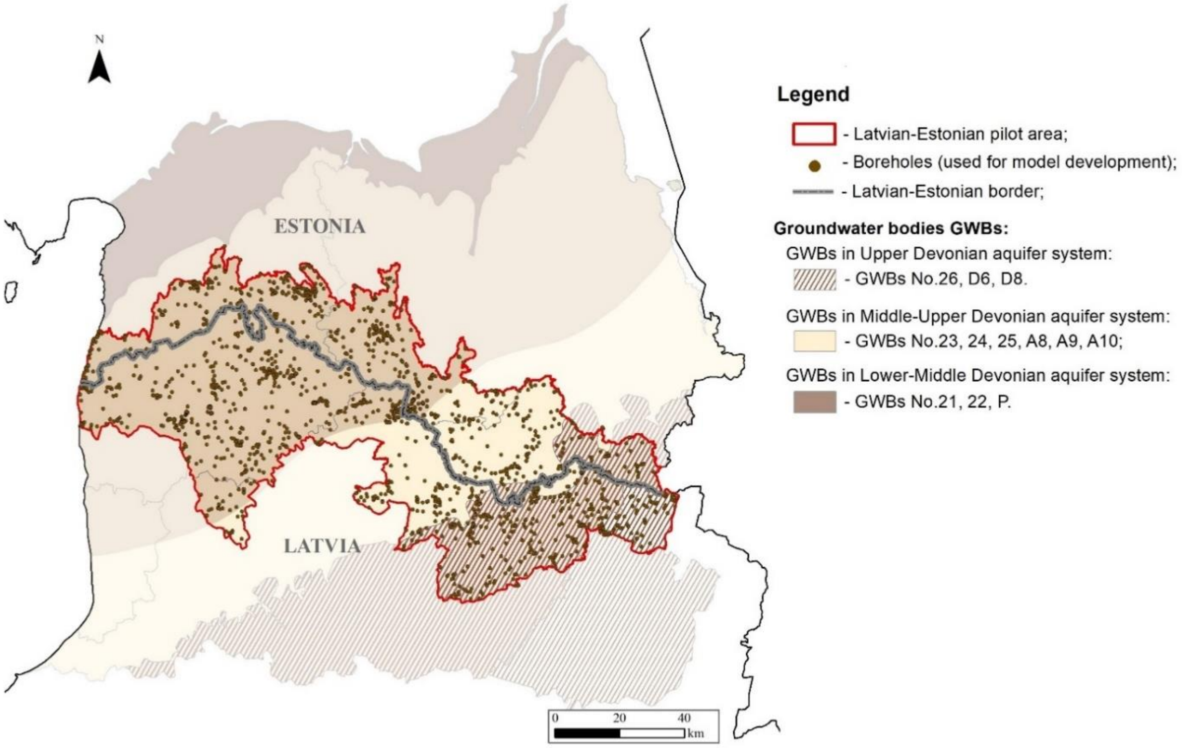


Figure 35 Boreholes used for conceptual model development

In addition to defining the boundaries of the territory, it is important to develop a conceptual understanding of groundwater movement. This helps to understand the ongoing hydrogeological processes in the pilot area. The information on the piezometric heads of aquifers in the PUMA model is useful for determining the directions of groundwater flows in the area. Also, within the framework of this project, modeling of transboundary groundwater flows and calculations of water mass balance have been performed. More detailed information on modeling of Latvian-Estonian transboundary groundwater flows and water balance calculations is described in Chapter 6.

The PUMA model is built on the most recent and comprehensive data available at the time of its development (year 2010). Although some data has been updated since that time, namely, groundwater abstraction data and the number of installed wells has increased, the analysis of the changes in abstraction rate indicates that this factor is negligible as the abstraction rate in the pilot area has only minor fluctuations.

Accordingly, the results obtained from the PUMA model have been used for the Latvian-Estonian pilot area characterization. For the area identified above, Table 4 with the assumed aquifers parameters is summarized.

Table 4 Characteristics of the aquifers based on PUMA model

Description	Aquifer system	Model layer	Hydraulic properties	Prevailing sediment	Thickness of the aquifer/aquitard, m	Hydraulic conductivity, m/d	Transmissivity coefficient, m^2/d	Primary hydrostatic pressure
Quaternary deposits	Quaternary	Q1	aquifer	Sand, loam	60 - 180 (max 237)	1.2 - 6.4	10-210	Unconfined
		Q2	aquitard					
		Q3	aquifer					
		Q4	aquitard					
Upper-Middle Devonian active water exchange zone. Numerous aquitards are very thin, therefore only local importance	Pļaviņas-Ogre	D3kt+og	aquifer	Dolomite, sandstone, marl, gypsum	35 - 105 (max 138)	0.5 - 1.3	20 - 180	Confined
		D3kt+og_sprost	aquitard					
		D3dg	aquifer					
		D3slp	aquifer					
		D3pl	aquifer					
		D3pl_sprost	aquitard					
	Aruküla-Amata	D3am	aquifer	Sandstone, siltstone, clay	80-240 (max 315)	0.7 - 5.2	55 - 1250	Confined
		D3am_sprost	aquitard					
		D3gj	aquifer					
		D3gj_sprost	aquitard					
		D2br	aquifer					
		D2br_sprost	aquitard					
		D2ar	aquifer					
Regional aquitard	Narva	D2nr_sprost	aquitard	marl, clay	30-105 (max 140)	$7.7x10^{-10}$	-	-

5 Numerical model of the transboundary aquifer of the Estonian-Latvian border

For the assessment of Latvian-Estonian transboundary groundwater resources, a formerly developed PUMA model results were used as this is the only regional scale groundwater model for the pilot area that fully encompass Latvian-Estonian pilot territory. Model is built on the most recent and comprehensive data available at the time of its development (year 2010) and, although some data has been updated since that time, groundwater heads in a regional scale were assumed to be suitable for the transboundary flow estimation needs as there are no significant changes in groundwater pressures since the time of development.

The PUMA model is built by University of Latvia, Faculty of Physics, Mathematics and Optometry and it is based on three-dimensional Darcy flow with free-surface and anisotropic conductivity for steady state solution (Virbulis et al. 2013). The model mesh is constructed using Finite Element Method (FEM), thus in a horizontal plane mesh is of irregular triangular shape. All boundary conditions are incorporated into the mesh, therefore all groundwater level observations (wells), hydrographic data (rivers, lakes) and abstraction wells are aligned with the mesh and each of these elements have their particular mesh node.

Schematization of hydrogeological conditions - stratification and accuracy of the model

Geological structure is divided into 42 layers distinguished on the basis of unit hydraulic properties and geological data resolution as well. Model includes aquitards and aquifers from Vendian up to Quaternary deposits.

The PUMA model meshes or elements are of triangular shape and the size of the mesh elements are spatially varying. The triangular mesh is built based on the network of lines and points to incorporate characteristic features such as borehole locations, country boundaries, rivers, contours of water bodies. Areas between these features were triangulated where each of the incorporated features is represented with mesh vertices. Therefore, areas with higher number of observations or other boundary conditions consist of smaller and more detailed meshes, while territories with limited information on geological settings and groundwater levels have larger meshes. As a result, the sizes of meshes change from less than 1 km^2 up to 10 km^2, while the majority of meshes are of smaller sizes. The entire mesh of the BAB model covers an area of 485,936 km^2 while Estonian - Latvian pilot site covers an area of 8,025 km^2 and is represented with 4569 mesh nodes.

The model is calibrated on the groundwater level measurements in the monitoring wells supplemented with head measurements in exploitation wells measured during well installation. Considering the distinct time dependence of head observations, the year 2010 is chosen as the reference year for the model scenario where observations from the surrounding years are taken into account through the weighting coefficients.

The optimization method L-BFGS-B (Bastani et al. 2010) is used for the calibration of the model. The calibration parameters are the horizontal and vertical hydraulic conductivities of the hydrogeological layers. The conductivities are assumed uniform throughout a whole individual layer. Initial values of the conductivities are taken from the available field pumping test measurements or based on the lithology of individual hydrogeological layers. The vertical conductivities are decreased 10 times in aquifers considering the anisotropic structure of the sedimentary layers. One coefficient per layer is changed during the optimization.

Hydrogeological parameters and model parameters

The PUMA model was developed using vast kind of data sources that is fully described by Virbulis et al. (2012), with the most important data sources being:

- DEM was taken from EU-DEM data with 25 m resolution (EU-DEM, 2014);
- precipitation and evapotranspiration data from KNMI-RACMO2 climate model was used as a boundary conditions. This dataset has a 25 km resolution and infiltration constructed as a weighted difference of 30 years averaged period;
- data for around 20,000 boreholes in the territory of Latvia from the database of the Latvian Environment, Geology and Meteorology centre (LEGMC), around 20,000 boreholes in the territory of Estonia from the database of the Estonian Land Board and few hundreds of boreholes in the territory of Lithuania obtained from the Lithuanian Geological Survey;
- geological and structural maps of the sub-Quaternary for Latvia;
- data from published geological cross-sections and other data sources.

The PUMA model is of regional scale and encompasses large territory, therefore for a more detailed description that contributes to the transboundary groundwater flow estimation procedure, a following subchapter is developed.

Model limits, boundary conditions

The Precambrian basement forms the impermeable bottom of the model as suggested by Levins et al. (1998) and Mokrik (1997). On the northern and western side of the BAB the basement reaches the earth's surface and the thickness of the model is zero. On the south-western side, the BAB borders the Danish-Polish basin with a zone of extensive faulting and this boundary is assumed to be impermeable according to Mokrik (1997). The eastern side of the BAB is connected with the Moscow Artesian basin and the south-eastern boundary is the Belarus-Masurian anticline. The thickness of the BAB at these boundaries is approximately 300 – 500 m. Zero water exchange is assumed through these boundaries.

Simple hydrological model is applied on the model's surface. The level of lakes, rivers and sea is fixed as a constant hydraulic head while infiltration is set as flux boundary condition on the surface elements. Infiltration is based on the regional climate model KNMI-RACMO2 from the ENSEMBLES project and set as a weighted difference of 30 years averaged precipitation and evaporation and further calibrated during the optimization of the model.

For groundwater abstraction estimation, only boreholes with large yields are considered. For the entire territory of BAB, a total of 49 wells in Lithuania (total abstraction of 45000 m^3/day), 161 in Latvia (184 000 m^3/day) and 172 in Estonia (24 000 m^3/day) are considered.

DEM data

For the territory of BAB there are several elevation models available with various resolutions and extents. Therefore, for the model topographic surface compilation of multiple models were created. For the largest part of the inland territories, EU-DEM digital relief model with 25 m resolution was applied (EU-DEM, 2014). For some small areas along the eastern border of BB, lower resolution CIGAR SRTM V4.1 was applied with a 90 m resolution (Jarvis et al. 2008). For the Baltic Sea territory, IOWTOPO2 DEM of the Baltic Sea bottom was used covering the entire area of interest with grid cell resolution of 2 km (Seifert et al. 2001). The Latvia-Estonia transboundary territory is completely covered by the EU-DEM model.

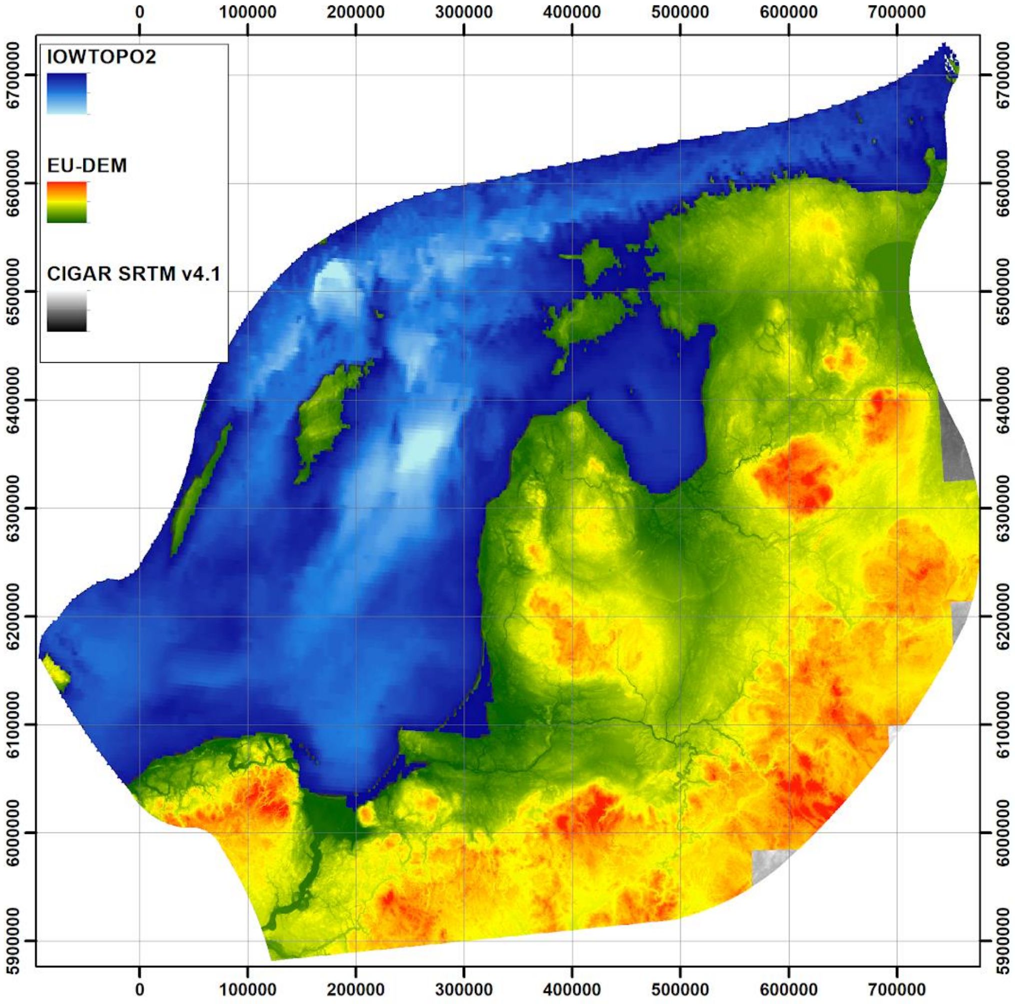


Figure 36 DEM for Baltic artesian basin

Characterization of the EE-LV pilot area within PUMA model

The area of Estonian-Latvian pilot area is 8025 km^2 and comprises a relatively small part of the regional PUMA model. Regional PUMA model has 42 distinct layers of aquifers, aquitards and aquicludes, while 18 of these layers are present in Estonian-Latvian transboundary pilot area (Table 4). There are 4 main components of the geological structure of the transboundary area:

- Quaternary aquifer system is the first water bearing aquifer in the whole pilot area while its importance is low due to limited quality and quantity of resources. Quaternary system was divided into 4 separate layers so that the model can better describe the heterogeneity of Quaternary sediments;
- Pļaviņas-Ogre aquifer system comprises mainly of carbonate rocks, but have limited extent in the transboundary area;
- The Aruküla-Amata aquifer system generally is the main source of drinking water in the transboundary area and covers the whole pilot area;
- Narva aquitard is of regional importance and it separates active water exchange zone from the deeper located slow water exchange zone.

The PUMA model meshes or elements are of triangular shape and the size of the mesh elements are spatially varying (Figure 37): areas with higher number of observations or other boundary conditions are comprised of smaller and more detailed meshes, while territories with limited information on geological settings and groundwater levels have larger meshes. As a result, the sizes of meshes change from less than 1 km^2 up to 10 km^2, while the majority of meshes are of smaller sizes (Figure 38).

As a result, Estonian-Latvian transboundary pilot area consists of 4569 mesh nodes for each individual layer, therefore total 82242 mesh nodes are present in the pilot area.

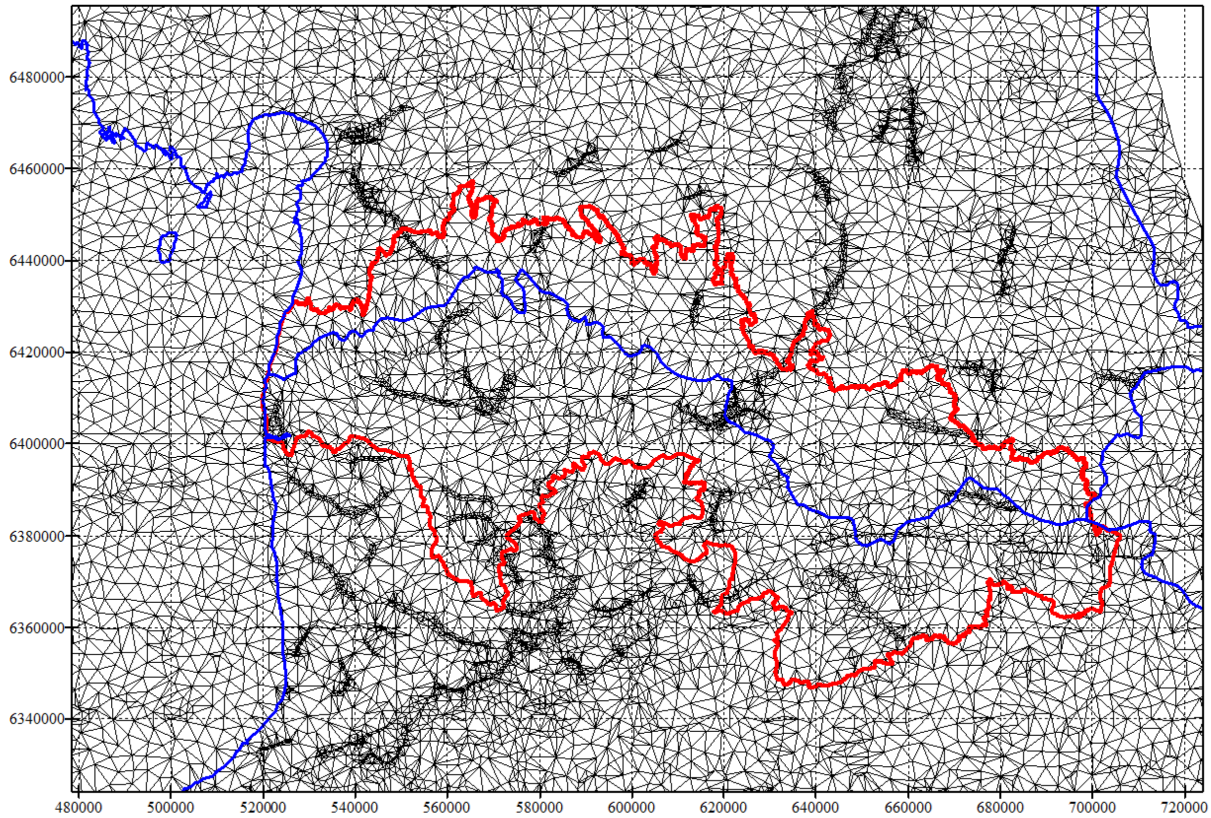


Figure 37 The spatial distribution of PUMA model triangle mesh elements within Estonian-Latvian transboundary pilot area (red line; blue line indicates terrestrial borderlines)

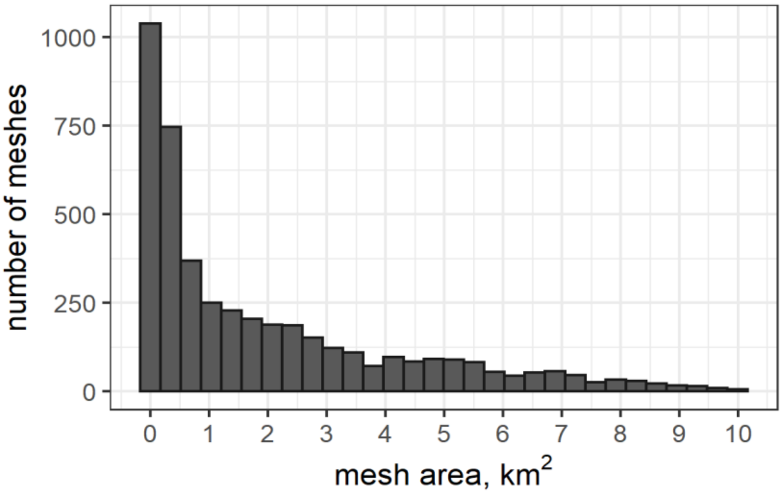


Figure 38 Distribution of sizes of meshes within Estonian-Latvian transboundary pilot area

A total of 1723 boreholes have been used for modeling the geological structure of the Estonian-Latvian transboundary pilot area, of which 1043 are on the Latvian side and 680 on the Estonian side, suggesting good observation coverage. However, a number of new wells have been installed on both sides of the border since 2010 that were not used in the PUMA model: there are 73 new wells in Latvian side and 369 new wells in Estonian side of the pilot area (Figure 39). The vast majority of the new boreholes are located next to the existing ones indicating that the geological structure cannot be significantly improved if the new boreholes would be implemented in the model.

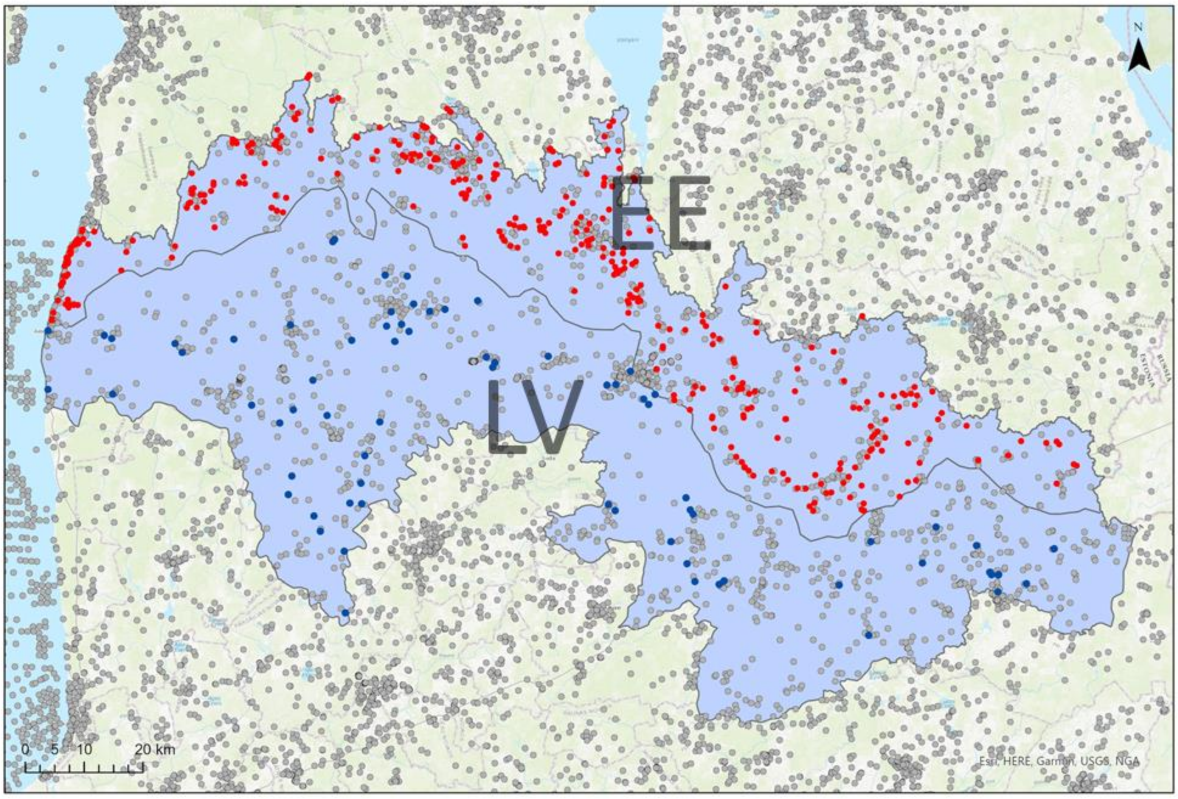


Figure 39 Boreholes used in the PUMA model geological structure development (gray points) and new boreholes since 2010 in Latvian (blue points) and Estonian (red points) side of transboundary area

Groundwater level observations from national groundwater monitoring networks and abstraction wells were used to calibrate the PUMA model. In total 1134 groundwater level observation points were used in the PUMA model for the EE-LV transboundary area: 927 wells are located in Latvian side and 207 wells in Estonian side of the transboundary pilot area (Figure 40).

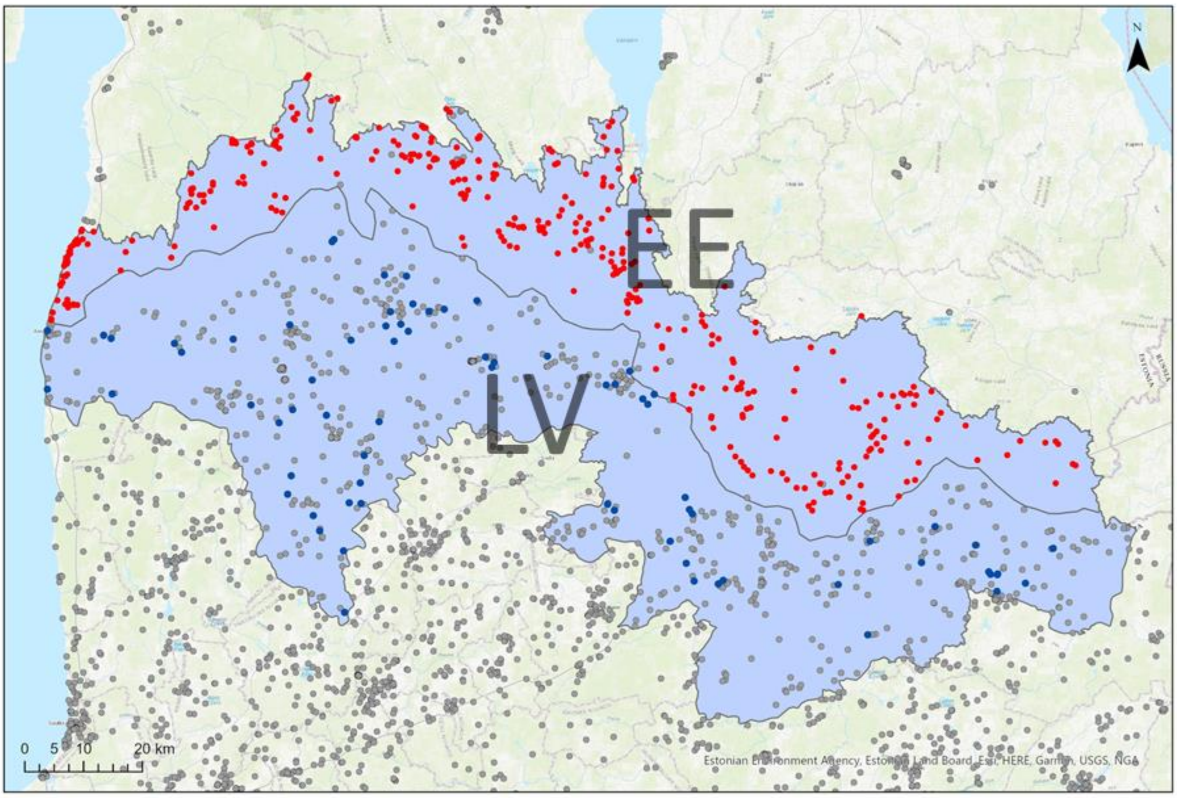


Figure 40 Groundwater level observation wells used in the PUMA model (gray points) and new observations since 2010 in Latvian (blue points) and Estonian (red points) side of transboundary area

Groundwater abstraction/intake discharge data in the PUMA model was taken for the year 2010. Total groundwater abstraction rate for the transboundary pilot area in the PUMA model is 5000 m^3/d that is populated in 50 distinct abstraction sites.

The calibration procedure in the PUMA model assigned weights for each observation point according to its “age” - i.e. older groundwater level measurements had lower impact on calibration procedure than newer observations which have higher credibility. Such implementation was necessary during PUMA development because many groundwater level observations were relatively old (Figure 41).

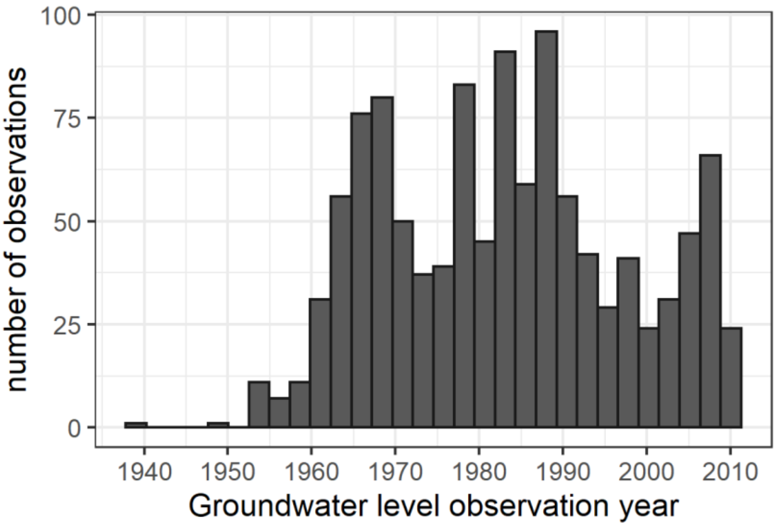


Figure 41 Groundwater level observations by the year of measurement used in the PUMA model

Hydrographic data

The PUMA model also includes constant head boundary conditions for hydrographic network - rivers and lakes (Figure 42). The river stages and lake levels were extracted from DEM data. The total length of rivers in the transboundary pilot area comprises 3362.2 km and lakes encompass the total area of 102.3 km^2.

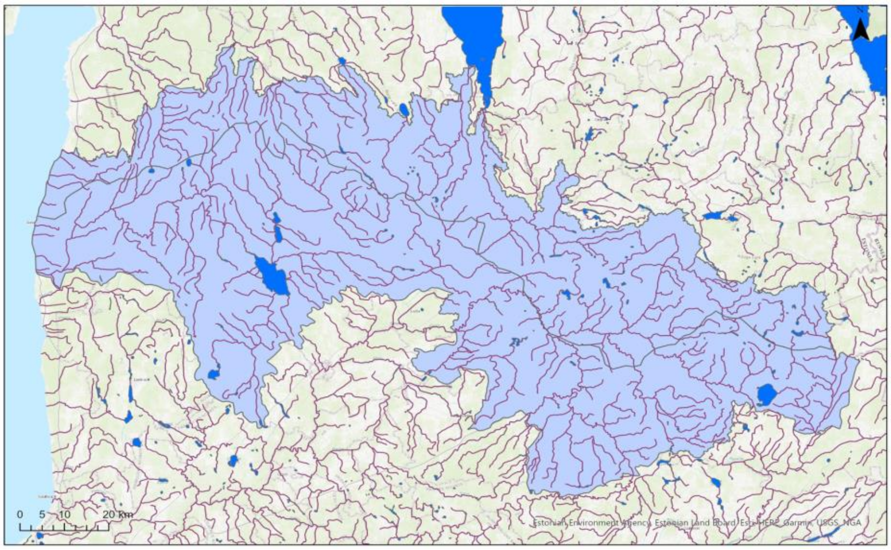


Figure 42 Hydrographic network in the transboundary pilot area of the PUMA model

Data on groundwater abstraction (geospatial)

Groundwater abstraction data in the Baltic States is used to set-up the sources of water abstraction. Groundwater abstraction/intake discharge data in the PUMA model was taken for the year 2010. Only wells with large yields are considered. Each abstraction source was distributed inside the enclosed finite volume element. Total groundwater abstraction rate for the transboundary pilot area in the PUMA model is 5000 m^3/d that is distributed in 50 distinct abstraction sites (Figure 43).

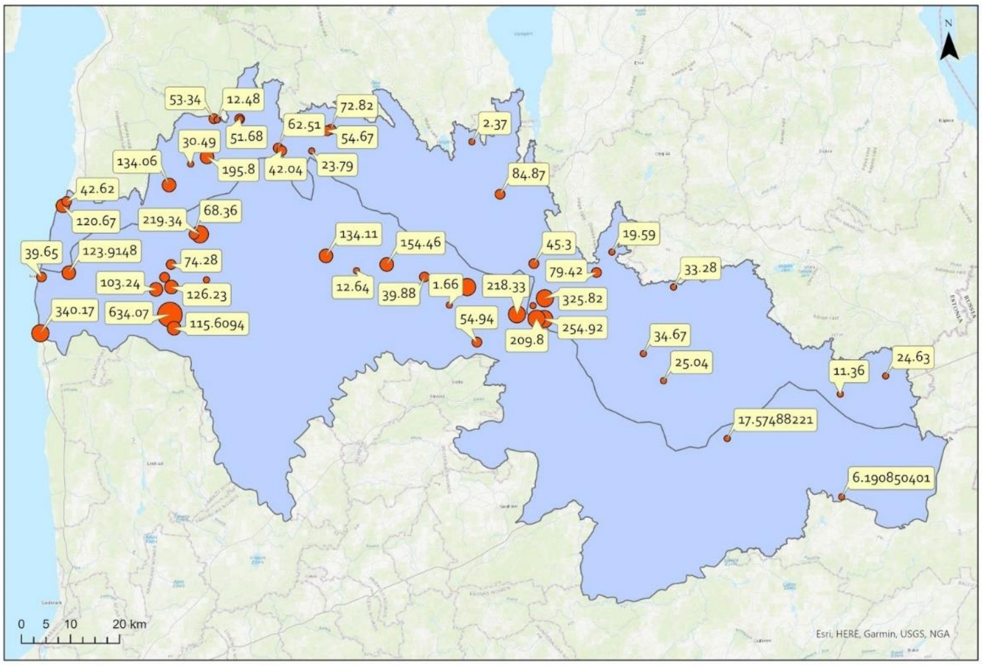


Figure 43 Groundwater abstraction rates in Latvian-Estonian transboundary pilot area

6 Assessment of transboundary groundwater flows by hydrodynamic modeling

A procedure for transboundary groundwater flow estimation was developed and applied to Estonian-Latvian borderline to assess transboundary groundwater flows. The procedure was developed to be relatively easily reproduced and using fully open-source tools, while also maintaining credibility of the results. The approach is based on analytical equations that govern groundwater flow according to piezometric gradient distribution and calculations are performed in a number of triangular shaped mesh elements along the borderline.

Application of the developed procedure is performed on Estonian-Latvian borderline where a number of aquifers, aquitards and aquifer systems are present. Estimation of transboundary groundwater flows were performed on three main aquifer systems (Pļaviņas-Ogre, Aruküla-Amata and Lower-Middle Devonian) that comprised a total of eight individual aquifers. Transboundary groundwater flows are estimated and presented in the report.

6.1 Methodology and materials

Semi-analytical approach for groundwater flow estimation

The developed groundwater flow estimation procedure is based on a relatively simple and reproducible approach that relies on Darcy's law - a fundamental groundwater flow equation.

According to Darcy's law, groundwater volumetric flow rate/total discharge (Q, m^3/day) through the cross-sectional area (A, m^2) of the flow depends on hydraulic conductivity (K, m/day) of the aquifer and the hydraulic gradient (i) as described in the equation and supporting Figure 44 below. The hydraulic gradient represents the rate that groundwater head changes (h1 – h2, m) in the flow direction per length unit (L, m). Cross sectional area is defined by the aquifer thickness (b, m) and the width of the cross section (B, m) perpendicular to the groundwater flow (Kresic 2007, Fitts 2002).

$$Q = A \cdot K \cdot i = B \cdot b \cdot K \cdot \frac{h_1 - h_2}{L}$$

where:

Q – volumetric flow rate/total discharge (m^3/day);
A – cross-sectional area of the flow (m^2);
K – hydraulic conductivity of the aquifer (m/day);
i – hydraulic gradient;
h1 – h2 – groundwater head change (m) in the flow direction;
L – segment length (m);
b – aquifer thickness (m);
B – width of the cross section (m) perpendicular to the groundwater flow.

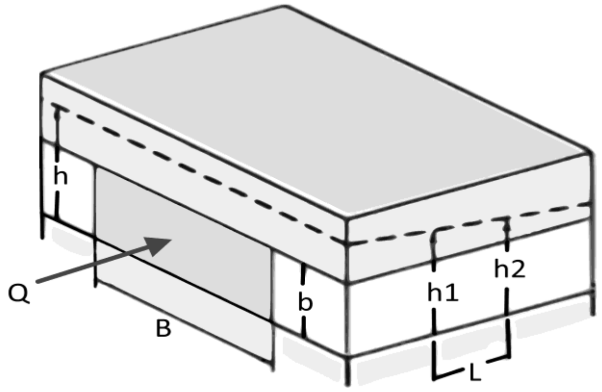


Figure 44 Schematic presentation of total discharge of groundwater in confined aquifer (Kresic, 2007)

The approach has its limitations: the equation in the procedure is really true for a 2-dimensional environment. Kresic (2007) notes that there are no simple and closed analytical solutions for a truly three-dimensional groundwater flow setting, which would include all possible heterogeneities and anisotropies. But he also emphasizes the usefulness of approximate analytical solutions based on different simplifications, as they provide satisfactory results for screening-level analysis or in cases of simple field conditions.

Applying the principle of flow conservation, groundwater flow from one model mesh element to adjacent one will be the same (Fitts, 2002). The PUMA model mesh elements are aligned along the country border, thus approximate calculation of groundwater flow across the border is feasible to be performed using the abovementioned equation if calculations are performed for every single mesh element next to the borderline.

Technical implementation of the semi-analytical groundwater flow estimation

The procedure to estimate transboundary groundwater flows was implemented by reproducible code in R statistical programming language through RStudio interface with minor assistance from QGIS to prepare mesh elements. The used fully open-source tools ensure repeatability by anyone interested in the procedure. The workflow of the transboundary groundwater flow estimation procedure consists of three main stages:

1. Preparation of input data (mesh elements, borderline segments and piezometric heads on the mesh nodes);
2. Calculation of groundwater flow across borderline segments for each mesh element that is connected to the borderline;
3. Calculation of total groundwater flows across the borderline for each individual aquifer or aquifer system.

Preparation of input data

For proper calculation of a transboundary groundwater flow, a proper input data must be prepared. In the GIS (QGIS) environment a borderline was prepared and mesh elements were selected if they had a direct connection with the borderline. The whole LV-EE borderline consists of 160 individual borderline segments - each segment has two mesh elements assigned having a one element on each side of the borderline (Figure 45). In total 320 individual mesh elements represent the whole borderline area that are used for further calculations.

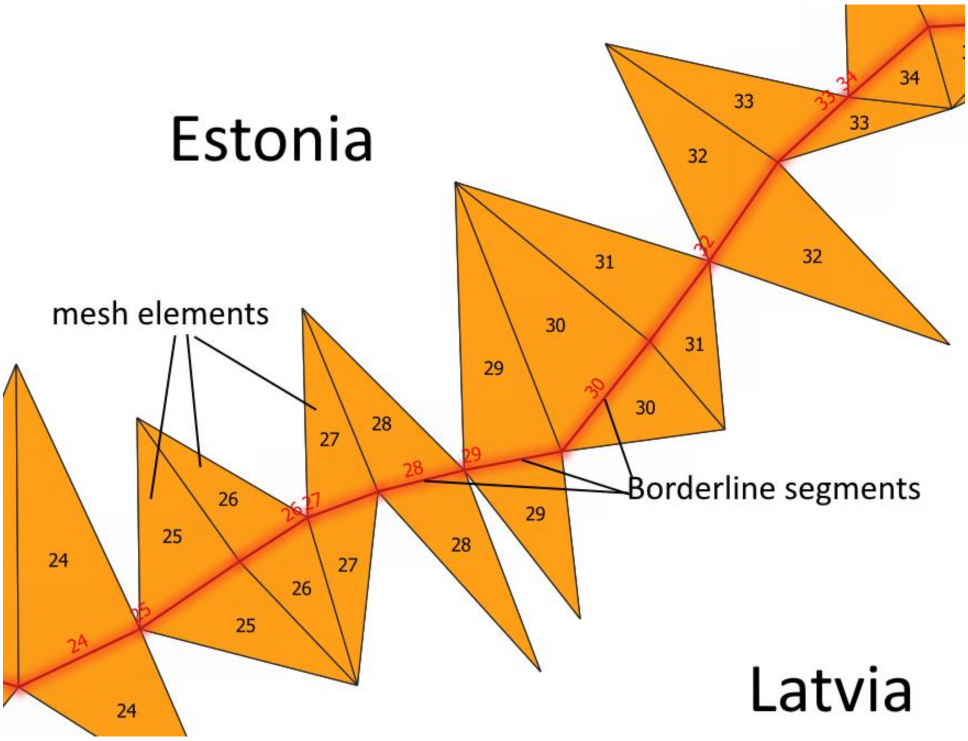


Figure 45 Example view on prepared mesh elements along the Estonian-Latvian borderline

Piezometric heads for all aquifers in the PUMA models are originally in the form of points that are attributed to the all three peaks of the mesh elements; therefore, it is possible to select all three piezometric head points that belong to a specific mesh element. Raw piezometric head data for each aquifer (Table 4) was extracted from the PUMA model for calculation of groundwater flows in each mesh element in the next step.

Calculation of groundwater flow across borderline segments

Groundwater flow across the borderline is calculated according to the methodology described in chapter 1.2. The components of equation 1 are calculated step-wise in each mesh element individually. The calculations are performed in a scripting manner in a R statistical programming language (R Core Team, 2021), spatial calculations were performed by using functions from the “sf” package (Pebesma, 2018).

For each mesh element all three triangle nodes are selected for an aquifer of interest and their piezometric head values used to calculate hydraulic gradient and the contribution factor to the borderline. All the required components of equation 1 plus contribution factor were calculated as following:

- **Width of the cross section** of the borderline segment is calculated as a length between the two mesh nodes that sits on the borderline (points 1 and 3 in the Figure 46);
- **Aquifer thickness** of the cross-section area is calculated as the difference between surfaces elevations of two successive PUMA model layers (Table 4);
- **Hydraulic conductivity** values are taken from the PUMA model according to the aquifer layer (Table 4);
- **Hydraulic gradient** is calculated as a groundwater head change in the flow direction. The practical implementation involves finding of equipotential line for the middle value of the three piezometric heads (yellow line in Figure 46), finding a groundwater flow line (blue line in Figure 46) that is perpendicular to the equipotential line and finding the length

between highest value piezometric head point and equipotential line (node 1 and red point in Figure 46). These calculations are based on Pythagoras theorem;

- **Contribution factor** is an additional element for equation 1, having a range from 0 to 1 that corresponds to the angle of the groundwater flow line (blue line Figure 46) to the borderline (red line in Figure 46). This factor is introduced to account for non-perpendicular flows across the borderline A contribution factor of 1 means that the angle between borderline segment and groundwater flow line is 90° and all the groundwater flow goes across the borderline, while factor of 0 means that groundwater flows parallel to the borderline segment and there is no flow across the borderline segment. Angles between 0 and 90° are translated to the contribution factor according to Pythagoras theorem.

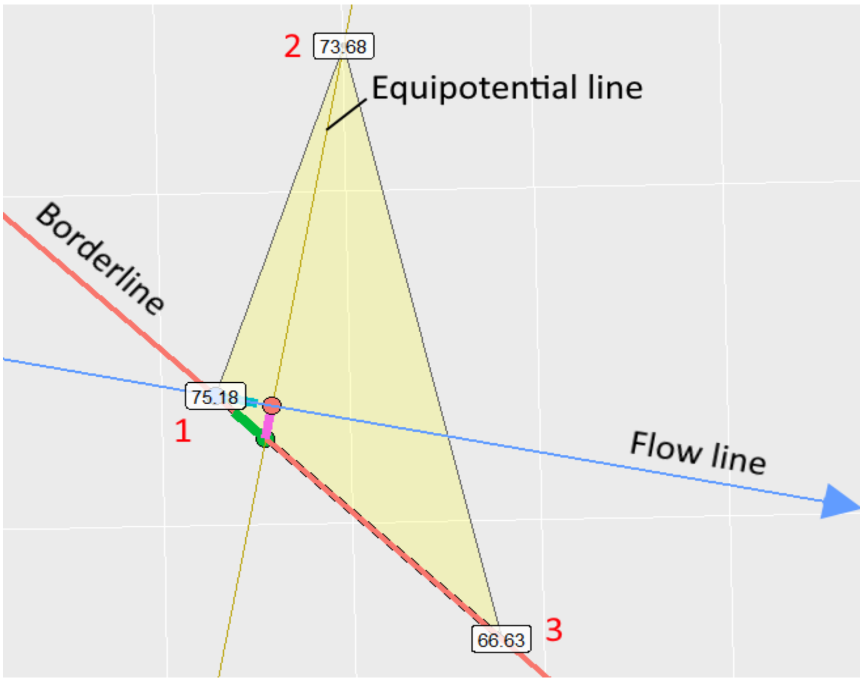


Figure 46 Principal components of calculation of groundwater flow direction and gradient in an example mesh element. Points 1-3 are mesh nodes that have piezometric head values from the PUMA model results

For each mesh element a total groundwater contribution to transboundary groundwater flow is calculated according to equation 1 taking into account all the calculated components. The resulting groundwater flow for each mesh element can have either positive or negative sign according to the direction of flow towards or from the borderline segment.

Calculation of groundwater flow for aquifers

The final step to estimate overall transboundary groundwater flow across Estonian-Latvian borderline is to summarise all the individual calculations of the mesh element that are attributed to a particular aquifer or aquifer system. The summarising was done for 7 individual aquifers represented in Table 4 (D_2*ar*, D_2*br*, D_3*gj*, D_3*am*, D_3*pl*, D_3*slp*, D_3*dg*), as well as for three aquifer systems (Pļaviņas-Ogre and Aruküla-Amata, Lower-Middle Devonian). For easier representation, the summarising was done in a way that positive sign indicates groundwater flow from Latvia to Estonia, while negative sign shows groundwater flow in opposite direction.

6.2 Results

The developed procedure for transboundary groundwater flow estimation was applied to the Estonian-Latvian borderline according to the procedure described in previous chapter. As a result, transboundary groundwater flow for main useful aquifers and aquifer systems are calculated and summarised in this chapter.

Transboundary groundwater flow across EE-LV borderline

The final results indicate that transboundary groundwater flow across Estonian-Latvian borderline varies between aquifers and aquifer complexes. All the flows/budgets represented in tables 5-7 are indicated in a way that outflow or positive sign indicates groundwater flow from Latvia to Estonia while inflow or negative sign indicates groundwater flow from Estonia to Latvia across the borderline (Tables 5-7).

The first useful groundwater aquifer system in the pilot area is Pļaviņas-Ogre aquifer system that contains Daugavas (D_3*dg*), Salaspils (D_3*slp*) and Pļaviņas (D_3*pl*) individual aquifers. Calculated groundwater budget suggests that 845.6 m^3/d water is flowing from Latvia to Estonia and 2333 m^3/d is flowing from Estonia to Latvia meaning that the total net flow is 1487.4 m^3/d that flows from Estonia to Latvia (Table 5). The majority of groundwater flow in this aquifer system is attributed to the Pļaviņas (D_3*pl*) aquifer.

Table 5 Transboundary groundwater flow in Pļaviņas-Ogre aquifer system

Aquifer	From Estonia to Latvia, m^3/d	From Latvia to Estonia, m^3/d	Total net Q, from Latvia to Estonia m^3/d
D_3*dg*	146.5	0.0	-146.5
D_3*slp*	55.7	0.0	-55.7
D_3*pl*	2130.7	845.6	-1285.2
Pļaviņas-Ogre aquifer system	2333.0	845.6	-1487.4

The second useful and the most important aquifer system in the pilot area is Aruküla-Amata aquifer system that includes Amata (D_3*am*), Gauja (D_3*gj*), Burtnieki (D_2*br*) and Aruküla (D_2*ar*) individual aquifers. Every aquifer has both inflows and outflows (Table 6), meaning that the groundwater flow pattern changes along the Estonian-Latvian borderline. In total, 5807.2 m^3/d groundwater is flowing from Estonia to Latvia and 9488.5 m^3/d is flowing from Latvia to Estonia through the aquifer system having a total net flow of 3681.3 m^3/d flowing from Latvia to Estonia.

The most intensive aquifer in the Aruküla-Amata aquifer system is Gaujas aquifer (D_3*gj*): in total 3658.2 m^3/d is flowing from Latvia to Estonia through this aquifer (Table 6). Aruküla aquifer (D_2*ar*) is the only aquifer in this aquifer system that has a net total flow from Estonia to Latvia, having a 742.1 m^3/d contribution.

Table 6 Transboundary groundwater flow in Aruküla-Amata aquifer system

Aquifer	From Estonia to Latvia, m^3/d	From Latvia to Estonia, m^3/d	Total net Q, from Latvia to Estonia m^3/d
D_3*am*	178.6	926.0	747.5
D_3*gj*	1141.8	4800.1	3658.2
D_2*br*	2148.4	2166.2	17.8
D_2*ar*	2338.4	1596.3	-742.1
Aruküla-Amata aquifer system	5807.2	9488.5	3681.3

Lower-Middle Devonian aquifer system is considered in the report as an extra aquifer system to assess groundwater flow across the Estonian-Latvian borderline. The Lower-Middle Devonian aquifer system indicates that total net groundwater flow of 1510 m^3/d is flowing from Latvia to Estonia.

Table 7 Transboundary groundwater flow in Lower-Middle Devonian aquifer system

Aquifer	From Estonia to Latvia, m^3/d	From Latvia to Estonia, m^3/d	Total net Q, from Latvia to Estonia m^3/d
Lower-Middle Devonian aquifer system	551.3	2061.3	1510.0

Spatial distribution of groundwater flow rates

Transboundary groundwater flow distribution along Estonian-Latvian borderline is uneven. The first useful groundwater aquifer system Pļaviņas-Ogre is presented only in a limited area of the pilot territory - in the East part of the pilot area. There are two distinct areas where relatively significant groundwater flow occurs: in the most distinct part of the borderline in the East groundwater flows from Estonia to Latvia (red colored sections in the Figure 47), while another part of the borderline located towards the center from the Eastern part is dominated by a groundwater flow from Latvia to Estonia, while with a much lower rate (green colored borderline sections in Figure 47).

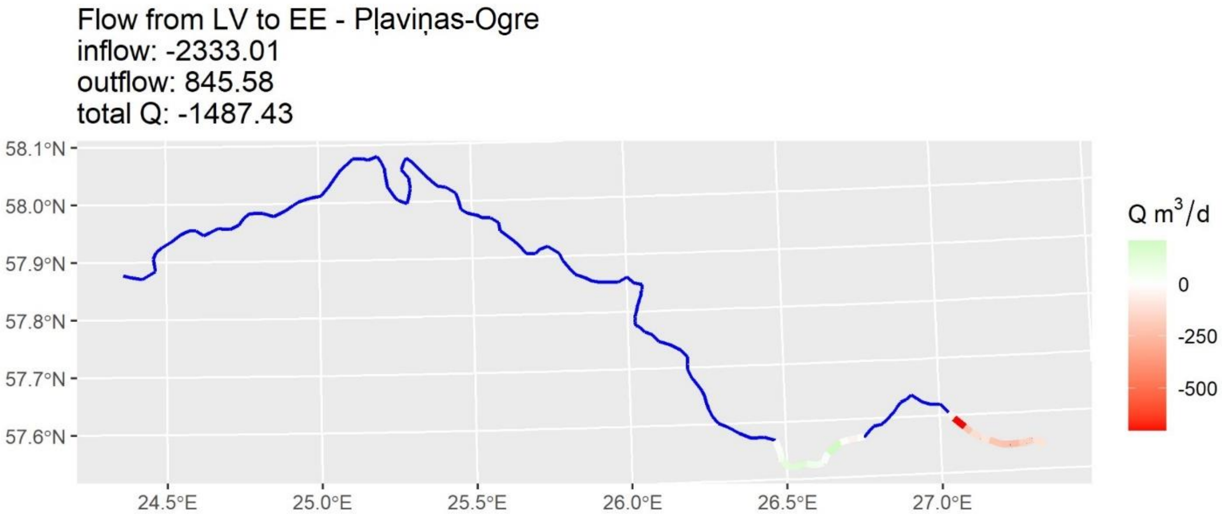


Figure 47 Estimated transboundary groundwater flows across Estonian-Latvian borderline in Pļaviņas-Ogre aquifer system (blue borderline sections - no aquifer system present)

The most important aquifer system in the Estonian-Latvian pilot area - Aruküla-Amata system is characterized by dual groundwater flows across the borderline: in Eastern part of the pilot area groundwater flows from Latvia to Estonia with a relatively high rate, whereas in the central part of the pilot area groundwater generally flows from Estonia to Latvia, but with a lower rate than in the East (Figure 48). As a result, the majority of transboundary groundwater flow occurs in the Eastern part of the pilot territory. Many parts of the transboundary area show no significant groundwater flow across the borderline - especially in the West part of the borderline and some areas in the central part.

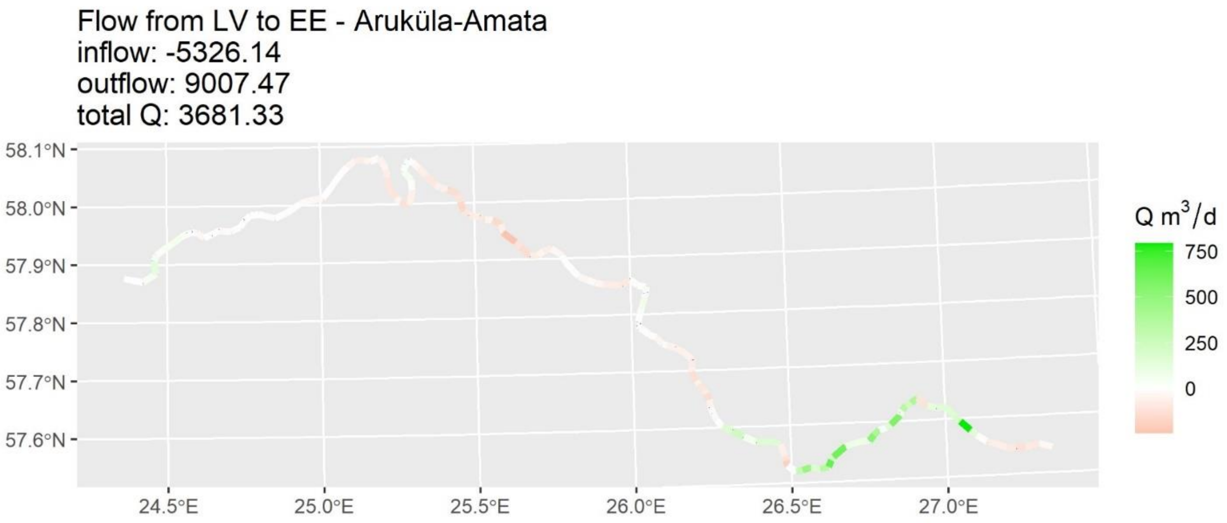


Figure 48 Estimated transboundary groundwater flows across Estonian-Latvian borderline in Aruküla-Amata aquifer system

In addition to most used aquifers, also transboundary groundwater flows were estimated for Lower-Middle Devonian aquifer system. The majority of transboundary groundwater flow occurs in the Eastern part of the pilot area in aquifer system (Figure 49), while the rest of the borderline have no distinct unidirectional pattern and generally have no significant transboundary groundwater flow.

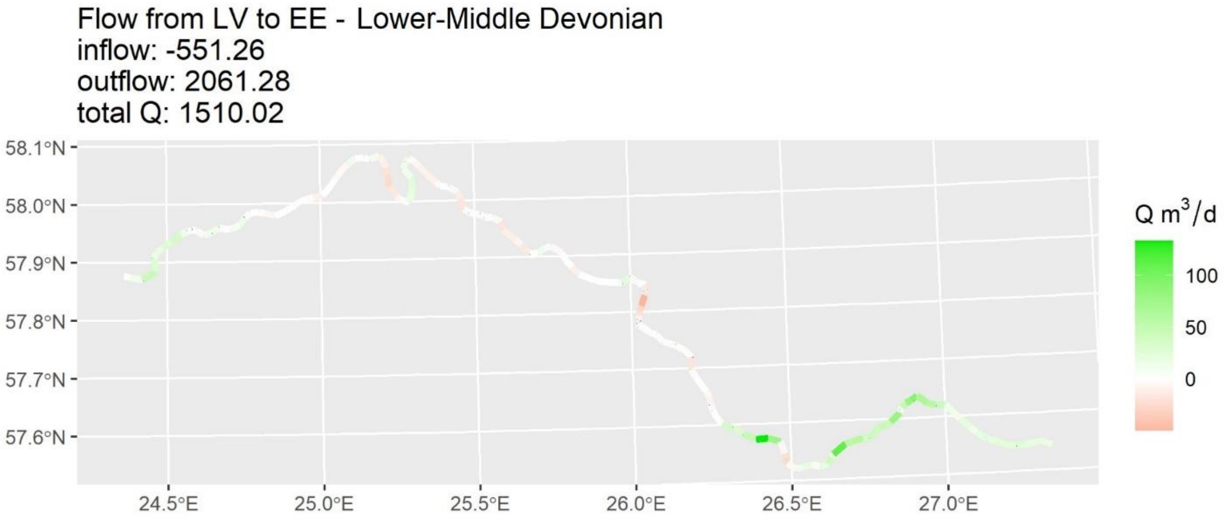


Figure 49 Estimated transboundary groundwater flows across Estonian-Latvian borderline in Lower-Middle Devonian aquifer system

6.3 Conclusions

A procedure for transboundary groundwater flow estimation was developed in a way that it ensures relatively easy applicability and repeatability because of using freely available open-source tools. The approach is based on analytical equations that govern groundwater flow according to piezometric gradient distribution and calculations are performed in a number of triangular shaped mesh elements along the borderline. Programming experience in R statistical programming language is necessary to perform the developed procedure, however, this approach is flexible and can be modified by an end user if needed.

The developed procedure was applied on Estonian-Latvian transboundary pilot area and transboundary groundwater flows were estimated for the two most important aquifer systems and an additional deeper lying aquifer. The procedure permitted to acquire results for each individual aquifer layer and summarise total flows for each aquifer complex. Furthermore, the results are in a GIS-like format therefore it is possible to identify the areas of significant groundwater flow across the border.

Majority of transboundary groundwater flow across Estonian-Latvian pilot area occurs in the Aruküla-Amata aquifer system with a total flow from Latvia to Estonia of 9488.5 m^3/d, a total flow from Estonia to Latvia of 5807.2 m^3/d and a total net flow of 3681.3 m^3/d that contributes to the flow from Latvia to Estonia. The majority of transboundary groundwater flow occurs in the Eastern part of the pilot territory. Total net flow in Pļaviņas-Ogre aquifer system is 1487.4 m^3/d that flows from Estonia to Latvia, while Lower-Middle Devonian aquifer system has a total net flow of 1510 m^3/d that flows from Latvia to Estonia with a significant flow occurring only in the Eastern part of the pilot area.

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