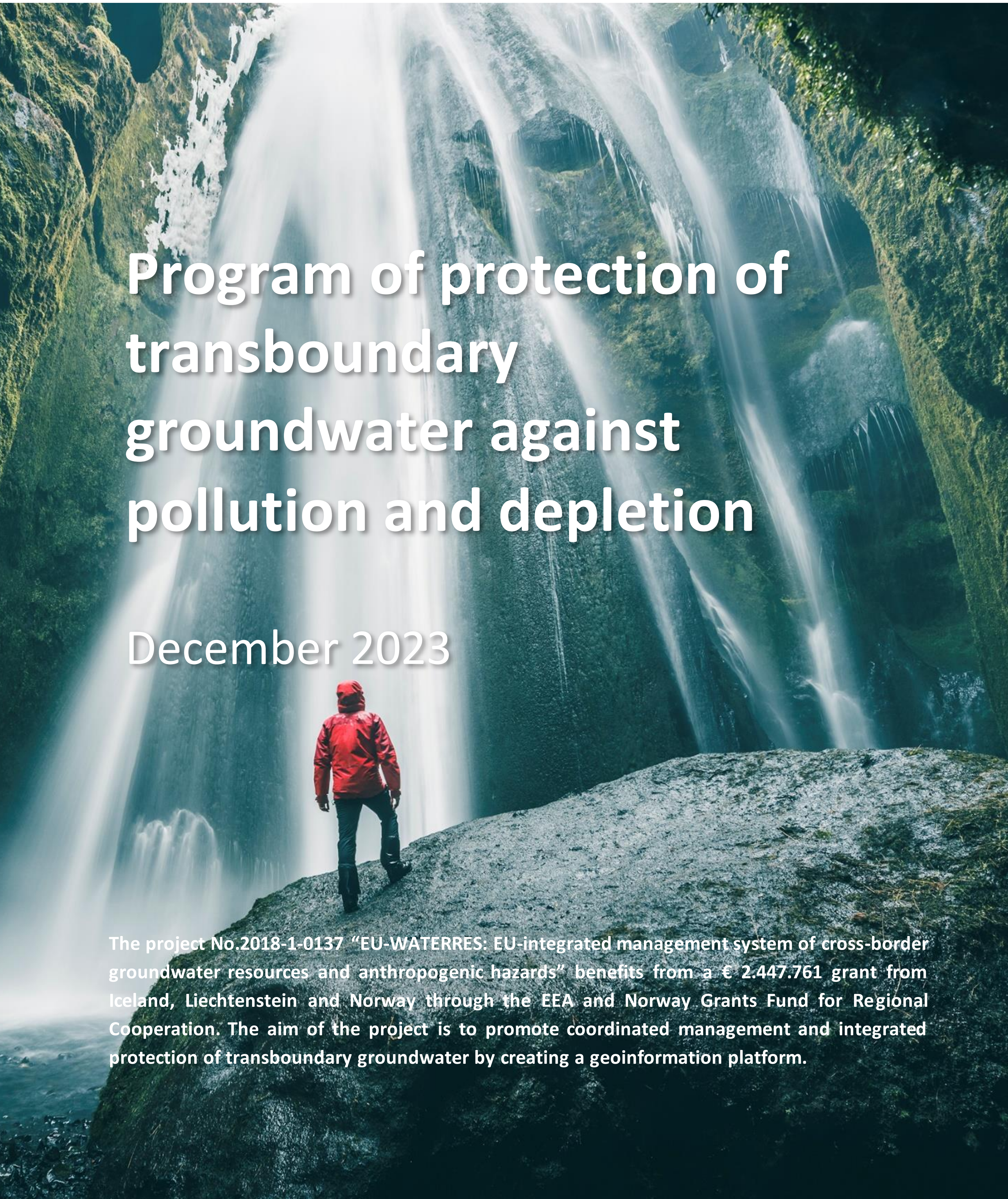
Iceland
Liechtenstein
Norway grants

Norway
grants



Program of protection of transboundary groundwater against pollution and depletion

December 2023

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.

Document code:	WP5 – Elaboration of solutions for coordinated use and integrated protection of transboundary groundwater
Title of document:	Program of protection of transboundary groundwater against pollution and depletion on the eastern border of UE
Reference activity:	Output 9. Adverse effects of human activities on the environment reduced
Dissemination level:	Public
Version	1
Date	31.12.2023
Scientific Editor	Tatiana Solovey (*Polish Geological Institute - National Research Institute*)
Authors (*Polish Geological Institute –NRI*):	Tatiana Solovey, Rafał Janica, Małgorzata Woźnicka, Małgorzata Przychodzka, Hanna Kolos, Agnieszka Brzezińska, Tomasz Gruszczyński (Uniwersytet Warszawski), Tetiana Melnychenko
Authors *(Zahidukrgeologiya)*:	Dmytro Panov, Natalia Pavliuk, Svitlana Sokorenko, Liubov Yanush, Halyna Medvid, Vasyl Harasymchuk
Authors (*Ukrainian Geological Company*):	Volodymyr Klos, Yurii Kharchyshin
Authors (*Latvian Environment, Geology and Meteorology Centre*)	Davis Borozdins, Krisjanis Valters, Jekaterina Demidko,
Authors (*Geological Survey of Estonia*)	Andres Marandi, Magdaleena Männik, Marlen Hunt
Authors (*University of Latvia*)	Jānis Bikše, Inga Retike
Authors (*Norvegian Geological Survey*)	Belinda Flem
Authors (Norwegian Water Resources and Energy Directorate)	Lars Stalsberg
Project coordinator	PGI-NRI

A Program for the protection of groundwater resources against pollution and depletion has been created and implemented for Estonian-Latvian and Polish-Ukrainian cross-border groundwater basins. The program has been developed on the basis of analysis of exploitation and water demand and analysis of anthropogenic impacts on resources of transboundary aquifers. This program includes delineation of the areas vulnerable to pollution and exposed to depletion or deficit of transboundary groundwater resources as well as a plan of actions, which aim is to improve or maintain good quality and quantity of groundwater resources.

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.

Scientific work published as part of an international project co-financed by the program of the Minister of Science and Higher Education entitled "PMW" in the years 2020-2023; agreement No. 5152 / RF-COOPERATION / 2020/2.

Table of content

List of Figures

List of tables

Abbreviations

AGR – Available Groundwater Resources

CAP – Common Agricultural Policy

DWD – Drinking Water Directive

EQSD – Environmental Quality Standards Directive

FD – Floods Directive

GD – Groundwater Directive

GWB – Groundwater Body

IAH – International Assotiation of Hydrogeologists

IHP – International Hydrological Program

ISARM – Internationally Shared Aquifer Resources Management

MGR – Main Groundwater Reservoir

ND – Nitrates Directive

PR – Prospective Resources

TAS – Transboundary Aquifer System

TBA – Transboundary Aquifer

USCB – Upper Silesian Coal Basin

WFD – Water Framework Directive

PART I

Program of protection of transboundary groundwater against pollution and depletion on the eastern border of UE

Polish – Ukrainian pilot area

1. Main pillars of the Transboundary Aquifers Systems protection strategy

The Water Framework Directive obliges EU Member States to develop and implement groundwater protection programs in order to achieve and maintain good groundwater status. One of the most difficult challenges is the concept of protecting Transboundary Aquifers (TBA) shared across national borders, because here a physical assessment is not sufficient. Political, cultural and historical variables also play an important role in understanding their complexity. Approximately 600 TBAs have been identified worldwide[1]. However, only 36% of identified TBAs have international agreements on transboundary groundwater[2]. The reason for this discrepancy is the "invisible" nature of groundwater and the lack of institutional capacity to manage groundwater.

Aquifers are characterized by a vertical structure and are often connected hydraulically, therefore a better term is "aquifer system". In the right geological structures, such a system can extend over huge areas, as exemplified by the northern Sahara aquifer system, which covers the countries of Algeria, Tunisia and Libya. Of course, such systems completely ignore administrative boundaries and are defined as Transboundary Aquifers Systems (TAS). In Poland, aquifer systems with high abundance and good water quality - called Major Groundwater Reservoirs - are of particular importance. Due to the strategic importance of their resources, these reservoirs require special protection and control of resource management, with priority given to collective water supply. First of all, groundwater protection action programs were developed for them.

The problem of TAS protection is a global challenge, the solution of which was initiated by the UNESCO International Hydrological Program (IHP). IHP's mission is to build international understanding and scientific cooperation among the world's nations to create strategies for the sustainable management and conservation of transboundary aquifers. In 2000, IHP and the International Association of Hydrogeologists (IAH) established the Internationally Shared Aquifer Resources Management (ISARM) initiative[3]. Since then, significant progress has been made in the designation of TBAs and the development of regional strategies for assessing and managing TBAs. These strategies aim to build links between science and policy. So the main message is: “a strong strategy is based on science, which can provide the knowledge base for decision making.”

The main pillars of the Strategy for the Management and Protection of Transboundary Aquifers are: (Figure 1):

1. Assessment,
2. Cooperation, and
3. Shared management

---

[1] Sindico, F., 2020. International law and transboundary aquifers. Elgar, Cheltenhan, PA.

[2] Rivera, A., Pétré , M., Fraser, C., Petersen-Perlman, J., Sanchez, R., Movilla, L., Pietersen, K., 2023. Why do we need to care about transboundary aquifers and how do we solve their issues? Hydrogeology Journal, 31: 27–30.

[3] UNESCO-IHP, FAO, UNECE, IAH, 2001. Internationally shared (transboundary) aquifer resources management: a framework document. UNESCO, Paris

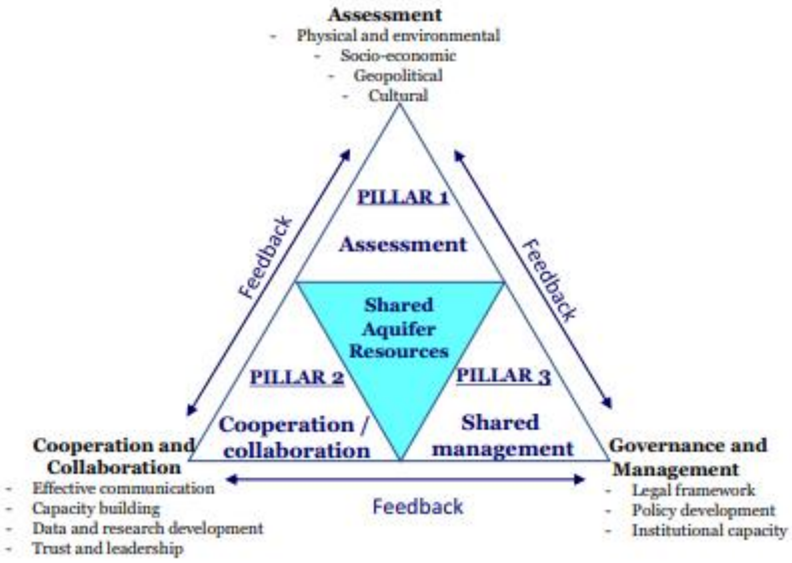


Figure 1. A three-pillar framework for efective transboundary aquifer management[4]

The "Assessment" pillar covers the mapping and full physical assessment of the TBA, its structure, resources, chemical and quantitative status. The knowledge acquired in the first pillar should be used in the decision-making process to support informed decisions at the management level in the third pillar. However, to achieve this level of understanding, cross-border cooperation and the right tools are necessary. Assessment of the physical system through international cooperation is the most important milestone that ultimately determines the possibility of developing a joint management strategy for TAS. Moreover, one more challenge remains: how to combine the scientific and technical recommendations contained in the strategy with the legal and institutional instruments of countries sharing common groundwater resources.

The „Asessment" pillar

The TAS assessment aims to create a compendium of knowledge about its structure and functioning. The diagnosis of TAS should take into account in particular:

- the geometric configuration of the layers that constitute the TAS (i.e., physical boundaries in three dimensions);
- geological and structural configuration (geological structure, including geological structures, tectonic elements and stratigraphic and lithological characteristics);
- hydrogeological configuration and corresponding hydrodynamic parameters (formation of aquifers, values of hydrogeological parameters);
- internal interactions (i.e. between aquifers, interaction with surface waters, transboundary water exchange);
- configuration of directions and rates of groundwater flow;
- time of hydrodynamic pressure and mass transfer (migration of contaminants);
- areas of natural recharge and dynamics of TAS recharge volume;

---

[4] Rivera, A., Pétré , M., Fraser, C., Petersen-Perlman, J., Sanchez, R., Movilla, L., Pietersen, K., 2023. Why do we need to care about transboundary aquifers and how do we solve their issues? Hydrogeology Journal, 31: 27–30.

- areas of natural groundwater drainage (springs, lakes, other rivers)
- dynamics of static water table levels and flow rates in time and space;
- balance and quantities of groundwater resources (renewable and available for development);
- geochemical characteristics of TAS;
- natural hydrogeochemical background;
- TAS's resilience in the face of extreme events such as floods and droughts;
- hotspot zones;
- infiltration of pollutants from human activities from the surface;
- susceptibility to TAS contamination.

The collection and international harmonization of the above data is the first and most important step towards understanding TAS. The most effective method is to present this data in a geospatial format, because analyzing it requires the use of an advanced tool, which is a mathematical model of filtration and mass transport. It is also necessary to verify the representativeness of national groundwater monitoring points in terms of suitability for assessing the status of TAS. The correct selection of monitoring points of transboundary importance is a difficult task and requires carrying out many different analyzes of spatial relations between factors shaping the conditions of transboundary groundwater flow and indicators expressing the TAS status. In such cases, the most effective method is hydrodynamic numerical modelling. Often, the existing network of cross-border monitoring points does not meet the transboundary criterion, which is one of the key arguments for the need to develop guidelines for the organization of cross-border groundwater monitoring networks. Measurement sessions should be synchronized, data collected in common databases, and standards unified.

The most important component of the "Assessment" pillar is the analytical and interpretive block. We have many research tools at our disposal, ranging from simple comparison using geoinformatic software (GIS type) of the spatial extent of the elements creating the hydrogeological system, through methods for determining the susceptibility of groundwater to pollution, to complex simulations using numerical flow models.

The basic approach used to interpret data is conceptualization. The components of this process in relation to model analyses are shown in Figure 2.

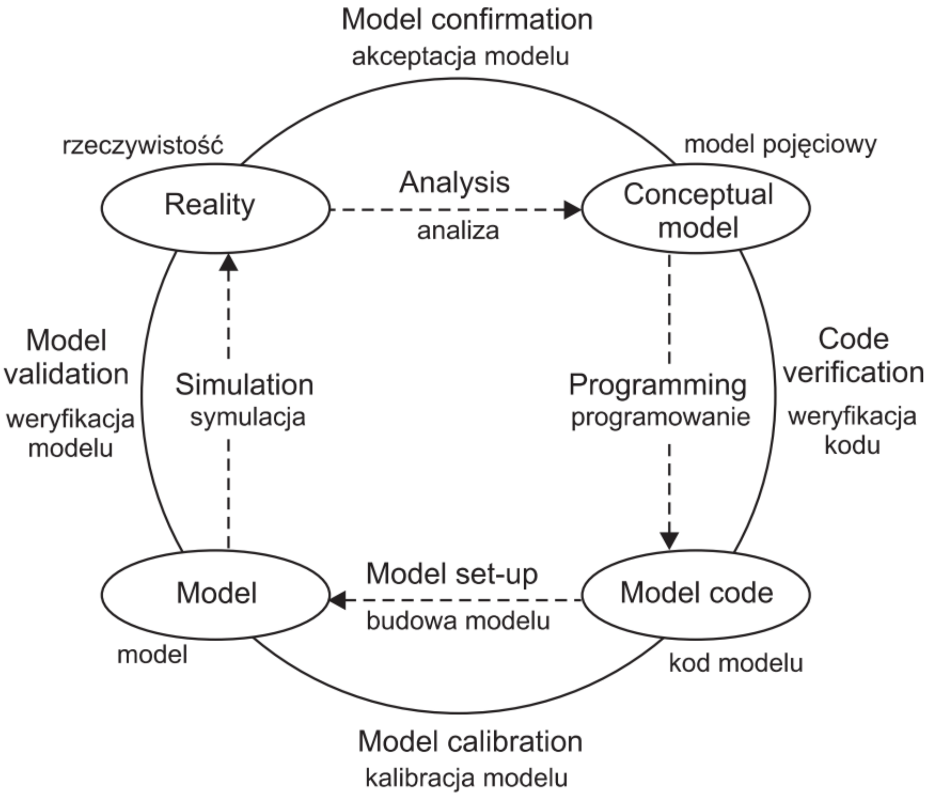


Figure 2. Basic modeling concepts and the relationships between them[5]

To serve as management tools, numerical models should have the appropriate structure and dimensions, based on a previously established concept, after which they should be calibrated and validated against the set objectives (a process that aims to reproduce the model as closely as possible to the reality that one wants to simulate). One can then create a variety of scenarios, especially those regarding:

- determining available groundwater resources within the framework of sustainable use;
- testing the impact of different groundwater exploitation scenarios on flow rates and water table levels in terms of planned economic development;
- predicting the development of hotspot zones and assessing their impact in terms of space and time;
- determining ways to protect or remediate contaminated resources..

There is also a significant challenge in identifying transboundary groundwater management entities where transboundary impacts are important. This problem can only be solved using a hydrodynamic modelling tool, in particular the definition of active groundwater flow zones across the international boundary. Guidelines in this area are still undeveloped.

Limited knowledge about TAS and the lack of cross-border groundwater monitoring in most regions of the world are common obstacles to a comprehensive TAS assessment and consequently create the problem of planning and management of shared groundwater resources. A great example of a cooperation framework aimed at improving knowledge about TAS is the results of the EU-Waterres

---

[5] Refsgaard, J.C., Henriksen, H.J., 2004. Modelling Guidelines—Terminology and Guiding Principles. Advances in Water Resources, 27: 71-82.

project, which is a joint venture in the assessment of the state of Estonian-Latvian and Polish-Ukrainian TAS. Using the modelling tool, the intended result was achieved in terms of resource assessment, cross-border monitoring concepts, and identification of hotspot zones.

The „Cooperation” pillar

The need for cooperation is obvious in all the pillars discussed. However, in this pillar, it is particularly important to identify relevant international principles and practices that can shed light on how TBA can be used in a way that is beneficial to both countries and in compliance with environmental protection principles. It is then necessary to consider whether such international rules and practices are mandatory without flexibility or whether they should be considered merely as guidelines that can be adapted to the specific conditions of their countries and a particular aquifer.

The currently applicable international law in the field of TBA is the Draft Articles on the Law of Transboundary Aquifers (the Draft Articles), developed by the United Nations International Law Commission in 2008. The Draft Articles have been annexed to UN General Assembly Resolution 63/124. A detailed analysis of the above document was carried out in the EU-Waterres report called "Assessment of the resources of transboundary groundwater reservoirs for the 2 pilot areas" in chapter 1.1. As practice shows, the UN Draft Articles still constitute non-binding guidelines for states, because the number of agreements and understandings regarding specific TBAs is increasing very slowly.

With regard to Polish-Ukrainian cooperation in the field of TBA, the state of legal regulation looks poor because the bilateral agreement regarding cooperation in the field of water management in border waters has not been updated since 1996 and does not take into account the guidelines of international law - the Draft Articles of the UN. Moreover, the current agreement focuses on surface waters, excluding groundwater. So, cooperation between Poland and Ukraine is in the initial phase, where nothing is happening at the institutional level yet, and the current diagnosis of TBA is included in scientific studies, and most of them were created in the EU-Waterres project.

The science-policy connection in relation to TBA often arises once a physical assessment has already been performed. So, in the Polish-Ukrainian case, the results of the EU-Waterres project presenting the physical assessment of TBA open up opportunities for initiating the next institutional stage of formalizing cooperation. This stage can be characterized as follows. Both countries are beginning to realize the complexity of their groundwater resources in border areas and accept that the aquifer intersects with their common border (i.e. they share a transboundary aquifer). Countries appreciate the need to manage TBA and are interested in identifying appropriate international principles and practices. At this stage it is very important that the scientific theory translates into the best information for informed decisions regarding shared management. In short, knowledge became a catalyst for further collaboration and, in some cases, full collaboration, the end result of which is joint management of TBA (Figure 3). Otherwise, the scientific results of cooperation in the field of TBA will not be consumed.

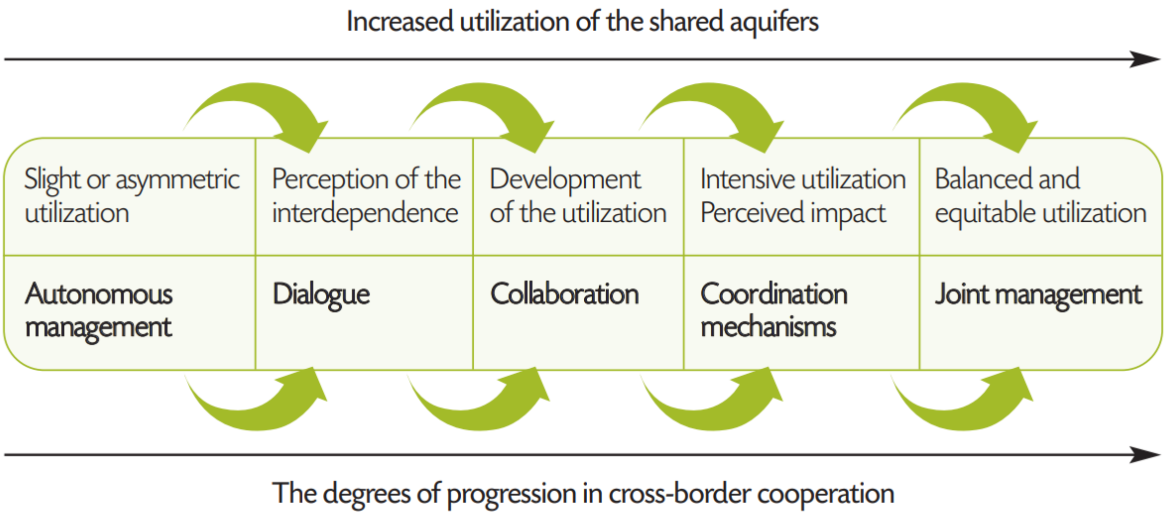


Figure 3. The degrees of progression in cross-border cooperation[6]

The „Shared management" pillar

The third pillar is based on institutional capacity, shaping joint management policies and creating water resources management plans between countries. In EU countries, the Water Framework Directive formalized this procedure by requiring the preparation of a single management plan for each cross-border groundwater and surface water body or, failing that, ensuring the coordination of management plans for cross-border bodies of water. Scientific support can only drive the development of strategies and plans for the joint management of groundwater resources. However, asymmetries and differences in the technological and economic capabilities of neighbouring countries may hinder, limit or even prevent the development of agreements on joint groundwater management. The most important thing is to realize that threats affecting the shared groundwater resource related to exploitation or water pollution can only be solved together, which involves the risk of potential international disputes. In such cases, the intervention - at the request of the country concerned - of international, multilateral institutions may help to unblock the situation.

Joint management of TAS requires the involvement of not only public administration entities from both countries, but also representatives of local governments from border areas, experts, non-governmental organizations, etc. The involvement of local authorities corresponds to the application of one of the principles of the Water Framework Directive - according to which responsibility for the use of water should be taken by the lowest possible authority in the administrative management hierarchy, or in other words, the level closest to citizens.

It is very important to include the local community in the discussion. The complexity and sensitivity of issues related to groundwater management in general and transboundary waters in particular require extensive educational, awareness-raising and information programs for officials, users and the public at large. In this context, it is necessary to take into account the differences resulting from the national specificity and the very diverse cultural dimension related to the traditions of using water resources. It is particularly important to make people aware of the need for "hydrolidarity" between neighbouring

---

[6] Machard De Gramont, H., Noël, C., Olivier, J., et al., 2011. Toward a joint management of transboundary aquifer systems: methodological guidebook. https://www.riob.org/IMG/pdf/guide-2-savoirENG.pdf.

communities sharing the same waters and the long-term process of cooperation necessary from the point of view of sustainable development. Therefore, it is important that the TAS protection program includes a section on informing and training interested parties in order to prepare them for joint activities. Necessary promotional activities to raise public awareness of the understanding of hydrogeological mechanisms in the context of transboundary flows of "invisible" groundwater and their economic and social consequences.

2. Management and protection of water resources in the light of European Union and national regulations

2.1. Management and protection of water resources in the light of European Union and Polish legislation

Assumptions of the EU water policy

Sustainable management of water resources is one of the pillars of the European Union's environmental policy. This policy is based on the principles of precaution, preventive action and removal of pollution at source, as well as the polluter pays principle. The EU's multiannual environmental programs provide the framework for future action in all areas of environmental policy. They form part of horizontal strategies and are also taken into account in international environmental negotiations.

Recognizing that water is essential for the life of humans, animals and plants and for the functioning of the economy, and taking into account that water protection and water management extend beyond the borders of individual Member States, Directive 2000/60/EC of the European Parliament was established in 2000 and the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (the so-called Water Framework Directive, WFD). This directive establishes a legal framework for protecting and restoring clean water resources across the EU and ensuring their sustainable use in the long term. The basis for its establishment was the following assumptions:

1. Water is not a commercial product like any other, but rather a heritage that must be protected, defended and treated as such.
2. European water resources are under constant pressure.
3. EU action is needed because of the cross-border nature of changes and a river basin approach is the best way to manage water resources.
4. Achieving good ecological and chemical status is necessary to protect human health, water resources, natural ecosystems and biodiversity.
5. Public involvement is essential.
6. Despite progress, more changes are required.
7. Water management is linked to many policy areas and their integration is essential for sustainable water use.
8. Climate change increases future challenges.

The primary objective of the WFD is therefore to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater that:

- prevent further deterioration and protect and improve the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly dependent on aquatic ecosystems;
- promote sustainable water use based on long-term protection of available water resources;
- pursue increased protection and improvement of the aquatic environment, inter alia, through specific measures for the progressive reduction of discharges, emissions and losses of priority hazardous substances and the cessation or phasing out of discharges, emissions and losses of priority hazardous substances;
- ensure a gradual reduction of groundwater pollution and prevent its further contamination;
- contribute to reducing the effects of floods and droughts.

The Water Framework Directive is supplemented by specific provisions as well as international agreements. Issues related to the protection of the chemical status of groundwater are regulated in detail by Directive 2006/118/EC on the protection of groundwater against pollution and deterioration of its status (Groundwater Directive, GD) and Directive 2020/2184 on the quality of water intended for human consumption (Drinking Water Directive, DWD). In addition to the legal acts mentioned above, the provisions of related directives also apply to the protection of groundwater (Table 1).

Extensive and periodically revised EU legislation in relation to issues related to the protection of water resources in the Community means that national regulations of Member States in this area are subject to frequent changes. At the same time, due to the multidimensional nature of groundwater protection, the mechanisms and legal instruments implemented are diverse. Preventive actions dominate, which is consistent with the basic principles of EU environmental policy, such as the principle of prevention and precaution. In the case of detected pollution, the principle of liability for damage applies (the polluter pays).

Table 1. Directives regulating the management of water resources in the EU

No.	Title of the directive	Directive No	Date of establishment
1	Directive establishing a framework for Community action in the field of water policy (Water Framework Directive - WFD)	2000/60/WE	23.10.2000 r
2	Directive on the protection of groundwater against pollution and deterioration (Groundwater Directive, GD)	2006/118/WE	12.12.2006 r.
3	Directive on the protection of waters against pollution caused by nitrates from agricultural sources (Nitrates Directive, ND)	91/676/EWG	12.12.1991 r.
4	Directive on the assessment and management of flood risks (Floods Directive, FD)	2007/60/WE	23.10.2007 r.
5	Directive on environmental quality standards in the field of water policy (EQS Directive)	2008/105/WE	16.12.2008 r.

6	Directive on the quality of water intended for human consumption (Drinking Water Directive, DWD)	2020/2184	16.12.2020 r.
7	Urban waste water treatment directive	91/271/EWG	21.05.1991 r.
8	Directive concerning the placing of plant protection products on the market	91/414/EWG	15.07.1991 r.
9	Directive on the protection of the environment, and in particular the soil, when sewage sludge is used in agriculture	86/278/EWG	12.06.1986 r.
10	Directive relating to the management of bathing water quality and repealing Directive 76/160/EEC	2006/7/WE	15.02.2006 r.
11	Directive establishing a framework for Community action in the field of marine environmental policy (Marine Strategy Framework Directive, MSFD)	2008/56/WE	17.06.2008 r.

The Water Framework Directive provides for the implementation of established objectives by taking actions under the so-called planning cycles (Figure 4). In each six-year cycle, a diagnosis of the water condition is carried out, an analysis of the pressure affecting the water condition is performed, and action programs are established and implemented to achieve the established environmental goals for individual water bodies. The next stage involves assessing the progress in implementing action programs and their effectiveness.

According to the WFD, environmental goals should be achieved in 2015, although in justified cases it is possible to extend this deadline for the next two cycles (until 2027). The Water Framework Directive allows for the introduction of derogations from the achievement of established environmental objectives by applying the procedure specified in Art. 4.4 – 4.7 WFD (extension of the deadline for achieving environmental goals or establishing a less stringent target). However, these procedures may only apply if a number of conditions are met and if there is a justification indicating that all possible actions have been taken to limit the adverse impact on the water status.

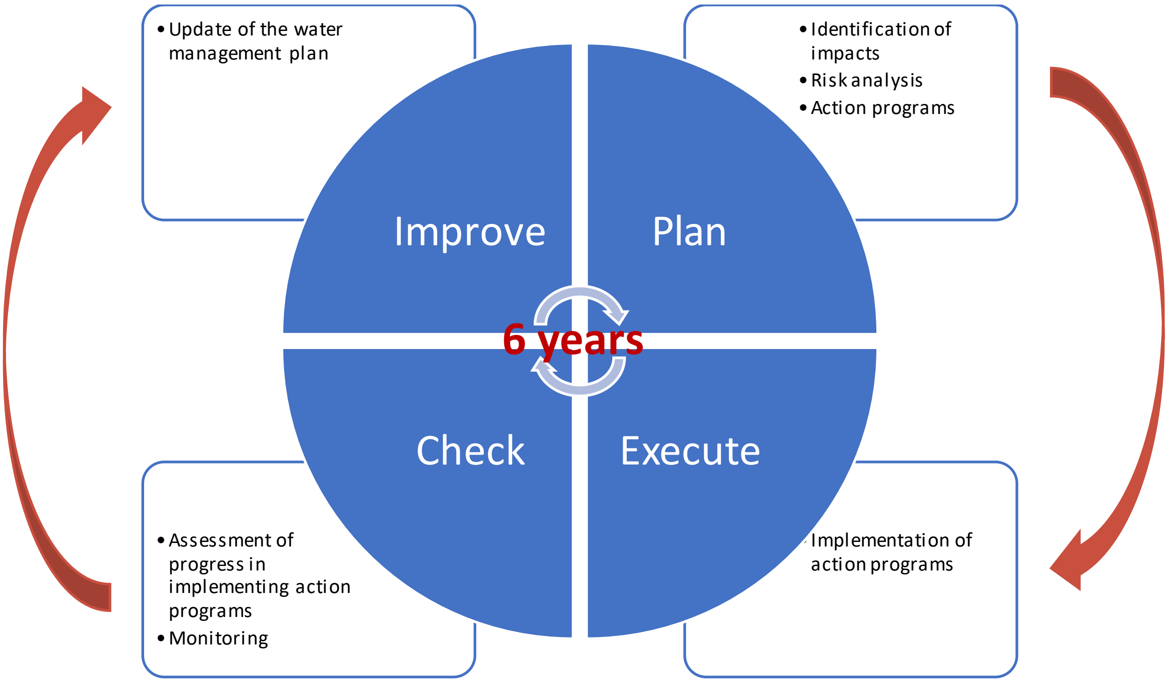


Figure 4. Scheme of activities within the planning cycle

Management of water resources in Polish legislation

The Water Framework Directive introduced a high priority for the protection of water resources, which was first implemented in Polish legislation by the Act of July 18, 2001 - Water Law, and then supplemented by the Act of July 20, 2017 - Water Law. Pursuant to Article 50 of the Act of July 20, 2017 - Water Law, waters, as an integral part of the environment and a habitat for organisms, regardless of whose property they are, are subject to protection..

The Water Law Act (Article 9, paragraph 1) specifies that water management is carried out in compliance with the principle of rational and comprehensive treatment of surface and groundwater, taking into account their quantity and quality. At the same time, water management takes into account the principle of common interests and requires cooperation between public administration, water users and representatives of local communities to the extent that allows for maximum social benefits. Moreover, water management is based on the principle of cost recovery for water services, taking into account environmental and resource costs as well as economic analysis. Water management is carried out in accordance with the public interest, preventing avoidable deterioration of the ecological functions of water and the deterioration of terrestrial ecosystems dependent on water. In order to ensure proper water management in river basin areas, water resources management requires:

- coordinating the activities specified in the river basin management plans with the competent authorities of the Member States of the European Union in whose territories the remaining parts of the river basin districts referred to in Article are located. 13 section 1;
- taking actions to establish cooperation with the competent authorities of countries located outside the European Union, on whose territories the remaining parts of the river basin areas referred to in Art. 13 section 1.

Water resources management, carried out taking into account the division of the country into river basin areas, water regions and catchments, serves to meet the needs of the population and the economy as well as to protect water and the environment related to these resources, in particular in terms of:

- ensuring adequate quantity and quality of water for the population,
- protection against flood and drought,
- protection of water resources against pollution and inappropriate or excessive exploitation,
- maintaining or improving the condition of aquatic and water-dependent ecosystems,
- providing water for agriculture and industry,
- creating conditions for energy, transport and fishing use of waters,
- meeting the needs related to tourism, sports and recreation.

The Water Law Act specifies instruments for water resources management, including water management planning, which serves to program and coordinate activities aimed at:

- achieving or maintaining good status of waters and water-dependent ecosystems, and protecting, improving and preventing further deterioration of aquatic, terrestrial and wetland ecosystems;
- improving the condition of water resources;
- promoting sustainable water use based on long-term protection of available water resources;
- reducing the amount of substances and energy introduced into water or land that may have a negative impact on water;
- improving flood protection and counteracting the effects of drought;
- achieving the environmental goals referred to in Art. 56, art. 57, art. 59 and in Art. 61.

The most important planning documents are water management plans in river basin areas, for which planning documentation is prepared (Table 2).

Table 2. List of planning documentation developed for water management plans in river basin areas

No**.**	**Planning documentation**
1	lists of water bodies
2	characteristics of water bodies, indicating artificial and heavily modified water bodies and water bodies at risk of not achieving environmental objectives
3	identification of significant anthropogenic impacts and assessment of their impact on the status of surface waters and groundwater
4	identification of the impacts of changes in groundwater levels
5	register of lists of protected areas
6	economic analyzes related to the use of water
7	water monitoring programs
8	lists of emissions and concentrations

Action programs to achieve established environmental goals are built using the DPSIR model, which takes into account the identification and analysis of pressure causative factors and their impacts, so that actions are aimed at reducing specific pressures (Figure 5).

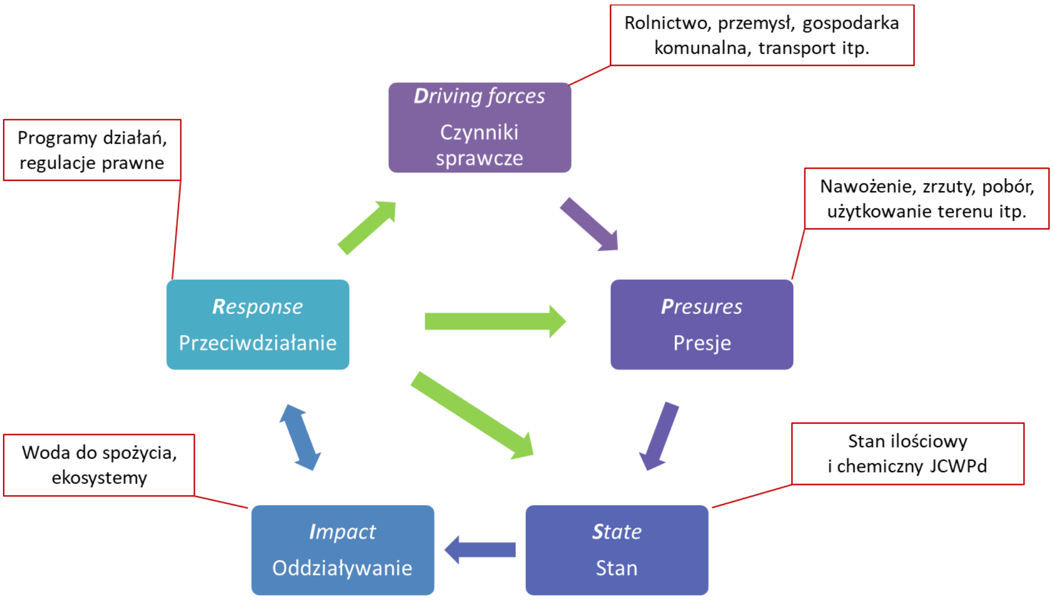


Figure 5. DPSIR model in water management planning

Water protection goals

Pursuant to Art. 51 of the Water Law, the main goal of water protection is to achieve environmental goals, which in relation to groundwater in Art. 59 of the Water Law Act are defined as:

1. preventing or limiting the introduction of pollutants into them,
2. preventing deterioration and improving their condition,
3. protecting them and taking remedial actions, as well as ensuring a balance between abstraction and recharge of these waters, so as to achieve their good status..

Actions aimed at achieving the environmental objectives set for groundwater bodies (GWB) consist in particular in gradually reducing groundwater pollution by reversing significant and persistent upward trends in pollution resulting from human activity, while the environmental objectives are achieved by taking the actions included in water management plans in the river basin areas (Article 60 of the Water Law).

The primary environmental objective for the GWB is to maintain or achieve good status, defined as the status achieved by a groundwater body if both its quantitative and chemical status is assessed as "good". The overall status of the GWB is therefore determined based on the assessment of the quantitative status and chemical status assessment, with the final result of the GWB condition assessment being determined by the worse result of the above assessment components.

Quantitative protection of groundwater

Quantitative protection of groundwater, understood as maintaining or achieving good quantitative status of groundwater bodies, should be implemented in water management plans in the river basin area. The basis for conducting effective quantitative protection is the result of the water balance, taking into account the volume of resources and abstraction (degree of use of groundwater resources/resource reserves). Attention should be paid to the two definitions in Polish legislation relating to groundwater resources.

The basis for groundwater balancing is the available groundwater resources (AGR), determined in balancing units, understood as river catchments designated for water management balancing, which are in hydraulic connection with groundwater, including recharge zones of groundwater intakes. Disposable groundwater resources are determined in accordance with the Geological and Mining Law and the Regulation of the Minister of the Environment of November 18, 2016 on hydrogeological documentation and geological and engineering documentation in the mode of preparing hydrogeological documentation, approved by the minister responsible for environmental affairs. They are determined in long-term average amounts in accordance with the course of their renewability, appropriate for the hydrogeological conditions prevailing in the balancing units, using methods of mathematical modelling of groundwater flow forecasted under the conditions of the permissible degree of resource development while maintaining environmental objectives in protected areas. The mathematical model is created on the basis of a detailed analysis of the results of geological, hydrogeological and hydrological reconnaissance, supplemented with designed research and field measurements, constituting a key element of the hydrogeological documentation determining the available resources of groundwater..

With respect to groundwater bodies, the Water Law introduces the concept of available groundwater resources (AGR). The input data for determining their size in the GWB, depending on data availability, are: available groundwater resources (AGR) determined in the balance units as part of the hydrogeological documentation or prospective resources (PR) determined in a manner estimated on the basis of hydrological methods. Available groundwater resources are converted, using the values of available (and/or prospective) resources modules characterizing a given water management region, into the total value of resources within the GWB, taking into account the share of the area of individual water management regions in a given GWB. The resources available in the GWB, constituting the basis for assessing the state of the GWB, are therefore a derivative of the available resources determined for the balance units.

The second element of the water balance is the amount of groundwater abstraction. The basic source of data in this area is information on the amount of water taken from intakes used to supply drinking water to the population, agriculture and industry. Until 2017, this information was obtained from fee databases maintained by marshal offices, and since 2018, in accordance with the provisions of the Act of July 20, 2017 - Water Law, the source of reference data is the Eden database, to which users report the abstraction volume every quarter. This database is maintained by individual catchment boards, which are regional units of the Polish Waters State Water Management Authority. An important element is also the collection carried out as part of the drainage of mines: areas of both active and closed mining plants. Drainage of parts of closed mining plants is necessary to protect the lower situated mining areas of active mines in the area from flooding. This problem concerns primarily the Upper Silesian Coal Basin (USCB).

Effective quantitative protection of groundwater should be carried out on the basis of the current and forecast results of the water balance carried out in the balance units and should consist in the use of water resources in accordance with the adopted priorities and hierarchy of individual water users. The Water Law Act introduces a number of legal instruments for the quantitative protection of groundwater in this sense. These include in particular:

1. establishing criteria for normal water use;
2. water law consent mechanism (issuing a water law permit for specific water use, accepting a water law notification or issuing a water law assessment);
3. establishing a hierarchy for groundwater users;
4. principle of cost recovery for water services;
5. water management control procedures;
6. planning in water management, including:
    a. water management plans in the river basin areas;
    b. flood risk management plans;
    c. plan to counteract the effects of drought.

Establishing a limit on the amount of water abstraction as part of normal water use to meet the needs of one's own household or farm is one of the most important principles of quantitative protection of water resources (Article 33 of the Water Law). It is assumed that abstraction in an amount not exceeding the annual average of 5 m^3 per day is a safe limit for the use of groundwater and does not lead to a deterioration of the quantitative status. However, due to the exclusion of abstraction as part of ordinary use of water from the measurement obligation (Article 36, paragraph 3 of the Water Law Act), combined with the exclusion from the provisions of the Geological and Mining Law of groundwater intakes up to a depth of 30 m, both the number of such intakes, as well as the amount of water drawn from them, remain outside the records. This creates difficulties in conducting water balances, and in certain situations, uncontrolled, intensive abstraction may have a real impact on the quantitative status of groundwater and the development of regional lowering of the groundwater table.

In the area of specific water use, the most important legal instrument that has a direct impact on the use of groundwater, and thus its quantitative protection, is a water permit, issued by way of a decision for a specified period, but no longer than 30 years, by regional offices of the State Water Management Authority "Polish Waters" (director of the territorially relevant regional water management board). In terms of the protection of groundwater resources, the water law permit applies not only to water services related to the abstraction of groundwater, but also to other activities carried out as part of the specific use of water and long-term lowering of the groundwater table and the construction of water facilities. The water law permit cannot violate the water management plan in the river basin area, and at the same time it should be emphasized that the Water Law Act in Art. 415 specifies cases in which a water permit may be withdrawn or restricted without compensation. With regard to the protection of the quantitative status of groundwater, the following conditions apply:

- groundwater resources have decreased naturally,

- there is a threat to achieving environmental goals and this is justified by data from water monitoring and the results of an additional review of water permits referred to in Art. 325 section 1 point 2 of the Water Law Act.

In addition to the above-mentioned principles set out in the Water Law Act, in the context of quantitative protection of groundwater, separate provisions also apply regarding procedures for conducting environmental impact assessments of projects that may have a significant impact on the environment (Act of October 3, 2008 on the provision of information about the environment and its protection, public participation in environmental protection and environmental impact assessments).

Due to the fact that all groundwater bodies designated in Poland meet the requirements specified in Art. 72 of the Water Law, the criteria for classifying them as water bodies intended for water abstraction for the purposes of supplying the population with water for human consumption, the provisions of the Act of June 7, 2001 on collective water supply and collective sewage disposal apply to the entire country.

Quality protection of groundwater

Qualitative protection, understood as maintaining or achieving good chemical status of groundwater bodies, is implemented on the basis of the provisions of the Water Law Act by introducing a number of prohibitions or restrictions on the use of land or the use of specific substances. This fulfils the overriding principle of protecting groundwater against pollution (the principle of prevention). These types of regulations include in particular:

- prohibition of discharging sewage directly into groundwater;
- prohibition of introducing sewage into the ground in accordance with the conditions specified in Art. 75 point 3 of the Water Law Act;
- prohibition of introducing rainwater or snowmelt water into open or closed stormwater drainage systems used to discharge atmospheric precipitation directly into groundwater;
- restrictions on agricultural use of sewage, in accordance with Art. 84 section 4 of the Water Law Act;
- implementation of an action program aimed at reducing water pollution with nitrates from agricultural sources and preventing further pollution (the so-called nitrate program);
- implementation of the national municipal wastewater treatment program.

In addition to those mentioned above, the protection of the chemical state of water resources also includes indications and recommendations intended for voluntary use. These include, among others: a set of recommendations of good agricultural practice, including tips on the periods and method of fertilization, the method of storing natural fertilizers and others.

Another form of quality protection of groundwater is the establishment of protection zones and areas. Pursuant to Art. 120 of the Water Law Act, ensuring the appropriate quality of water abstracted to supply the population with water intended for human consumption and supplying plants requiring high-quality water, as well as protecting water resources, is achieved by establishing:

- water intake protection zones,

- protection areas of inland water reservoirs (in relation to groundwater understood as the main groundwater reservoirs).

The main groundwater reservoirs (MGR) are geological structures or their fragments that have the highest abundance in hydrogeological regions. They currently or in the future constitute strategic water reserves as a source of water for human consumption. Due to the separation criteria: high water quality, abundance and potential high efficiency of intakes, MGRs constitute the most valuable fragments of hydrostructural units and aquifer systems and are subject to protection in accordance with the Water Law. MGR protection is implemented by establishing protective areas for them, within which prohibitions or restrictions on land use or water use may apply, in order to protect these water resources, primarily against degradation of their quality (chemical state). The MGR protection area is established by the territorially competent voivode, at the request of Polish Waters, by an act of local law (Article 141 of the Water Law Act).

Protective zones of groundwater intakes are areas where orders, prohibitions and restrictions regarding land use and water use apply. The protection zone of the groundwater intake, covering only the area of direct protection, is established by the State Holding "Polish Waters", and covering the area of direct protection and additionally the area of indirect protection - by the voivode. Establishing a protection zone covering the direct protection area is mandatory for all water intakes, excluding intakes for ordinary water use. The area of indirect protection, covering the intake area, is designated on the basis of findings from the hydrogeological documentation. The protection zone including the direct protection area and the indirect protection area is established on the basis of a risk analysis.

The Act of July 20, 2017 - Water Law introduced the obligation to perform a risk analysis, including the identification and assessment of threats to the quality of groundwater abstracted to supply drinking water to the population. In the event of a high risk, it is recommended to establish an intake protection zone including the intermediate protection area. The introduction of protection zones contributes to the elimination and reduction of threats through appropriate land use and the use of water in resource intake areas.

Groundwater monitoring and assessment of the state of GBW

Pursuant to Art. 52 of the Water Law, water protection is carried out, in particular, taking into account the results of the condition assessment. Pursuant to Art. 349 section 8 of the Water Law Act, research and assessment of the state of groundwater in terms of physicochemical and quantitative elements is performed by the state hydrogeological service. These tasks are part of the State Environmental Monitoring and are used to obtain information on the state of groundwater for the purposes of planning water management and assessing the achievement of environmental goals. The results of the assessment of the state of the GWB in connection with the result of the pressure and impact analysis constitute the basis for taking corrective actions aimed at reducing pressure, limiting pollution and, as a result, achieving environmental goals, which directly translates into water protection.

The assessment of the state of GWB is based on nine classification tests and two supporting analyses, focused on the needs of various groundwater recipients, the so-called receptors (terrestrial ecosystems dependent on groundwater, surface water, water intended for consumption). The final GWB status assessment is the result of aggregating the results of all classification tests. A necessary condition for determining good condition in the examined GWB is a positive result of the condition assessment of all tests.

It is also worth noting that in accordance with the provisions of the Regulation of the Minister of Maritime Economy and Inland Navigation of October 9, 2019 on the forms and methods of monitoring surface water bodies and groundwater bodies, monitoring of groundwater bodies is carried out in a way that allows detection significant and persistent trends in increasing pollutant concentrations caused by anthropogenic impacts (§ 11, point 2). As part of the condition assessment, an analysis of trends in the concentrations of physical and chemical indicators is carried out, as well as the identification of significant and persistent upward trends in pollutant concentrations. A significant and sustained upward trend means any statistically and environmentally significant increase in the concentration of pollutants in groundwater, which requires reversal of this trend. According to the Groundwater Directive (Annex IV, Part B, point 1), the starting point for initiating actions to reverse significant and persistent upward trends is when the concentration of a pollutant reaches 75% of the values of the parameters of the groundwater quality standards specified in Annex I and the threshold values established in accordance with art. 3 of the Groundwater Directive and specified in the Regulation of the Ministry of Environmental Protection and Water Management of October 9, 2019 on the criteria and method of assessing the status of groundwater.

As part of the analysis of trends in changes in pollutant concentrations at points, a forecast of the concentration values of individual indicators is also made by extending the trend line until the end of a given planning cycle. The legal regulations do not refer to forecasting time series analyses, however, predicting significant and sustained upward trends in the next planning cycle is an important element in tracking changes in pollution concentrations and provides the opportunity to assess the risk of not achieving or maintaining good status. Analysis of trends in the concentrations of physical and chemical indicators on representative monitoring data, as well as the identification of significant and persistent upward trends in pollutant concentrations, makes it possible to obtain a coherent and comprehensive assessment of the chemical status of groundwater. It also allows, with an appropriate level of certainty and precision, to distinguish natural changes from anthropological changes. Thanks to this, measures can be taken early enough to prevent or at least mitigate environmentally significant unfavourable changes in the quality of groundwater.

Assessment of the implementation of WFD goals

At the end of the second water cycle, the European Commission took action to assess the implementation of the assumptions of the two key directives in the field of water resources management, i.e. the WFD (together with related directives) and the Floods Directive in all Member States during the period of validity of both directives. The assessment period covered two cycles of water management plans and the first cycle of plans to prevent the effects of drought. The assessment of the achievement of the objectives under these two directives has been combined because the preparation and implementation of management plans by Member States under the WFD and the Floods Directive should be coordinated. Fitness Check, ended in autumn 2018, and in February 2019, the European

Commission published the Report from the Commission to the European Parliament and the Council on the implementation of the Water Framework Directive and the Floods Directive (At the end of the second water cycle, the European Commission took action to assess the implementation of the assumptions of the two key directives in the field of water resources management, i.e. the WFD (together with related directives) and the Floods Directive in all Member States during the period of validity of both directives. The assessment period covered two cycles of water management plans and the first cycle of plans to prevent the effects of drought. The assessment of the achievement of the objectives under these two directives has been combined because the preparation and implementation of management plans by Member States under the WFD and the Floods Directive should be coordinated. Fitness Check, ended in autumn 2018, and in February 2019, the European Commission published the Report from the Commission to the European Parliament and the Council on the implementation of the Water Framework Directive and the Floods Directive (COM (2019) 95 final, 2019).).

The Commission's report reveals significant improvements in WFD information and reporting compared to the previous planning cycle. More Member States prepared the required documents on time, with more comprehensive and reliable information. Two decades of water policy regulated at EU level have brought results - the trend of continuous decline in water quality has been reversed. The Commission emphasizes that compliance with the WFD objectives is gradually improving. However, despite appropriate legislative action and investments in many Member States, improving water quality in many river basins will take more time. While the vast majority of groundwater bodies have achieved good status, less than half of surface water bodies are still in good status.

Compared to the first planning cycle (2010-2015), a small number of water bodies achieved improved status, which may be due to the late identification of impacts, the longer period required to develop effective action programs, the response time to expected impacts, but also to stricter quality standards and improved monitoring and reporting that the status of a body of water that was previously considered "unknown" was in fact "unsatisfactory".

In terms of monitoring and assessment in each water category, the EC drew attention to the still insufficient spatial coverage of the observation and research network and the incomplete and often expert assessment of the water condition. At the same time, with regard to groundwater, the improvement in the quality of monitoring data was appreciated. The Water Framework Directive is complemented by the Groundwater Directive, which includes, in particular, a list of relevant pollutants and threshold values for the assessment of chemical status. Both directives also work in synergy with other EU law, such as the Drinking Water Directive and the Nitrates Directive. According to the EC, monitoring of the chemical status of groundwater in the EU still does not meet the requirements, and a significant number of groundwater bodies are not monitored or monitored to an incomplete extent.

As a result of the fitness check procedure, the European Commission drew attention to several problems that may pose a threat to the achievement of the WFD objectives. First of all, the objectives of the action programs of individual Member States are ambitious to varying degrees. Derogations provided for in Article 4 WFDs currently cover around half of European water bodies. Individual Member States assess the circumstances used to justify an exemption in very different ways. The Commission concluded in its assessment of the river basin management plans that:

- there is generally no adequate and transparent justification of the criteria used to apply exemptions;
- the interpretation of the different reasons for applying exemptions varies significantly between Member States;
- the broad use of exemptions may reflect the low level of ambition in many plans to achieve environmental objectives.

The second significant problem noticed by the European Commission is the fact that most Member States exempt small amounts of water from the obligation to control or register, which raises concerns of the European Commission in connection with the increasingly frequent problems of drought.

Moreover, the impact of agriculture on water resources was again identified as one of the most significant impacts posing a potential risk of deterioration or failure to achieve environmental goals, both in the form of excessive water abstraction (quantitative status) and in the form of diffuse pollution (chemical status). The EC draws attention to the need to increase support from activities under the Common Agricultural Policy (CAP) for the use of voluntary measures that may be necessary to achieve the objectives of the Water Framework Directive.

Regarding the problem of impacts exerted by sectors other than agriculture in terms of pollutants causing failure to meet the requirements regarding chemical or ecological status, the EC concludes that further progress in this direction is necessary, assessing as insufficient the measures introduced to limit or stop discharges into water with certain pollutants.

The progress of member states regarding protected areas was also assessed as insufficient, and in particular the EC draws attention to the lack of knowledge about the state of ecosystems and impacts on protected areas, as well as the lack of defining any goals in relation to protected areas.

Droughts were also listed among the significant problems of water management. One of the key measures to mitigate the effects of drought are drought relief plans, but they have not been adopted in all river basin districts. However, it should be expected that in the next water cycle, Member States will intensify activities in this area.

2.2. Management and protection of Ukraine's water resources in the light of EU and Ukrainian legislation

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

The Water Code, which was adopted in 1995, is the main law in Ukraine that regulates legal relations to ensure the conservation and reproduction of water resources, protection of water from pollution and depletion, rational water management, prevention of harmful effects of water and elimination of their consequences, and improvement of the condition of water bodies (https://zakon.rada.gov.ua/laws/show/214/95-%D0%B2%D1%80#Text).

The policy of high standards and rational management of water resources introduced in the EU has always been a benchmark for Ukraine. On July 1, 1999, Ukraine acceded to the Convention on the Protection and Use of Transboundary Watercourses and International Lakes to strengthen national measures for the protection and environmentally sound management of transboundary surface and groundwater (https://zakon.rada.gov.ua/laws/show/801-14#Text). In July 2003, Ukraine ratified the Protocol on Water and Health to the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (https://zakon.rada.gov.ua/laws/show/1066-15#Text).

The signing of the Association Agreement between Ukraine and the European Union and its Member States in 2014 obliged Ukraine to implement European standards in various spheres of public life following 29 directives and regulations contained in Annex XXX to the Association Agreement. The gradual process of reforming the water resources management system, aimed at achieving its compliance with the developments of the modern management system implemented in the European Union, started in Ukraine within the framework of 6 Directives, namely: Water Framework Directive (2000/60/WE), Floods Directive (2007/60/WE), Marine Strategy Framework Directive (2008/56/WE), Waste Water Directive (91/271/EWG), Drinking Water Directive (2020/2184) and Nitrates Directive (91/676/EWG).

The implementation of the provisions of the EU Water Framework Directive into the Water Code of Ukraine began with the adoption of the Law of Ukraine "On Amendments to Certain Legislative Acts of Ukraine Regarding the Implementation of Integrated Approaches to the Management of Water Resources Based on the Basin Principle", adopted by the Verkhovna Rada of Ukraine on October 4, 2016 (https://zakon.rada.gov.ua/laws/show/1641-19#Text). In accordance with the Law, 9 river basins were allocated, the boundaries of river basin districts, sub-basins and water management areas were approved, and a new regional level of water resources management was introduced through the creation of Basin Water Resources Departments in each of the twelve water regions.

The implementation of the provisions of the EU Water Framework Directive into the Water Code of Ukraine began 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 a Basin Basis", adopted by the Verkhovna Rada of Ukraine on October 4, 2016 (https://zakon.rada.gov.ua/laws/show/1641-19#Text). The law designated 9 river basins, approved the boundaries of river basin districts, sub-basins, and water management areas, and introduced a new regional level of water management by establishing Basin Water Resources Management Offices in each of the twelve water regions.

In 2018, the Cabinet of Ministers of Ukraine approved the Procedure for State Monitoring. According to this document, the subjects of state water monitoring are the Ministry of Environmental Protection and Natural Resources of Ukraine - in terms of monitoring marine waters, the State Water Agency and the State Emergency Service of Ukraine - in terms of monitoring surface waters, the State Service of Geology and Mineral Resources of Ukraine - in terms of state monitoring of groundwater bodies. The overall coordination and organization of monitoring is entrusted to the Ministry of Environment.

In January 2019, by order of the Ministry of Environmental Protection and Natural Resources of Ukraine, the "Methodology for defining surface and groundwater bodies" was approved.

In 2020, the Ministry of Environmental Protection and Natural Resources of Ukraine issued the Order "On the approval of plans-schedules of the process of developing drafts of river basin management plans."

In 2022, a State Water Monitoring Program was approved, including the procedure for diagnostic and operational monitoring of groundwater bodies.

In 2023, the State Targeted Scientific Program of Integrated Water Resources Management until 2030 was approved, which fundamentally changes approaches to water resources management in Ukraine.

To date, River Basin Management Plans have been developed for nine river basins, which are undergoing the stage of public hearings and discussions. Their approval is expected by the end of 2024.

In general, the WFD has a significant level of implementation, which was achieved thanks to the introduction of amendments to 13 Laws of Ukraine and the approval of 30 legislative acts. Another 9 changes necessary for the implementation of the Directive are being developed (Table 3).

Some level of implementation is also observed in the implementation of Commission Directive 2010/75/EU of July 31, 2009, which establishes technical specifications for chemical analysis and monitoring of water status. 2 legislative acts were adopted and the transition to the new version of three international standards was carried out:

DSTU ENISO/IEC 17025:2019 (ISO/IEC 17025:2017 IDT) "General requirements for the competence of testing and calibration laboratories";

DSTU EN ISO 11885:2019 (EN ISO 11885:2019; ISO 11885:2007, ITD) Water quality. Determination of selected elements by optical emission spectrometry with inductively coupled plasma (ICP-OES);

DSTU ISO 13528:2016 Statistical methods for application during the verification of professional level using interlaboratory comparisons (ISO 13528:2015, IDT).

Ukraine has achieved a significant level of implementation with the implementation of the Framework Directive on Maritime Strategy. Here, changes were made to 5 Laws of Ukraine and 8 legislative acts were approved. Waiting for 5 amendments.

Table 3. List of EU Directives implemented in Ukrainian legislation

NO	Directive	Directive's cipher	Implementation level
1	Directive establishing a framework for Community action in the field of water policy (Water Framework Directive - WFD)	2000/60/WE	significant
1a	Directive laying down, according to Directive 2000/60/EC, technical specifications for chemical analysis and monitoring of water status	2009/90/ЄС	some
2	Directive concerning the protection of waters against pollution caused by nitrates from agricultural sources (Nitrates Directive)	91/676/EWG	good
3	Directive on the assessment and management of flood risks (Floods Directive)	2007/60/WE	significant
4	Directive on the quality of water intended for human consumption (recast) (Drinking Water Directive)	2020/2184	some

5	Directive concerning urban waste-water treatment (Waste Water Directive)	91/271/EWG	some
6	Directive establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)	2008/56/WE	significant

The level of implementation of the Nitrates Directive is assessed as good - 4 Laws of Ukraine have been amended, 3 legislative acts have been approved, and 3 amendments to the law are being developed. In particular, in 2020, an interdepartmental working group on the implementation of the Nitrate Directive was established, which undertook to develop a Methodology for determining zones vulnerable to nitrate compounds and a Code of Best Agricultural Practices. The Government also made changes to the Technical Regulation of Detergents (regarding the prohibition of phosphates in detergents and laundry detergents), approved a plan of measures for state market surveillance and state control of products regarding the compliance of detergents with the requirements of the Technical Regulation of Detergents.

To implement the Flood Directive, Ukraine has already passed the main stages: the legislation was brought into line; pre-estimated flooding risks; threat maps and flood risk maps have been developed. The Flood Risk Management Plans for individual territories within river basin districts for 2023-2030 were approved in October 2022.

The implementation of the Wastewater Directive in Ukraine has also started. In January 2023, the Law of Ukraine "On Wastewater Disposal and Treatment" was adopted (https://zakon.rada.gov.ua/laws/show/2887-20#Text). To fulfill the requirements of the Law, more than 20 regulatory documents of the technical direction have been developed, supplemented and clarified.

The law defines the guarantees of consumers' rights in the field of wastewater disposal; powers of central executive authorities and local government bodies; requirements for local rules for the acceptance of wastewater into the centralized drainage systems of the settlement, as well as the obligations of the subjects of relations in the field of wastewater disposal. Gradual development in 11 strategic directions is foreseen. By Article 12 of the Law, the local government must adopt the following normative acts:

- local rules for accepting wastewater into the centralized drainage systems of the settlement;
- local rules for the collection, transportation and treatment of wastewater in the settlement from objects that are not connected to the centralized drainage systems;
- local rules for accepting surface wastewater into the surface wastewater drainage system of the settlement.

Regarding the implementation of the provisions of the Directive on the quality of water intended for human consumption (2020/2184), which repealed Directive 98/83/EC and became its "successor". Back in 2010, the State Sanitary Rules and Regulations (DSanPiN 2.2.4-171-10) "Hygienic Requirements for Drinking Water Intended for Human Consumption" came into force in Ukraine, which was developed to implement the European requirements of Directive 98/83/EC on drinking water. Today, state executive authorities, local governments and organizations that carry out sanitary and epidemiological surveillance are guided by the latest version of the DSanPiN as amended in 2015, in which some sanitary rules and regulations are stricter than those provided for by European standards (https://zakon.rada.gov.ua/laws/show/z0452-10#Text).

On February 15, 2022, the Law "On the Nationwide Targeted Social Program "Drinking Water of Ukraine" for 2022-2026" was adopted. The program provided for the implementation of more than 1,747 infrastructure projects in the regions during 2022-2026. These are projects for the construction and reconstruction of water supply and drainage networks, water intake facilities, water treatment facilities, basic laboratories for monitoring the quality of drinking water, and wastewater and equipping them with modern control and analytical equipment, etc.

The possibility of financing priority projects to provide people with drinking water, including in rural areas, was also foreseen. The implementation of these plans and programs is currently on hold due to the war.

On June 23, 2022, the leaders of the 27 EU member states decided to grant Ukraine the status of a candidate for membership in the European Union. To become a full member of the EU, it is necessary to implement all Acquis communautaire (acquis) in the field of environment and climate change. According to the European Commission itself, this is about 200 acts.

In November 2023, the European Commission published an analytical report assessing Ukraine's ability to assume the obligations of the EU membership perspective. The report contains a detailed analysis of the current state of our country in terms of harmonization of its legislation with the EU acquis, a set of common rights and obligations of the European Union. In its reports, the European Commission assessed the level of approximation of Ukraine's legislation to the EU acquis based on a questionnaire, as well as relevant information obtained through intensive dialogue over the years under the Association Agreement to evaluate their implementation. The European Commission's conclusion: "Ukraine has some level of preparation in the area of the environment and climate change. Good progress was made in this chapter, despite Russia's war of aggression. On the environment, legislation was adopted aiming at further alignment on horizontal issues, water quality, waste management, chemicals and noise" **(**https://neighbourhood-enlargement.ec.europa.eu/system/files/2023-11/SWD_2023_699%20Ukraine%20report.pdf**).**

Thus, today, despite Russia's full-scale invasion, our state is very actively working on further steps in reforming the country in order not to lose the pace of our integration.

3. Identification of areas at risk of groundwater pollution within the Polish-Ukrainian Cross-Border Aquifer System using the hydrogeochemical anomaly method

The identification of areas at risk of contamination within the TAS was driven by the need for transboundary aquifer management and agreements to protect these sensitive shared resources. For this purpose, a methodology was developed to identify "hotspots" in transboundary aquifers that exhibit groundwater quality problems. Chemical data used in this study were provided by the State Geological Surveys of both countries and processed using spatial and other analysis techniques. With this information, policymakers and government officials have the opportunity to target those hotspots that require further research, targeted cross-border management, and potentially governing cross-border agreements.

The subject of the analysis was a set of hydrogeochemical data collected in the study area in the years 2000-2022. On the Ukrainian side, data was obtained from 260 measurement points, most of which were drilled wells and piezometers. Unfortunately, not all points had complete analyzes available, so the ion balance could only be prepared for 207 of all tested samples. The scope of analyzes on the Ukrainian side usually included macronutrients, nitrates and occasionally pH. Additionally, in most analyzes only the total concentration of sodium and potassium was available, and only occasionally were the concentrations of individual components determined. The spatial arrangement of measurement points is uneven. The data concerns mainly intakes located in the vicinity of larger urban centers, in particular the Lviv agglomeration, as well as in the vicinity of Stryj, Dobrobycz and Szkło. Between clusters with a high density of sampling points, there are vast areas practically devoid of measurement points. It was also not possible to obtain data for the north-eastern part of the research area covered by the EU-Waterres project. On the Polish side, data were obtained from 15 points of the groundwater monitoring network distributed quite evenly along the border zone, but the density of the measurement network here is clearly lower than on the Ukrainian side. In the Polish part of the area, testing covered mainly drilled wells and one spring. Some points had long measurement sequences covering the years 2000-2022. This made it possible to track time trends relating to long-term changes in the chemical composition of groundwater. Both on the Polish and Ukrainian side of the border, the tested waters were collected from aquifers developed in the Cretaceous (mainly carbonate medium), Neogene (carbonate and siliceous medium) and Quaternary (silica medium) formations.

The hotspot identification method presented here is based on the concept of positive hydrogeochemical anomalies, i.e. an increase in the hydrogeochemical background. It is based on the assumption that each positive hydrogeochemical anomaly signals a transformation of the chemical composition caused by the influence of natural or anthropogenic factors, i.e. pollution. Based on certain premises and expert knowledge, the impact of natural factors can be determined quite precisely. In this way, anthropogenically determined hydrogeochemical anomalies are separated. These areas were then classified as hotspots - areas at risk of groundwater contamination.

Ionic composition of the tested waters

Most of the tested water samples, for which it was possible to prepare an ion balance, were characterized by chemistry typical of the waters of the hypergenesis zone. These are most often fresh, two- or three-ion waters (Figure 6). The hydrochemical types are dominated by HCO3-Ca (43%), HCO_3-Ca-(Na+K) (13.5%), HCO_3-Ca-Mg (13%) and HCO_3-SO_4-Ca (13%). The remaining samples represented polyionic waters, with bicarbonates usually dominating the anion side, and only occasionally the dominant share of sulphate or chloride ions was visible (Figure 7).

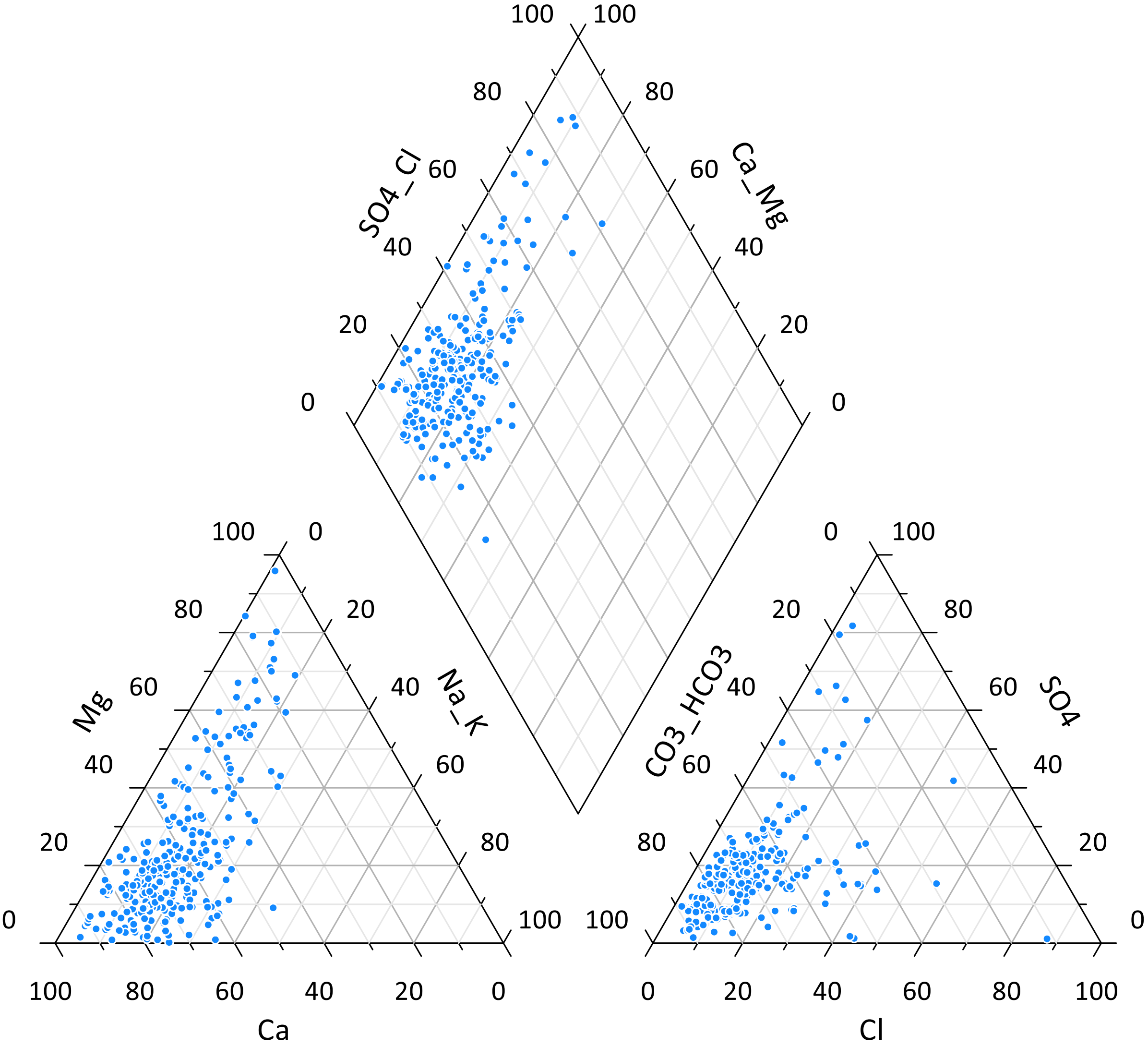


Figure 6. Chemical composition of groundwater in the research area of the EU-Waterres project

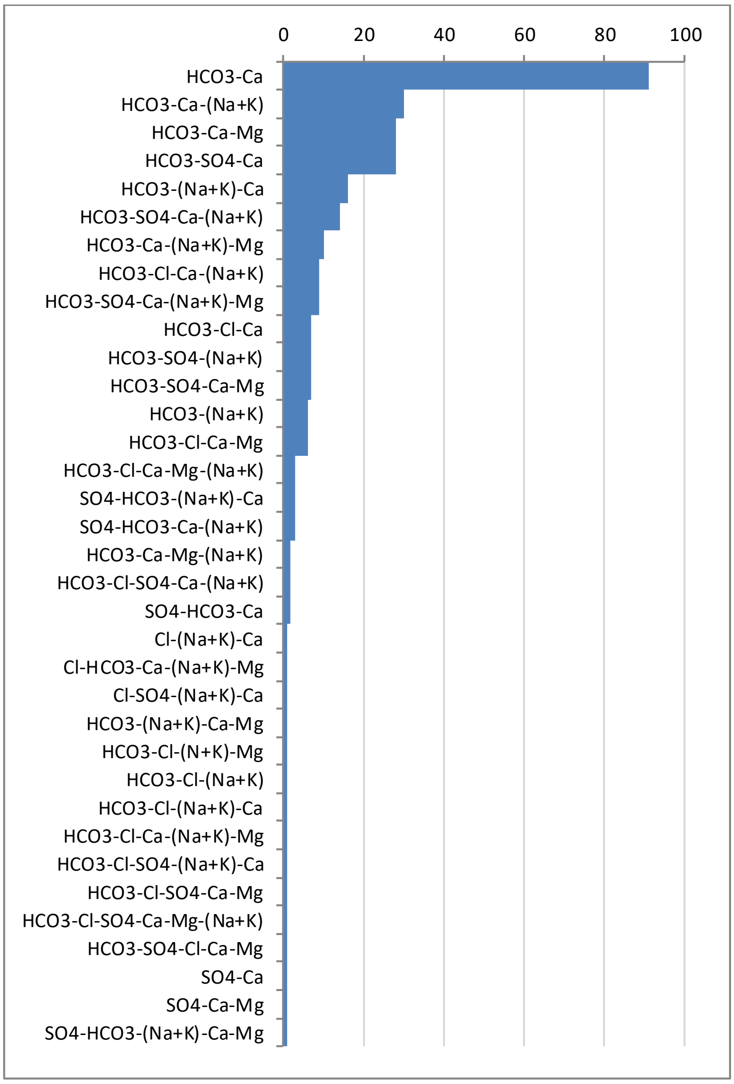


Figure 7. Hydrogeochemical types of water

Mineralization (Total Dissolved Solids)

Water mineralization was determined as the sum of components dissolved in 207 samples in which full macrocomposition determinations were available. Nearly 90% of the samples tested were freshwater (mainly acratopega). Mineralization calculated for the remaining samples exceeded 1000 mg/L. In order to determine the typical range of variability of the examined feature, its empirical distribution was examined and then (after rejecting outliers) descriptive statistics were calculated. The empirical distribution of mineralization shows features of a multi-mode distribution, with the highest abundance observed in the range of 650 - 700 mg/L (Figure 8). At the same time, the data are characterized by significant dispersion around the central tendency of the collection, which is confirmed by the high standard deviation value (406.6 mg/L). Both the median and the arithmetic mean are located in the highest frequency interval or in its immediate vicinity and amount to 650.8 and 716.7 mg/L, respectively. This indicates that the distribution is symmetrical, although it differs significantly from the normal distribution. In this situation, it was decided to determine the limits of the typical range of mineralization variability using the 16th and 84th percentile method. On this basis, the range of hydrogeochemical background mineralization in the studied area was determined in a wide range of 310 - 1123 mg/L.

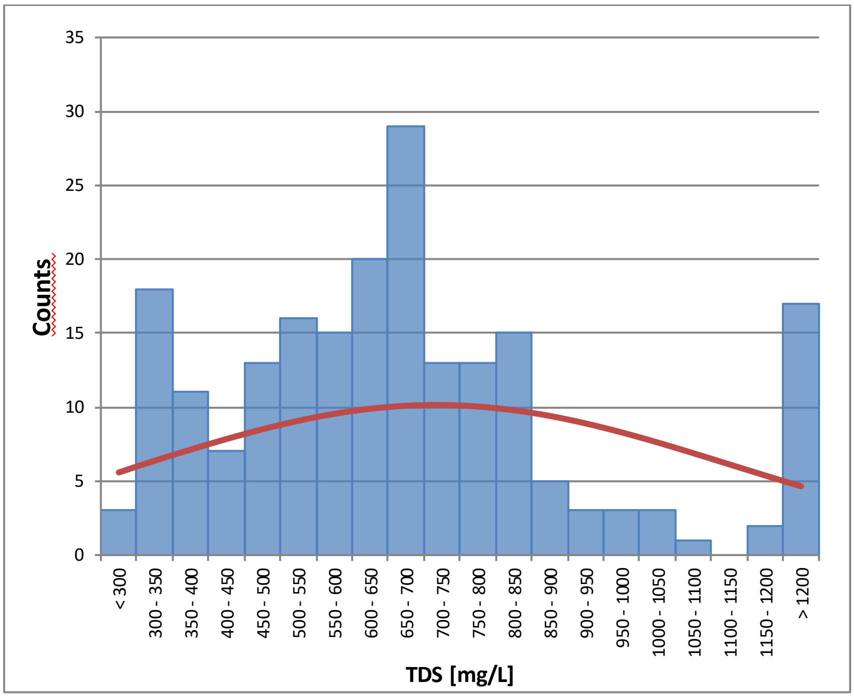


Figure 8. Empirical distribution of total groundwater mineralization (N = 207)

Values falling outside the background range were treated as anomalous, and their spatial distribution within the hydrochemical field was examined. For this purpose, point mineralization values were interpolated using the Spline method (Figure 9). The spatial distribution of mineralization obtained in this way is subject to uncertainty resulting from the variable density of the measurement network and cannot be treated as a reliable representation of reality. However, it can be used to interpret spatial trends from a qualitative perspective.

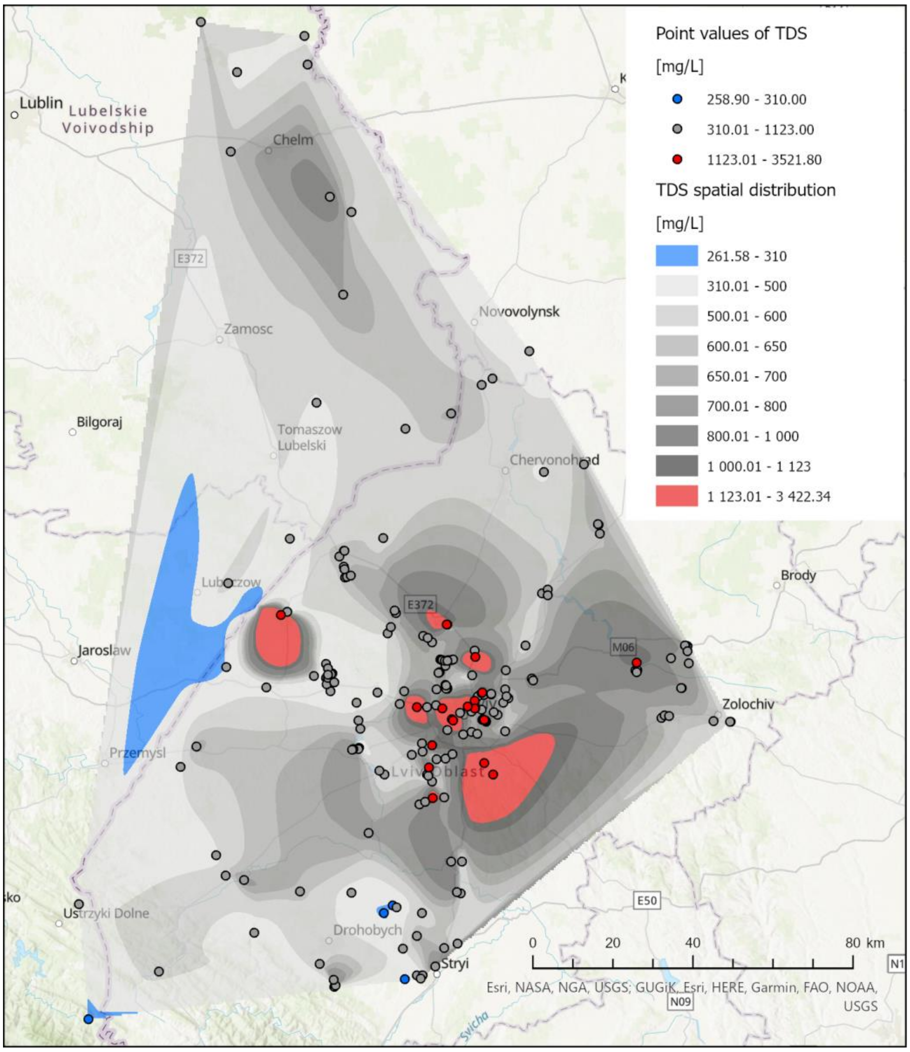


Figure 9. The occurrence of positive (red) and negative (blue) anomalies in general mineralization against the background of the spatial trend

The obtained image indicates that the areas of water with increased mineralization are related to both geogenic and anthropogenic factors. In the studied area, high water mineralization occurs mainly in areas where water is drawn from the Cretaceous zone and the medium is carbonate in nature. At the same time, attention is drawn to the clear concentration of positive anomaly values in the vicinity of urban centers, in particular the Lviv agglomeration and the border sulfur mining area. This indicates that the chemical composition of shallow groundwater in these areas has been significantly changed as a result of anthropopressure.

Comparison of the empirical distributions of general water mineralization divided into individual aquifers confirms the conclusions drawn on the basis of the analysis of the spatial distribution of this feature. The highest mineralization values were observed in water taken from the Cretaceous zone (carbonate medium). This is confirmed by both the average value and the limit values of the hydrochemical background, which are clearly higher than in the case of water drawn from the Quaternary and Neogene reservoirs (Figure 10, Table 4).

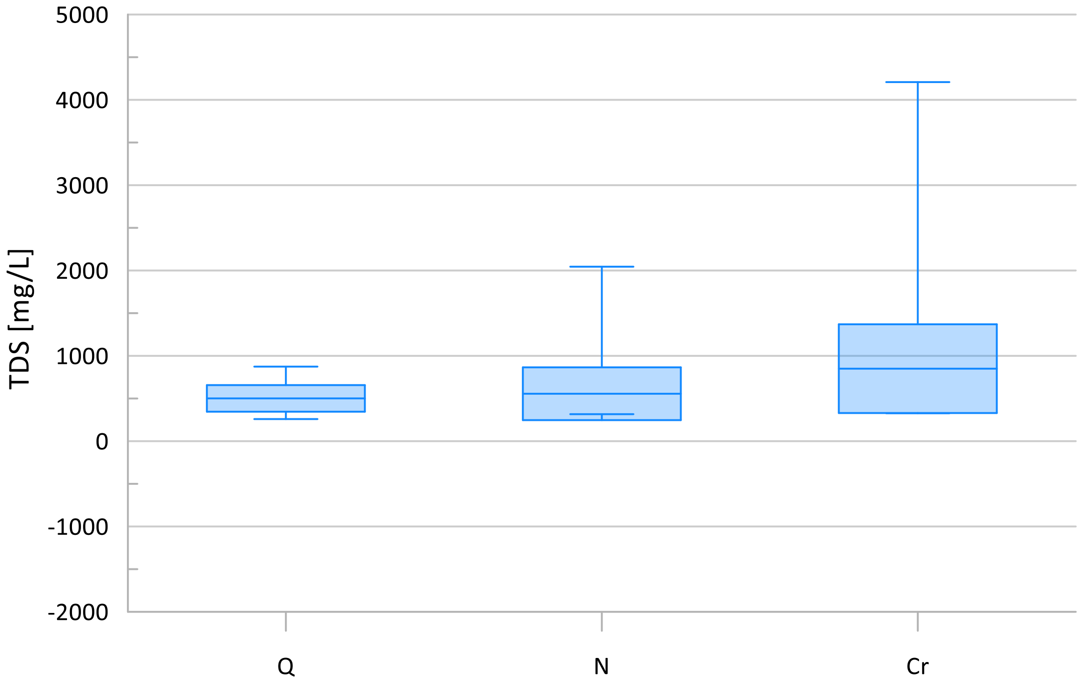


Figure 10. Comparison of empirical distributions of total mineralization of groundwater taken from the Quaternary (Q), Neogene (N) and Cretaceous (Cr) levels
(average values, a range of one standard deviation around the expected value, and extreme values are plotted on a box-and-whisker chart).

Table 4. Average water mineralization and the range of hydrochemical background in the division into aquifers

Aquifer	Mean [mg/L]	Lower background range [mg/L]	Upper background range [mg/L]
Quaternary	501	348	654
Neogene	555	249	862
Cretaceous	849	332	1367

Data obtained from the Polish groundwater monitoring network also made it possible to track changes in mineralization over time. For most points, no clear temporal trends were observed or the changes were seasonal in nature. However, in individual points, apart from seasonal changes, there was a significant upward trend, which may indicate changes in the chemical composition as a result of anthropopressure (Figure 11, Figure 12).

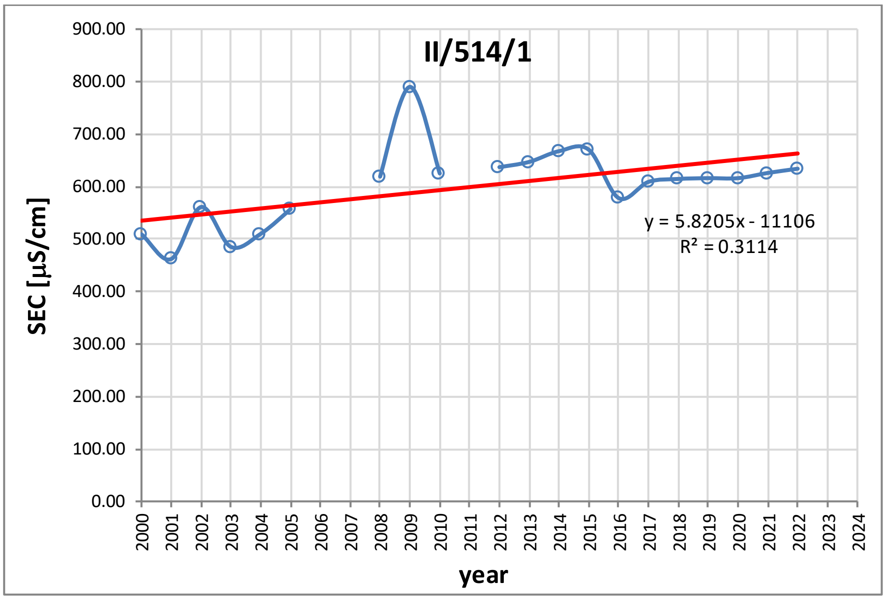


Figure 11. Changes over time in the specific electrolytic conductivity of water taken into monitoring network point No. II/514/1

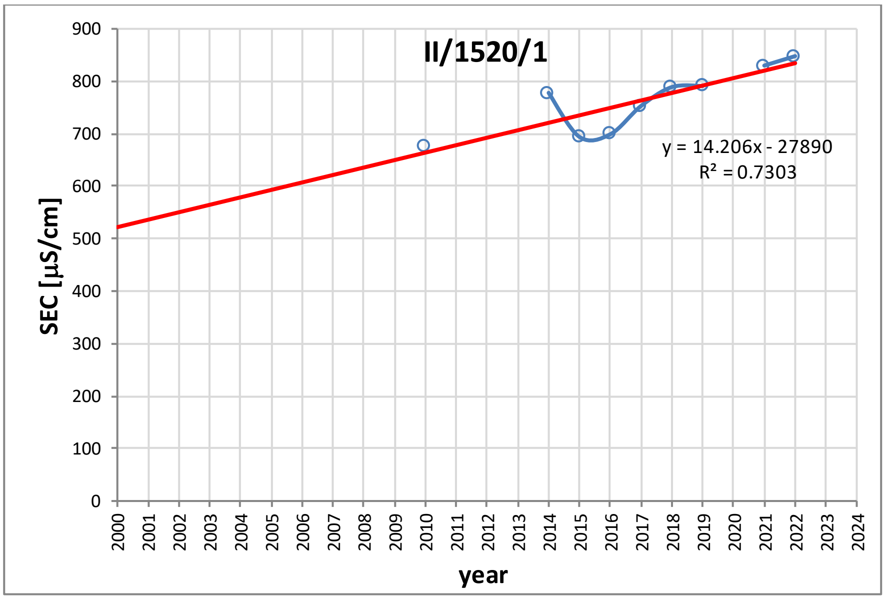


Figure 12. Changes over time in the specific electrolytic conductivity of water taken into monitoring network point No. II/1520/1

Groundwater pH

At measuring points on the Ukrainian side, water pH was measured sporadically, and the obtained data set is characterized by a low population. As a result, both spatial data analysis and analysis by aquifer were impossible. Due to the above difficulties, the analysis of water pH was limited to examining the empirical distribution, determining the background range and tracing time trends in the Polish part of the area. The empirical pH distribution is symmetrical and close to the normal distribution (Figure 13). The mean and standard deviation here are 7.23 and 0.5, respectively. The typical range of variability, which also determines the background range, is between 6.74 and 7.73, which indicates that neutral water dominates in the study area. At most measurement points included in the Polish groundwater monitoring network, no clear time trends were recorded. The exception is point number II/583/1, which, in addition to seasonal changes, recorded a significant downward trend (Figure 14). In this case, the lowering of the pH value may result from anthropopressure.

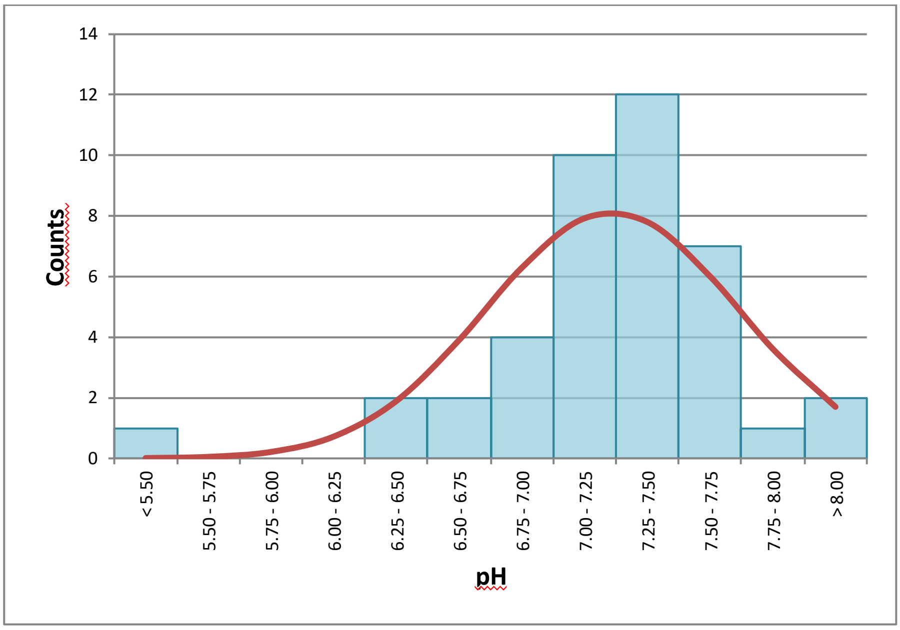


Figure 13. Empirical pH distribution of groundwater (N = 41)

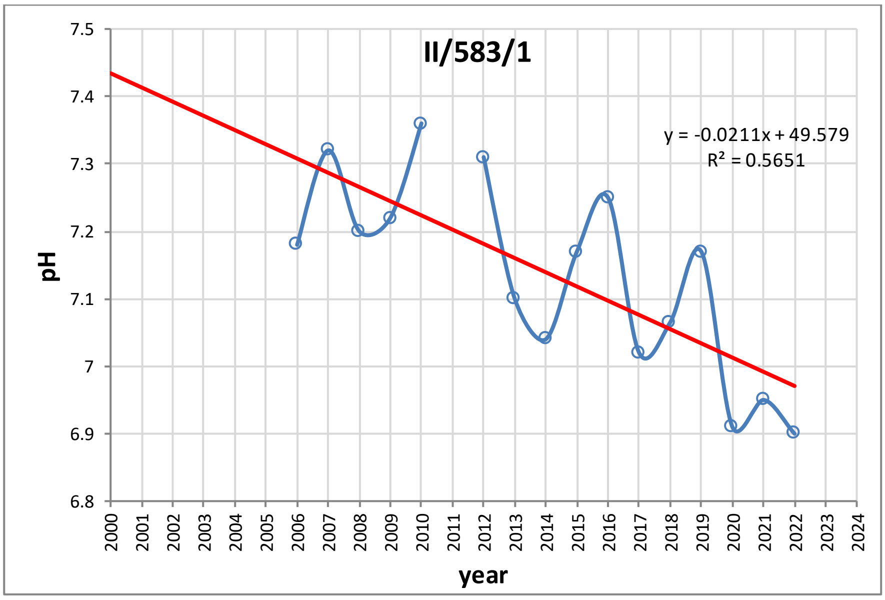


Figure 14. Changes over time in the pH of water taken into monitoring network point No. II/583/1

Bicarbonates

Bicarbonate concentrations were tested based on the results of determinations made in 227 groundwater samples. The empirical distribution of this feature obtained on this basis is close to the normal distribution (Figure 15). The measures of the set's central tendency expressed as the arithmetic mean and median have the values of 364.1 and 372.3, respectively. It is worth noting that these are similar values, which indirectly indicates the symmetrical distribution. At the same time, the data are characterized by dispersion, which can be described by the standard deviation value (101.7 mg/L). In this situation, it was decided to set the limits of the typical range of bicarbonate concentration variability at a distance of one standard deviation around the arithmetic mean. On this basis, the hydrogeochemical background range for bicarbonate concentration in the studied area was determined to be 262 - 466 mg/L (Table 5).

Table 5. Average bicarbonate concentrations and the range of hydrochemical background in the division into aquifers

Aquifer	Mean [mg/L]	Lower background range [mg/L]	Upper background range [mg/L]
Quaternary	296	206	386
Neogene	301	217	384
Cretaceous	410	323	496

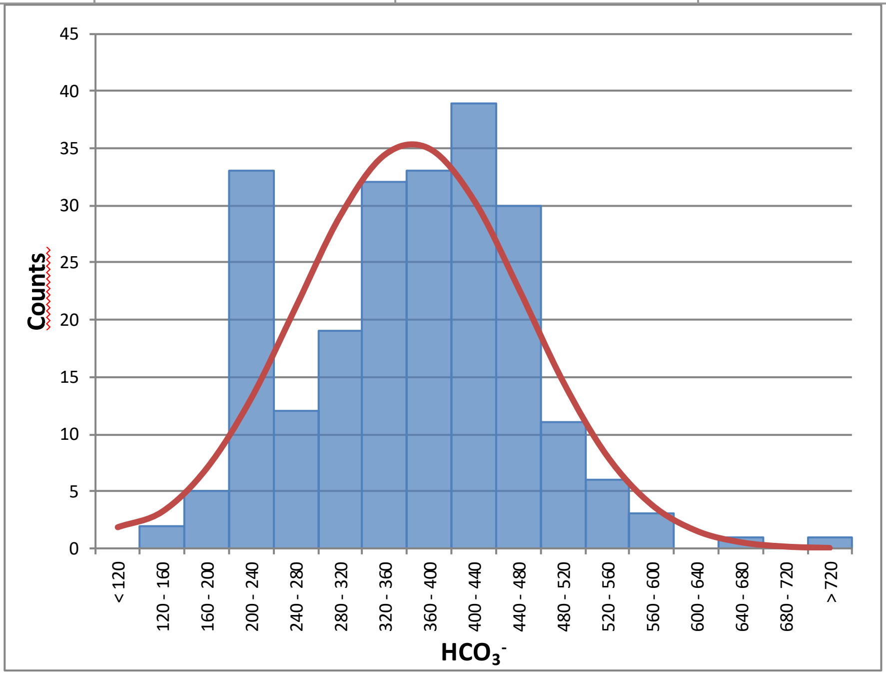


Figure 15. Empirical distribution of bicarbonate concentration in groundwater (N = 227)

Values exceeding the background range were treated as anomalous, and then their spatial distribution was examined using the same methodology as in the case of mineralization and with analogous limitations in the area of interpretation (Figure 16). As in the case of general mineralization, the highest concentrations of HCO_3^- ions were found in the areas of the useful Cretaceous aquifer, which indicates the dominant role of the geogenic factor in shaping the spatial distribution of this feature. This is confirmed by the empirical distribution of bicarbonate concentrations in the aquifer distribution. The highest concentrations of HCO_3^- were observed in water drawn from the Cretaceous zone (carbonate medium). This is reflected in the average values obtained for each subpopulation of results, as well as in the limit values of the hydrochemical background, which clearly differ from the concentration values in water drawn from the Quaternary and Neogene reservoirs (Figure 17, Table 5). In addition to the geogenic factor, an anthropogenic factor may also be responsible for increased bicarbonate concentrations. This is supported by the fact that numerous points where bicarbonate concentrations within the positive anomaly range were found are concentrated in the area of the Lviv agglomeration.

The analysis of time trends in points of the monitoring network allowed the identification of two points on the Polish side where a significant time trend was recorded. In the case of point II/514/1 it was a strong upward trend (Figure 18), while in point II/338/1 it was a decreasing trend (Figure 19).

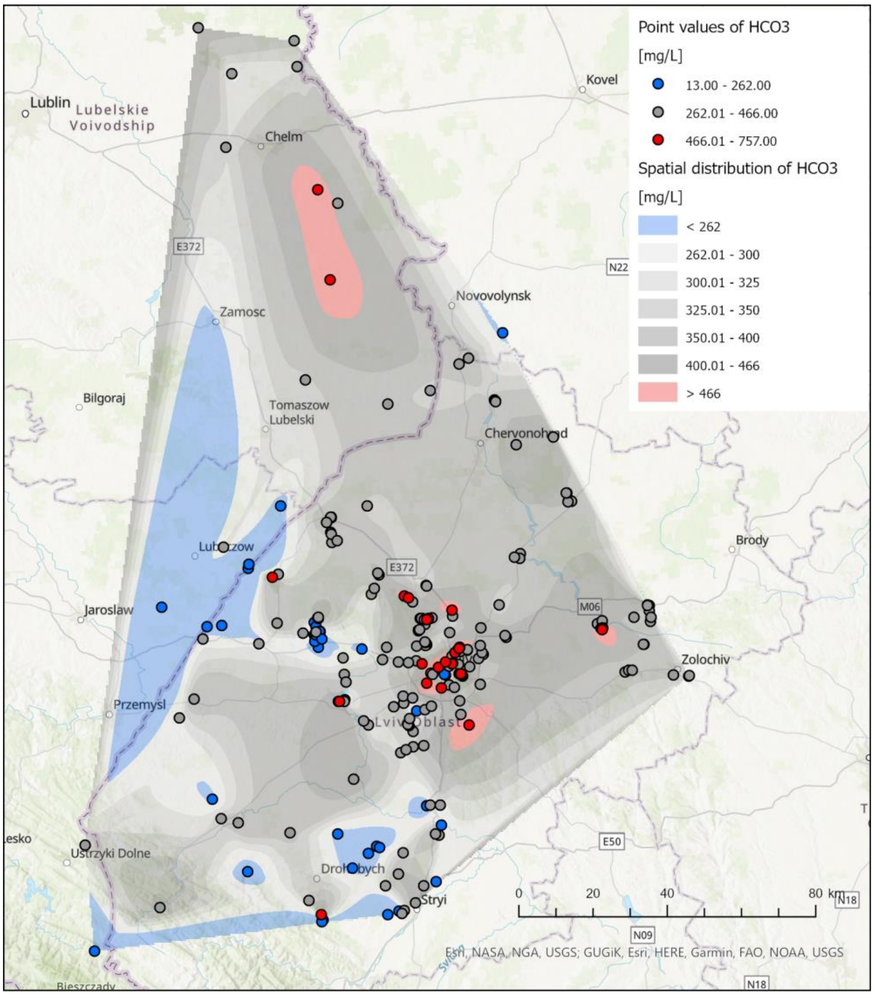


Figure 16. Occurrence of positive (red) and negative (blue) anomalies in bicarbonate concentration against the background of the spatial trend

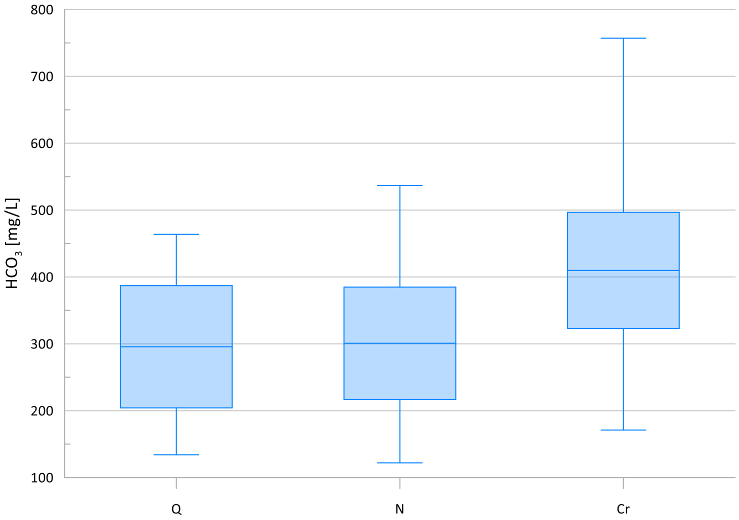


Figure 17. Comparison of empirical distributions of bicarbonate concentrations in groundwater drawn from the Quaternary (Q), Neogene (N) and Cretaceous (Cr) levels
(average values, a range of one standard deviation around the expected value, and extreme values are plotted on the box-and-whisker chart).

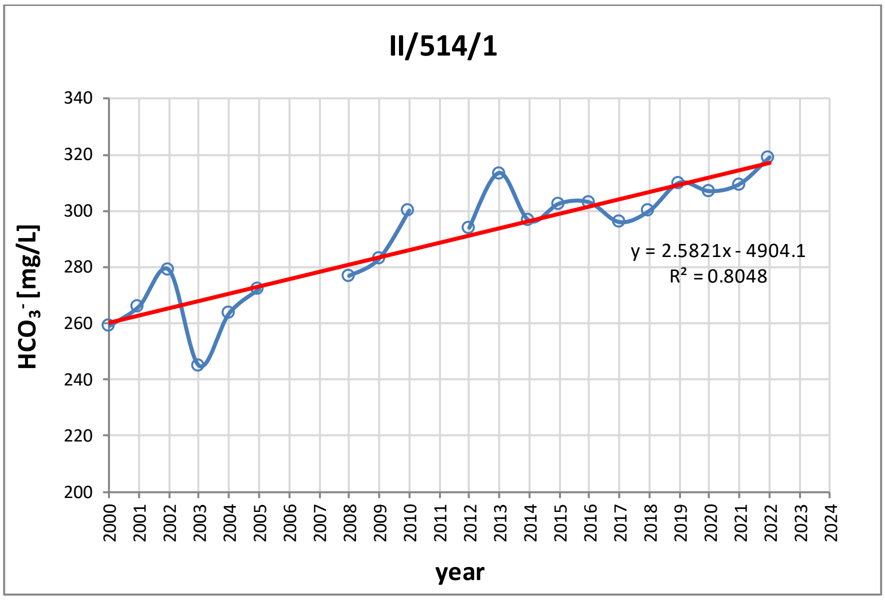


Figure 18. Changes in bicarbonate concentration in intake water over time

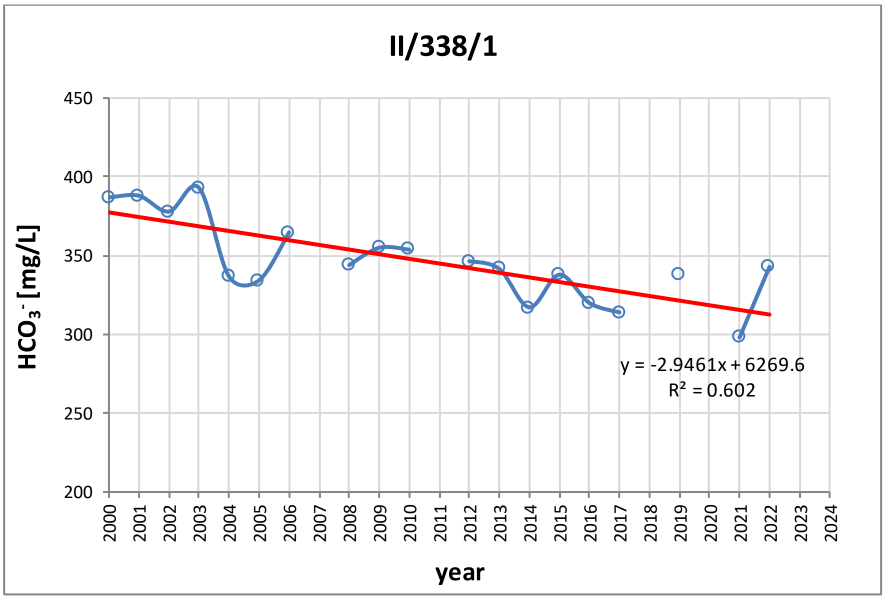


Figure 19. Changes in bicarbonate concentration in intake water over time

Sulphate

The analysis of the sulphate concentration field was based on the results of determinations in groundwater samples obtained from 268 measurement points. The empirical distribution of this feature in the studied population of results is clearly asymmetric, with marked negative skewness. Therefore, it was decided to equalize the distribution logarithmically (Figure 20), and the values of decimal logarithms of the concentration of the SO_4^{2-} ion were used to assess both the measures of the central tendency of the set and the dispersion. The distribution obtained as a result of logarithmic equalization is close to normal. The mean and standard deviation obtained from this distribution were used to determine the hydrochemical background in the range of 22 - 139 mg/L. These data were used to assess the spatial distribution of SO_4^{2-} ion concentrations. The results of the analysis, although subject to uncertainty, indicate a clear contrast between the Polish and Ukrainian parts of the study area. All positive anomalies are concentrated on the Ukrainian side, while on the Polish side there is a clear negative anomaly (Figure 21). The observed spatial regularity cannot be easily explained by the influence of a geogenic factor. All the main geological structures here are approximately perpendicular to the border line and continue on both sides of it. This means that the geochemical type of the rock medium on both sides of the border is similar, and the differences in sulphate content should be related to the development, cover and method of using the land surface. It should be noted that on the Ukrainian side of the study there are large urban centres that do not exist in the part of the Polish border covered by the research or were not covered by the research (a much sparser measurement network).

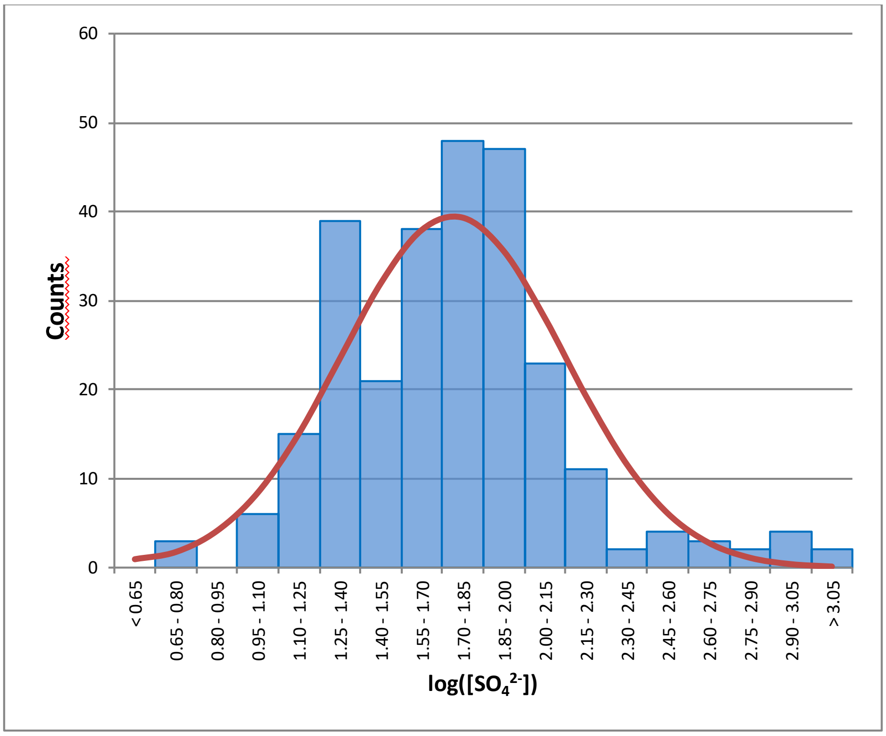


Figure 20. Logarithmically adjusted empirical distribution of sulfate concentrations in groundwater (N = 268)

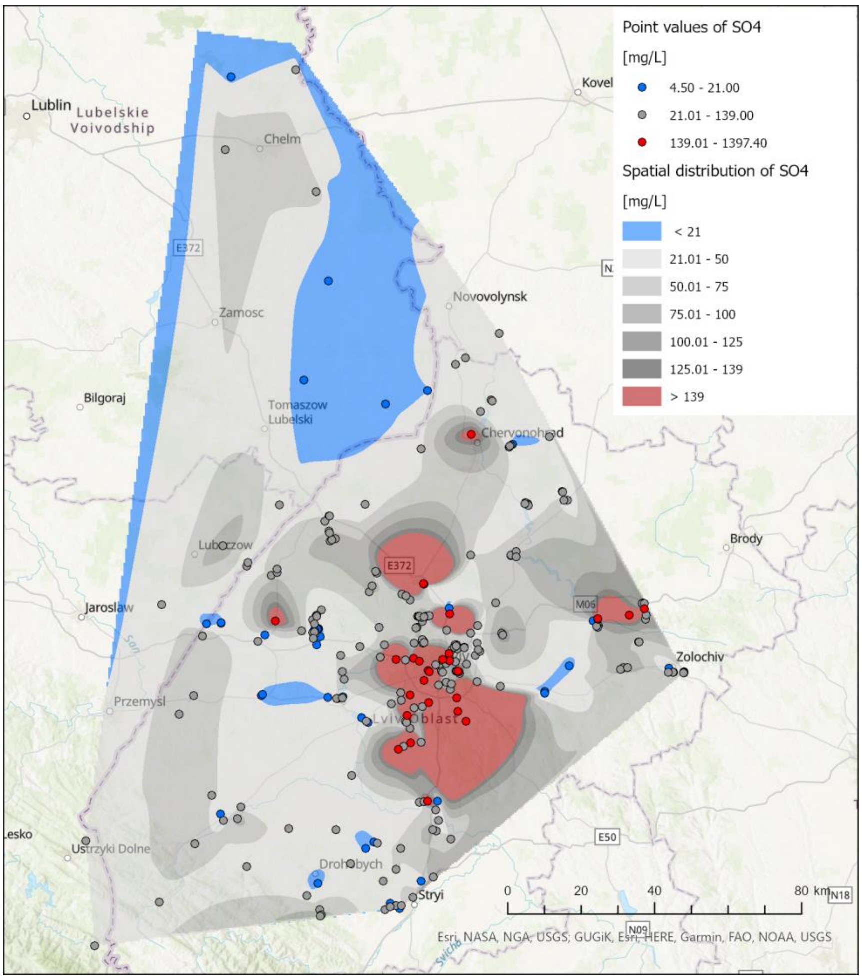


Figure 21. Occurrence of positive (red) and negative (blue) anomalies in sulfate concentration against the background of the spatial trend

Comparison of subpopulations of results based on the age of the aquifer indicates that the spatial distribution of sulfate concentrations is also determined by the geogenic factor. Comparison of logarithmically balanced empirical distributions indicates clearly lower concentrations of sulfates in the Quaternary waters compared to waters taken from Cretaceous formations. The distribution for the Neogene, however, is clearly bimodal, and the local maxima of the distribution are grouped around values typical for the Quaternary and Cretaceous levels (Figure 22).

In two monitoring points on the Polish side of the border, clear increasing trends in sulphate content were recorded over the last two decades (Figure 23, Figure 24). A particularly important trend occurs in the case of point II/514/1, which, combined with changes in the concentrations of other components observed at this point, indicates a significant deterioration of water quality as a result of anthropopressure.

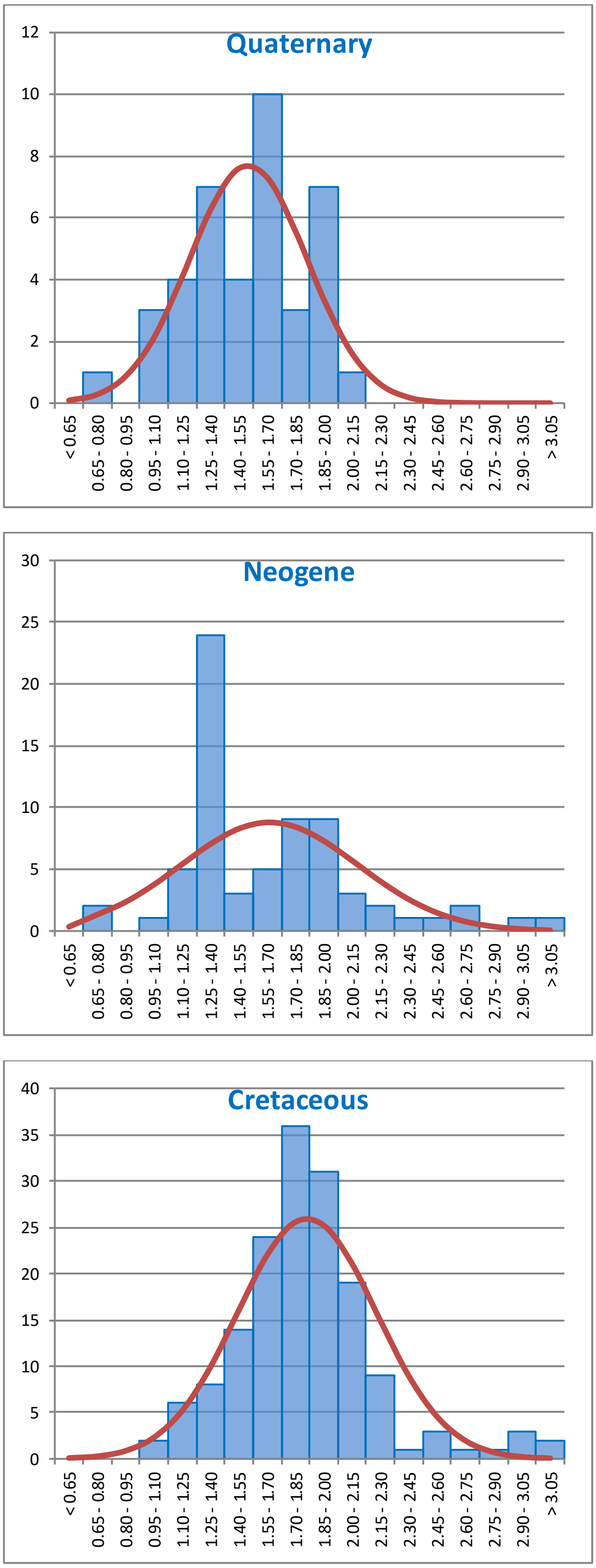


Figure 22. Comparison of logarithmically equalized empirical distributions of sulfate concentrations in groundwater taken from the Quaternary (N = 40), Neogene (N = 69) and Cretaceous (N = 160) levels

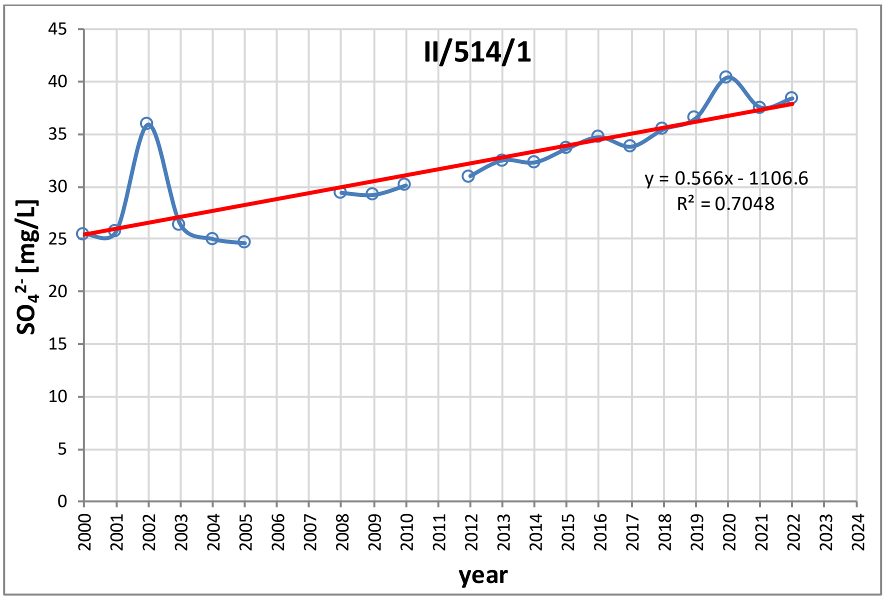


Figure 23. Changes over time in the concentration of sulphates in water taken into monitoring network point No. II/514/1

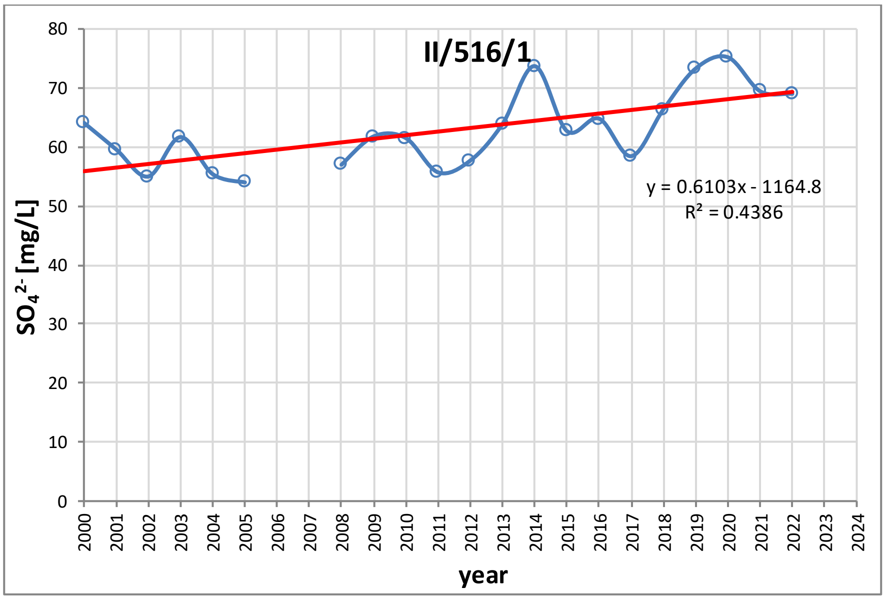


Figure 24. Changes over time in the concentration of sulphates in water taken into monitoring network point No. II/516/1

Chlorides

The spatiotemporal distribution of chloride concentrations was assessed based on the results of determinations in groundwater samples obtained from 266 measurement points. As in the case of sulphate concentrations, the empirical distribution of chlorides is clearly asymmetric, with a marked negative skewness. As a result, it was also decided to logarithmically equalize the distribution (Figure 25), and the resulting distribution is close to normal. On this basis, the hydrochemical background range was determined to be 12 – 68 mg/L. Then, using the Spline method, a map of the spatial distribution of Cl^- ion concentrations was prepared. As in the case of SO_4^{2-} ions, also in the case of chloride ions, there is a clear contrast between the Polish and Ukrainian sides. Again, all positive anomalies occur on the Ukrainian side, while on the Polish side there is a clear negative anomaly (Figure 26). The observed spatial diversity should be associated primarily with different methods of development, coverage and use of the land surface. The way the measurement network is organized on both sides of the border is also important. On the Polish side, this network is much rarer and, unlike on the Ukrainian side, there are no large number of measurement points within large cities.

The role of the geogenic factor in the case of chlorides is much less clear than in the case of sulphates. The empirical distributions of the concentrations of this ion in water drawn from individual aquifers are similar and indicate very similar ranges of the hydrochemical background (Figure 27).

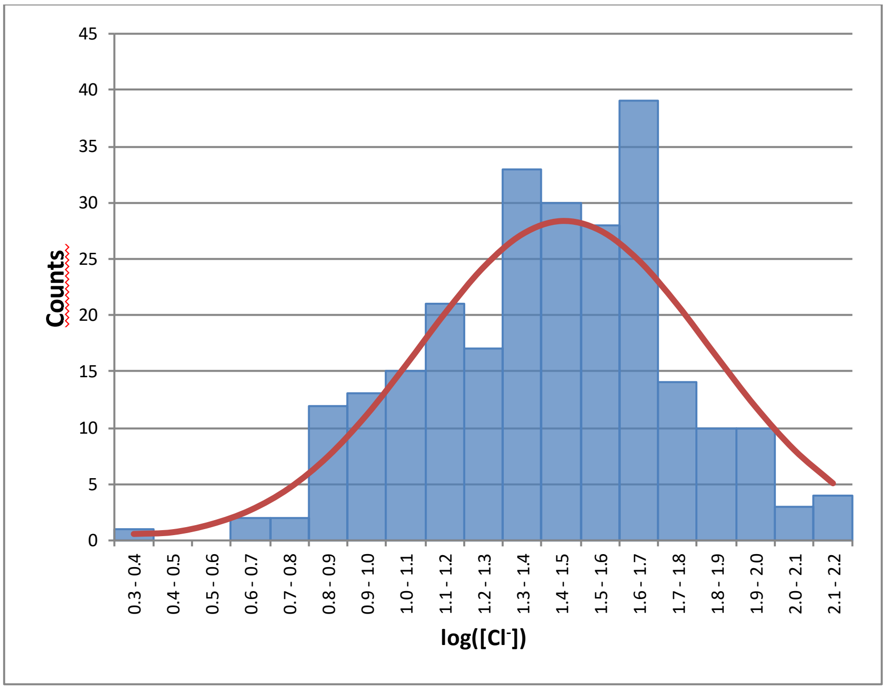


Figure 25. Logarithmically adjusted empirical distribution of chloride concentrations in groundwater (N = 266)

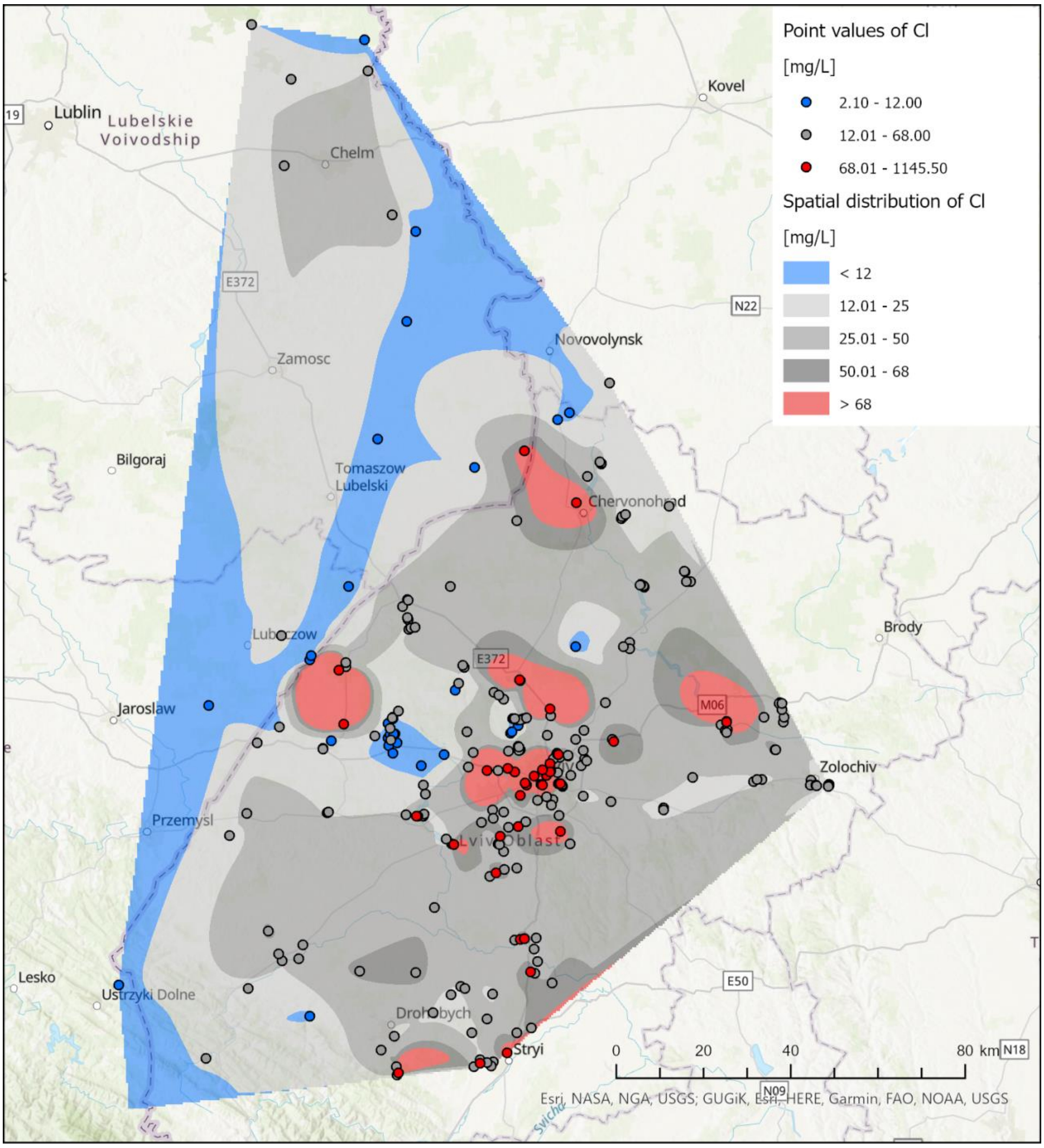


Figure 26. Occurrence of positive (red) and negative (blue) chloride concentration anomalies against the background of the spatial trend

As in the case of sulphates, clear increasing trends in chloride content were recorded at two monitoring points on the Polish side of the border (Figure 28, Figure 29). A particularly significant trend was again noted in point II/514/1, and a slightly less pronounced trend in point II/592/1.

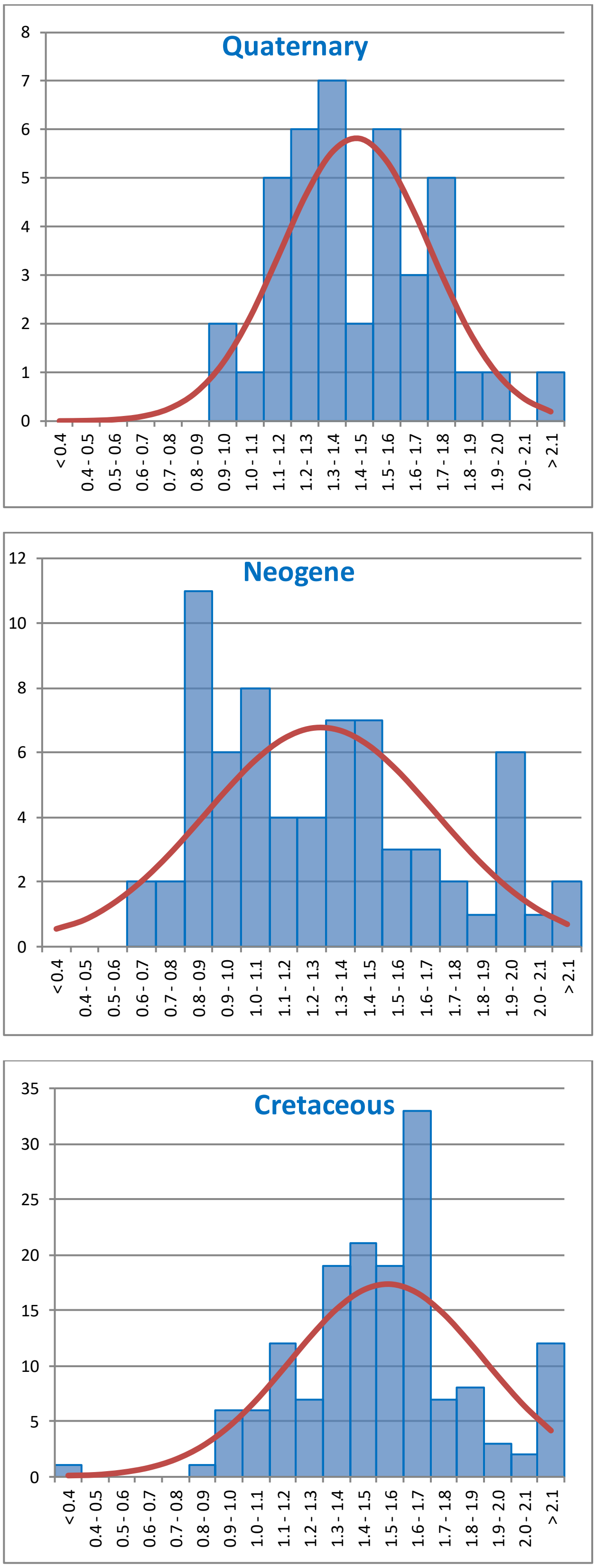


Figure 27. Comparison of logarithmically equalized empirical distributions of chloride concentrations in groundwater taken from the Quaternary (N = 40), Neogene (N = 69) and Cretaceous (N = 157) levels

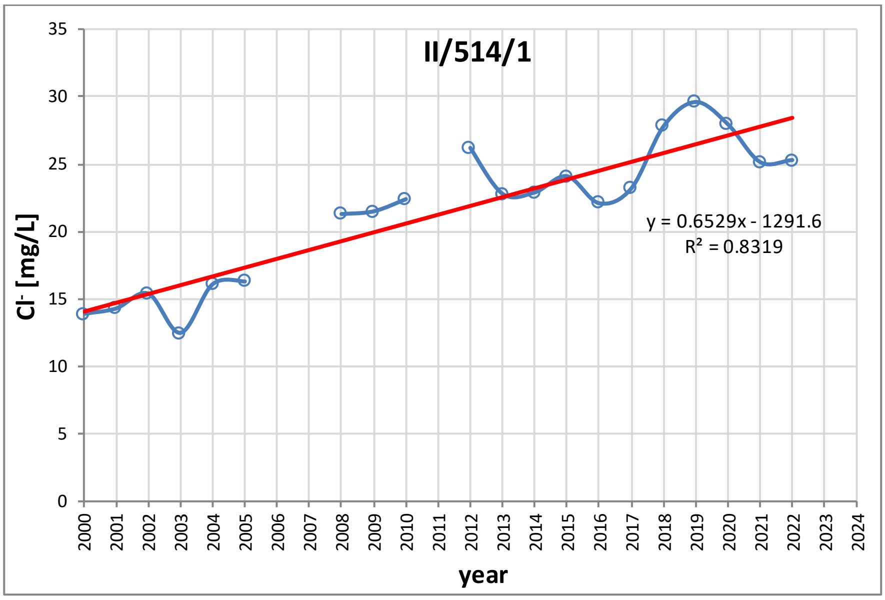


Figure 28. Changes in chloride concentration over time in water taken at monitoring network point No. II/514/1

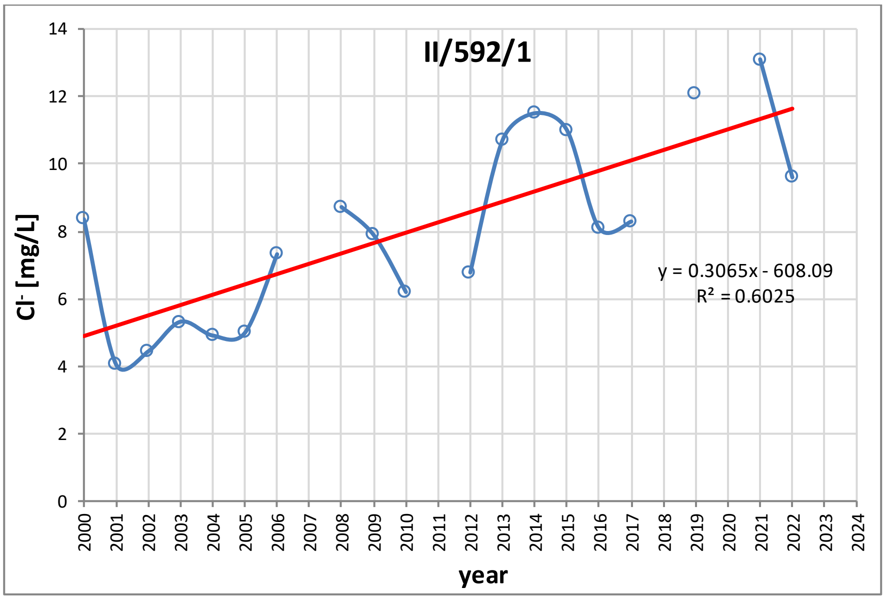


Figure 29. Changes over time in the concentration of chlorides in water taken into monitoring network point No. II/592/1

Nitrates

Nitrate concentrations on the Ukrainian side were measured only at a few points, which is why the obtained data set contains only 36 data points. This makes it impossible to reliably assess the variability of the concentrations of this component in spatial terms, so the data analysis was limited to examining the empirical distribution and tracing time trends in the Polish part of the area. The empirical distribution of nitrate concentrations is clearly skewed and has been logarithmically normalized (Figure 30). On this basis, a typical range of variability was determined, which also determined the background range from 0.57 to 6.76 mg/L. Clear temporal trends were recorded in 5 out of 15 measurement points included in the Polish groundwater monitoring network. In the case of points numbered II/514/1, II/338/1, II/1518/1 and II/1520/1, these were increasing trends (Figure 322, Figure 33, Figure 344, Figure 355), and in the case of the last two points the series do not include first decade of this century. A different situation was noted at point number II/516/1, where, after a clear downward trend in the first decade of the century, the concentrations stabilized (Figure 31).

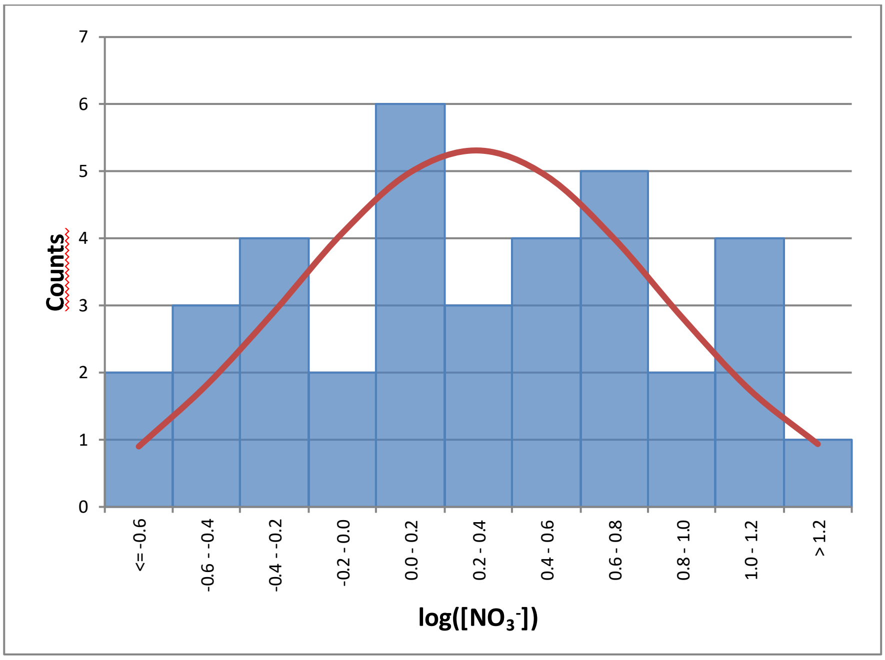


Figure 30. Logarithmically adjusted empirical distribution of nitrate concentrations in groundwater (N = 36)

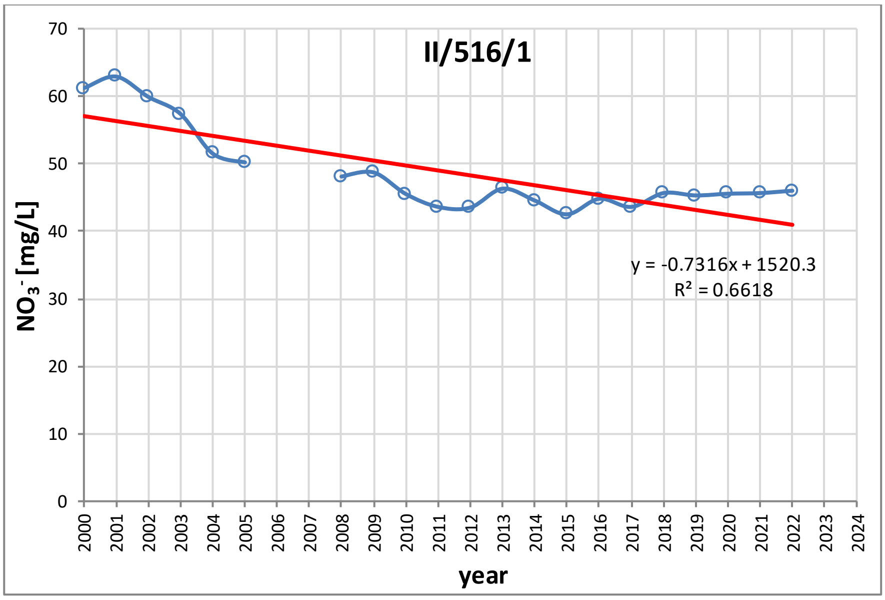


Figure 31. Changes over time in the concentration of nitrates in water taken into monitoring network point No. II/516/1

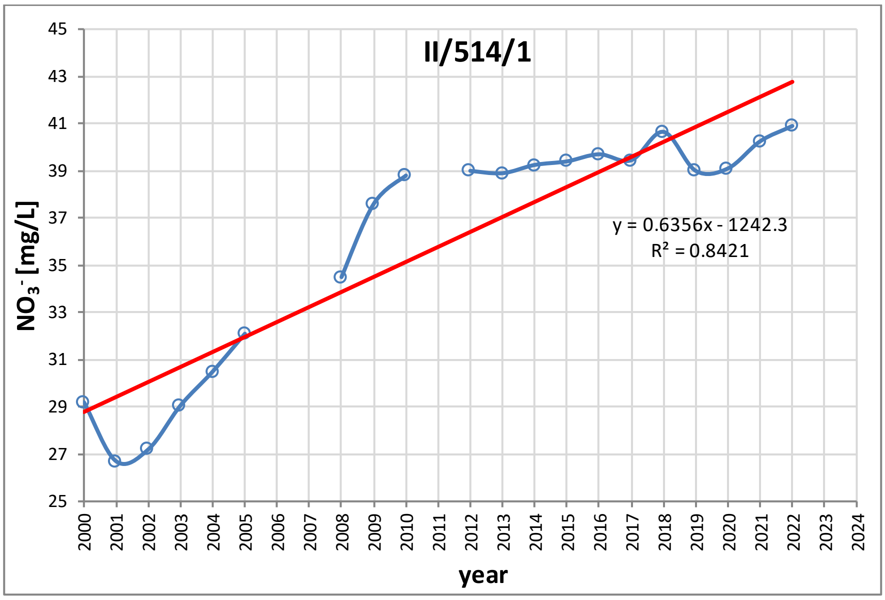


Figure 32. Changes over time in the concentration of nitrates in water taken into monitoring network point No. II/514/1

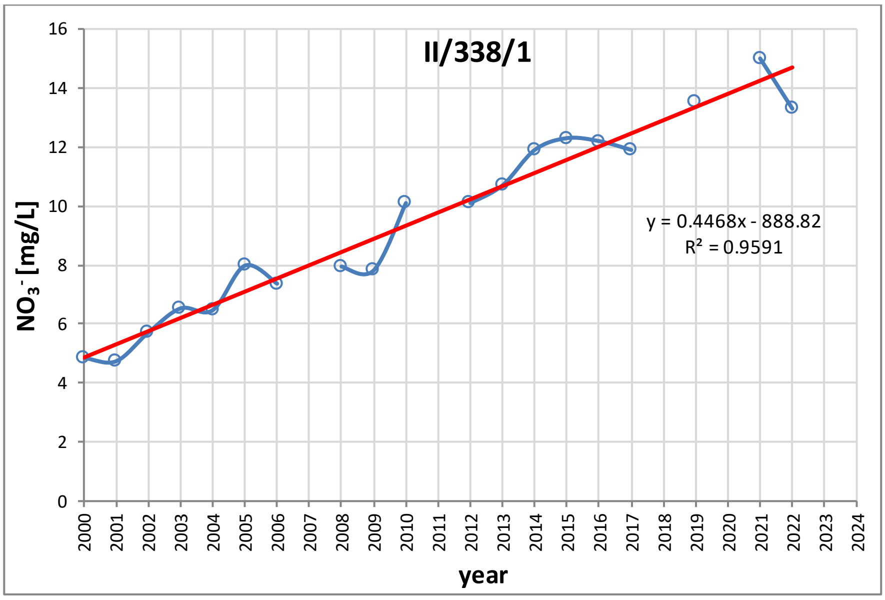


Figure 33. Changes over time in the concentration of nitrates in water taken into monitoring network point No. II/338/1

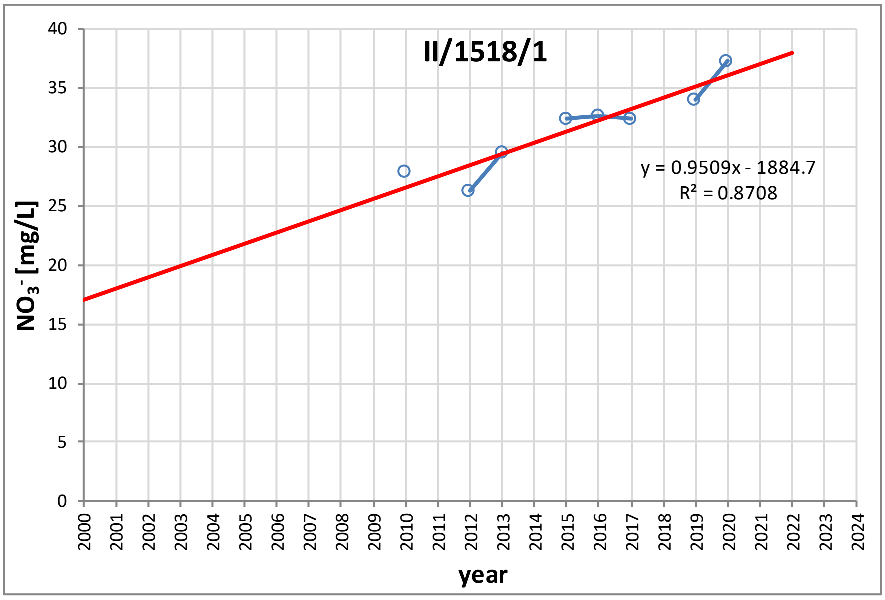


Figure 34. Changes over time in the concentration of nitrates in water taken into monitoring network point No. II/1518/1

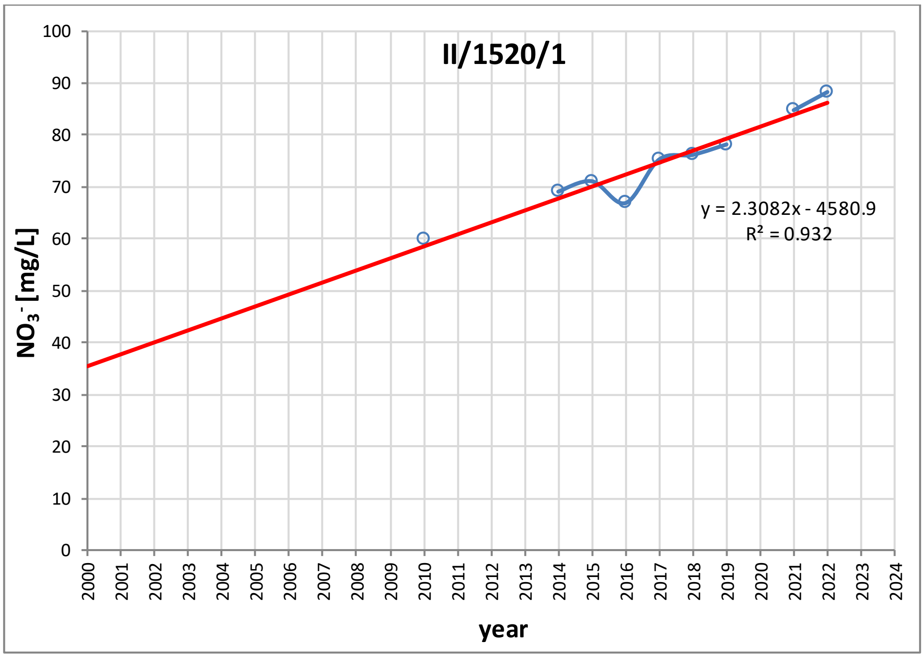


Figure 35. Changes over time in the concentration of nitrates in water taken into monitoring network point No. II/1520/1

Calcium

To assess the distribution of calcium ion concentrations, the results of laboratory determinations of groundwater samples obtained from 239 measurement points were used. The empirical distribution of Ca^{2+} concentrations is unimodal and close to normal (Figure 36). The average value of the concentration of this ion was 112.9 mg/L, with a standard deviation of 65.5 mg/L. The limits of the typical variability range can be located at a distance of one standard deviation from the expected value, which means that the hydrogeochemical background range is 47 - 178 mg/L (Table 6). The spatial distribution of calcium concentrations is closely related to the geogenic factor. The highest concentrations are recorded in the zones of the Cretaceous aquifer, where the carbonate medium dominates (Figure 37). High calcium concentrations are also recorded in water taken from Neogene formations. The lowest concentrations were observed in water drawn from valley units filled with Quaternary sand and gravel alluvia (Figure 38, Table 6). The calcium content in groundwater is also influenced by anthropopressure, which is confirmed by the spatial distribution of positive anomalies in the concentration of this component, which are concentrated primarily in the area of the Lviv agglomeration.

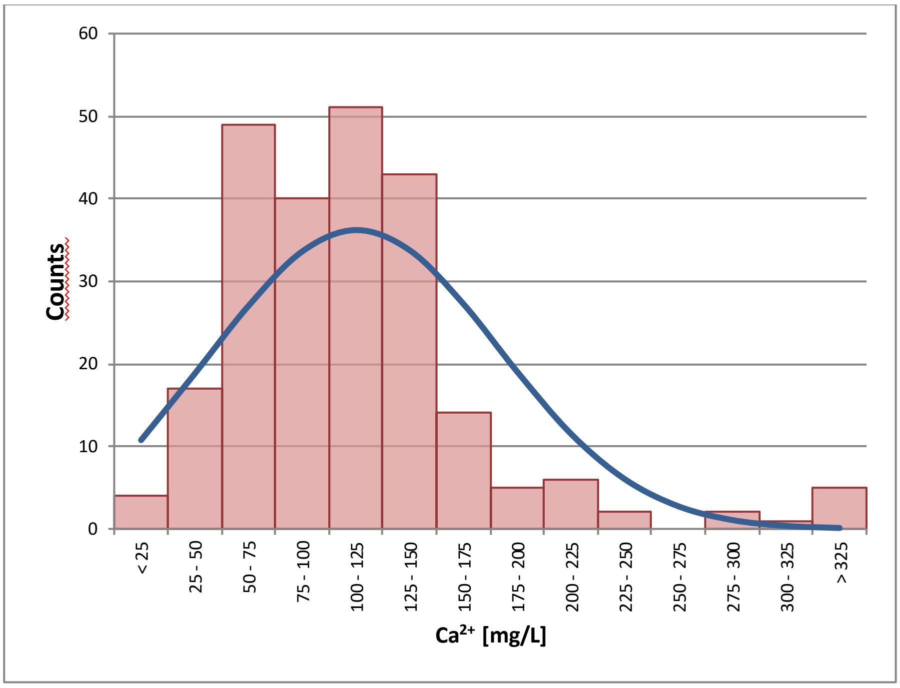


Figure 36. Empirical distribution of calcium concentration in groundwater (N = 239)

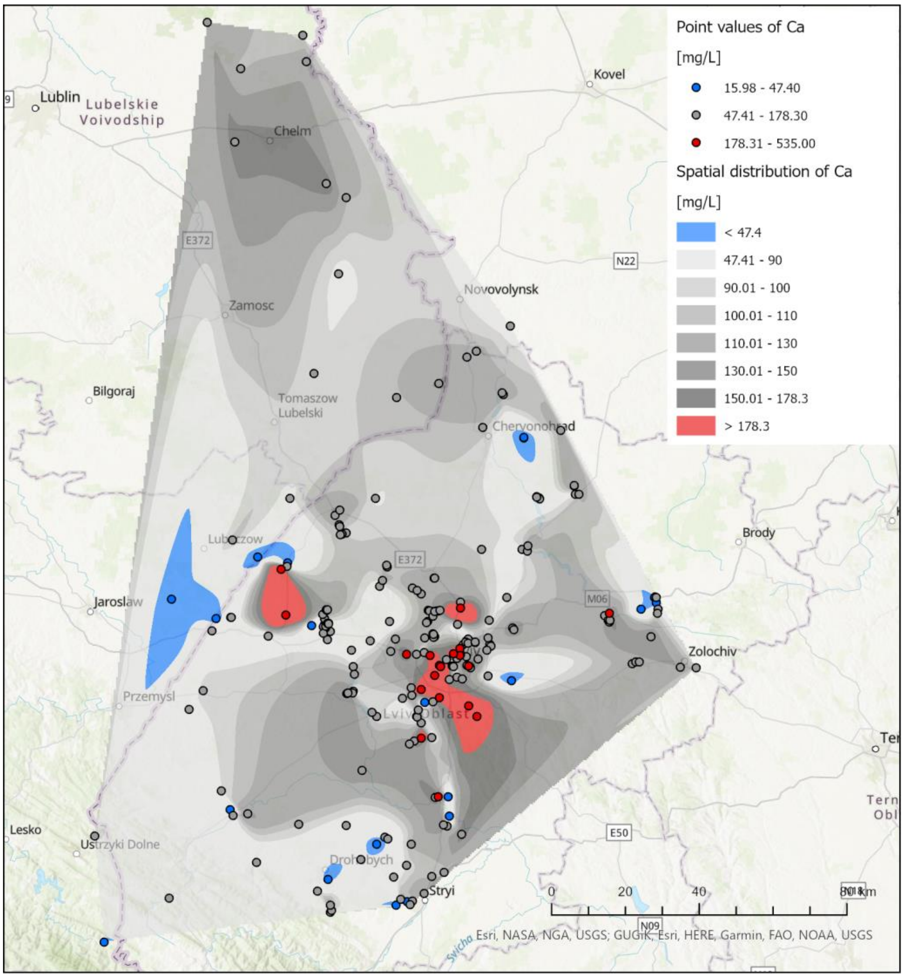


Figure 37. The occurrence of positive (red) and negative (blue) anomalies in calcium concentration against the background of the spatial trend

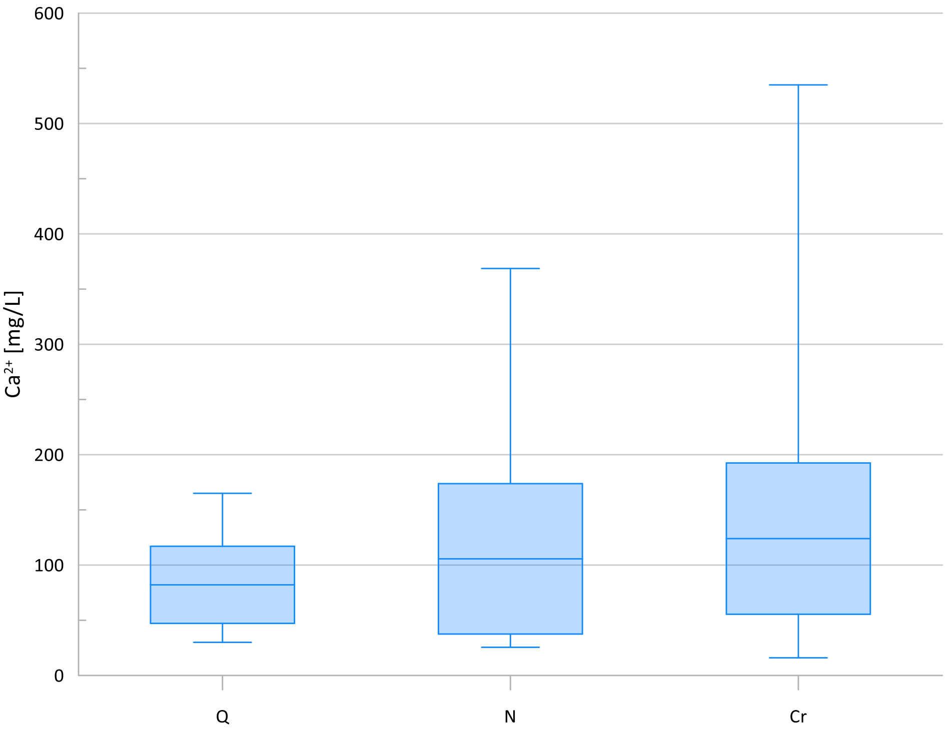


Figure 38. Comparison of empirical distributions of calcium concentration in groundwater drawn from the Quaternary (Q), Neogene (N) and Cretaceous (Cr) levels
(mean values, a range of one standard deviation around the expected value, and extreme values are plotted on a box-and-whiskers chart).

Table 6. Average calcium concentrations and the range of hydrochemical background in the distribution of aquifers

Aquifer	Mean [mg/L]	Lower background range [mg/L]	Upper background range [mg/L]
Quaternary	82	48	117
Neogene	106	38	173
Cretaceous	124	56	192

Clear time trends relating to the concentration of the calcium ion were recorded at four research points on the Polish side (Figure 39, Figure 40, Figure 41, Figure 42), in two it was increasing (II/514/1, II/1520/1) and in two it was decreasing (II/516/1, II/337/1). In the first case, changes in the concentrations of the described component may result from anthropopressure, while the decrease in concentrations may be caused by ion exchange processes or changes in the solubility of calcite resulting from the partial pressure of carbon dioxide.

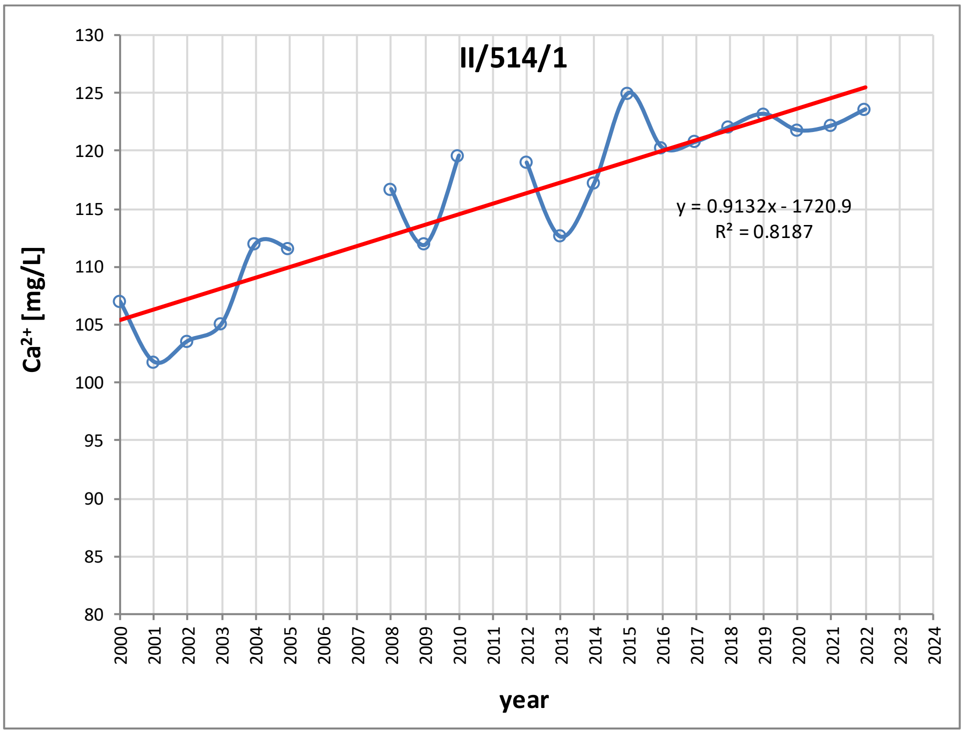


Figure 39. Changes over time in the concentration of calcium in water taken into monitoring network point No. II/514/1

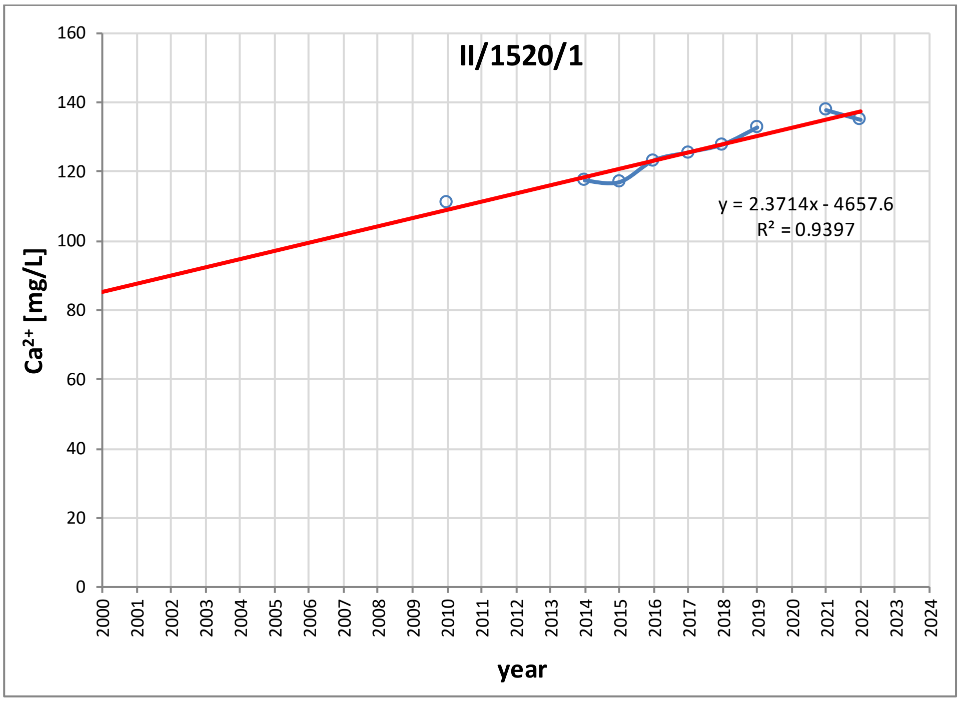


Figure 40. Changes over time in calcium concentration in water taken in monitoring network point No. II/1520/1

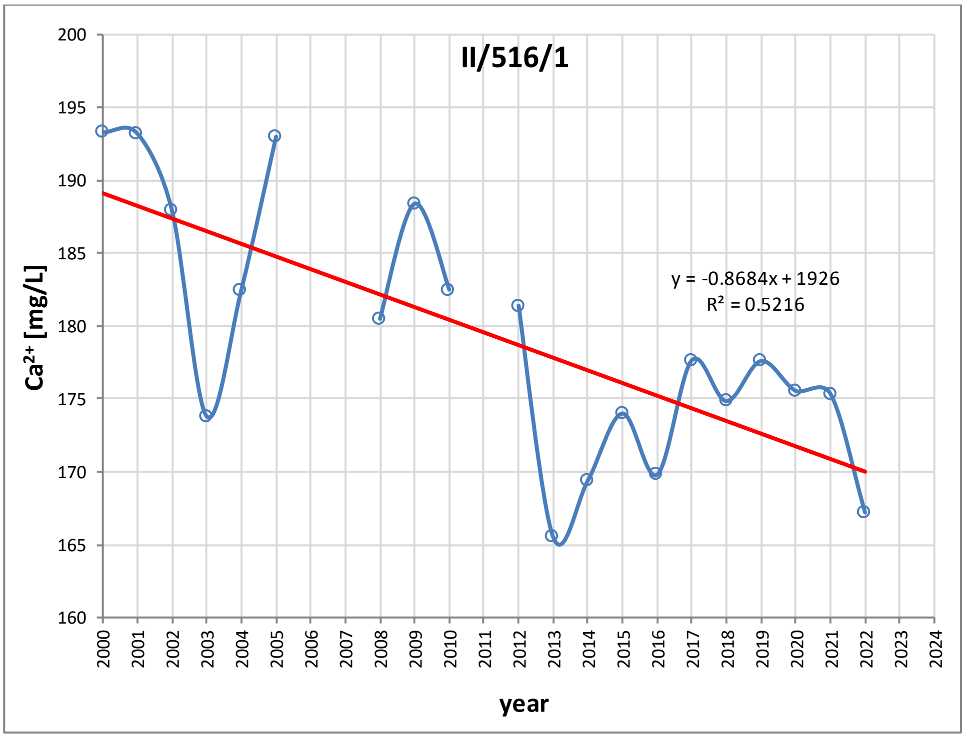


Figure 41.Changes over time in the concentration of calcium in water taken into monitoring network point No. II/516/1

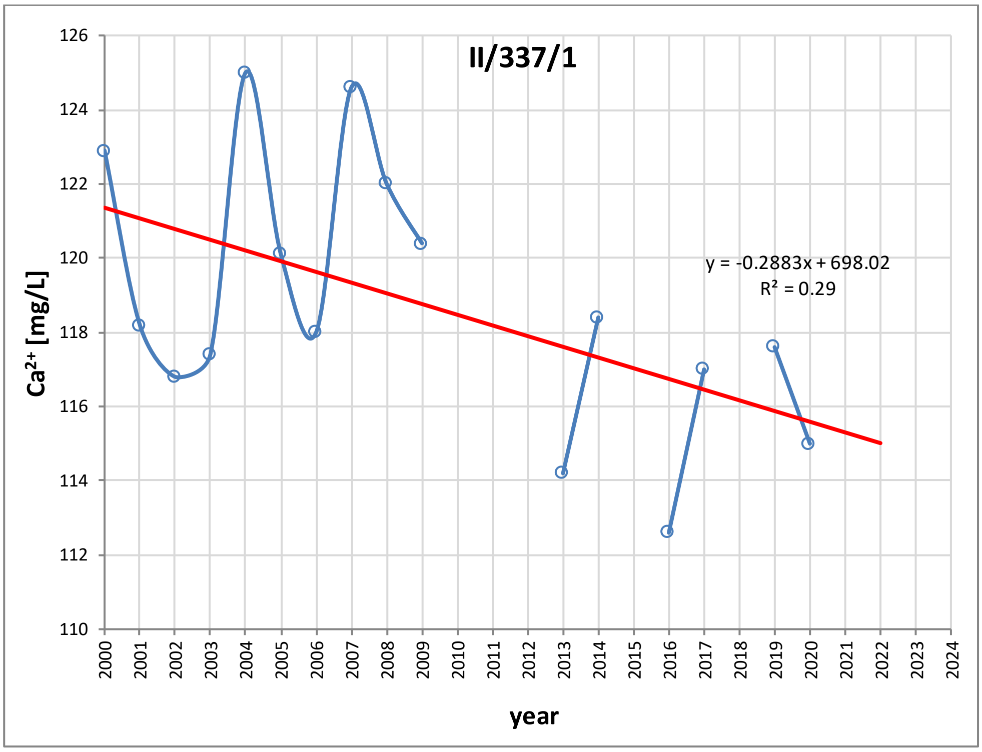


Figure 42. Changes over time in the concentration of calcium in water taken into monitoring network point No. II/337/1

Magnesium

The empirical distribution of magnesium ion concentrations obtained on the basis of the determination results in 237 groundwater samples is unimodal, with a clear negative skewness (Figure 43). Measures of the central tendency of the set expressed using the arithmetic mean and median are 18.6 and 15.8 mg/L, respectively, which results from the skewness of the distribution. At the same time, the data are characterized by dispersion, which can be described by a standard deviation value of 15.8 mg/L. The limits of the typical range of bicarbonate concentration variability were determined at a distance of one standard deviation around the arithmetic mean and have values of 3 and 34 mg/L. As in the case of calcium ions, high concentrations of magnesium are concentrated primarily in water drawn from the Cretaceous and Neogene reservoirs (Figure 444). This is confirmed by both the average values and the upper limits of the hydrogeochemical background determined independently for the subpopulations of results representing individual aquifers (Figure 455, Table 7). The analysis of time trends at points in the monitoring network allowed the identification of two points where a significant time trend was recorded. In the case of both point II/514/1 (Figure 46) and point II/598/1 (Figure 477) there was an upward trend, but in the case of the latter a shorter time series was available.

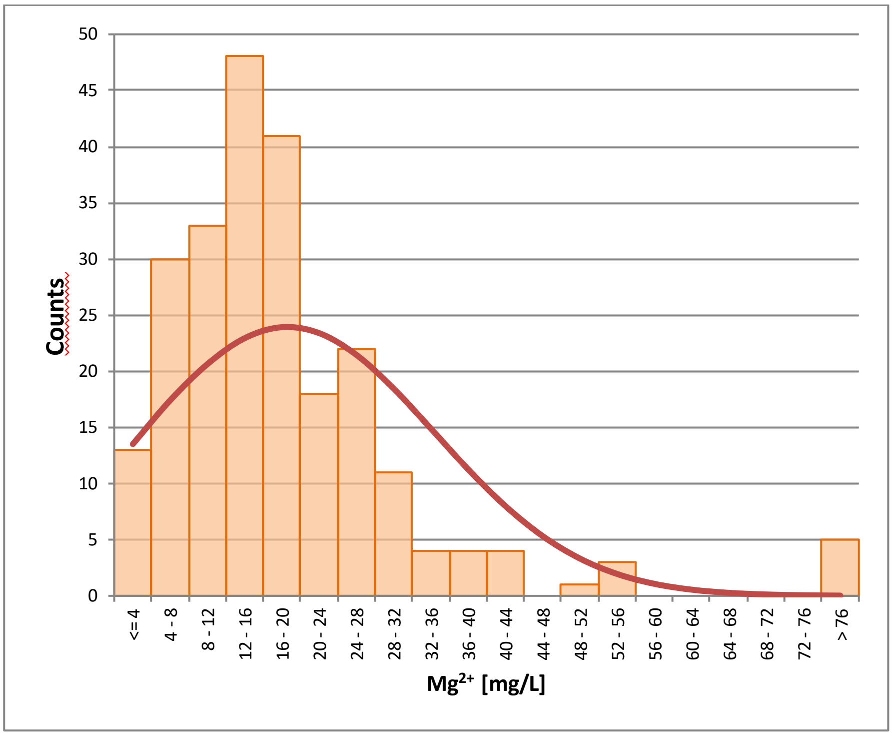


Figure 43. Empirical distribution of magnesium concentration in groundwater (N = 237)

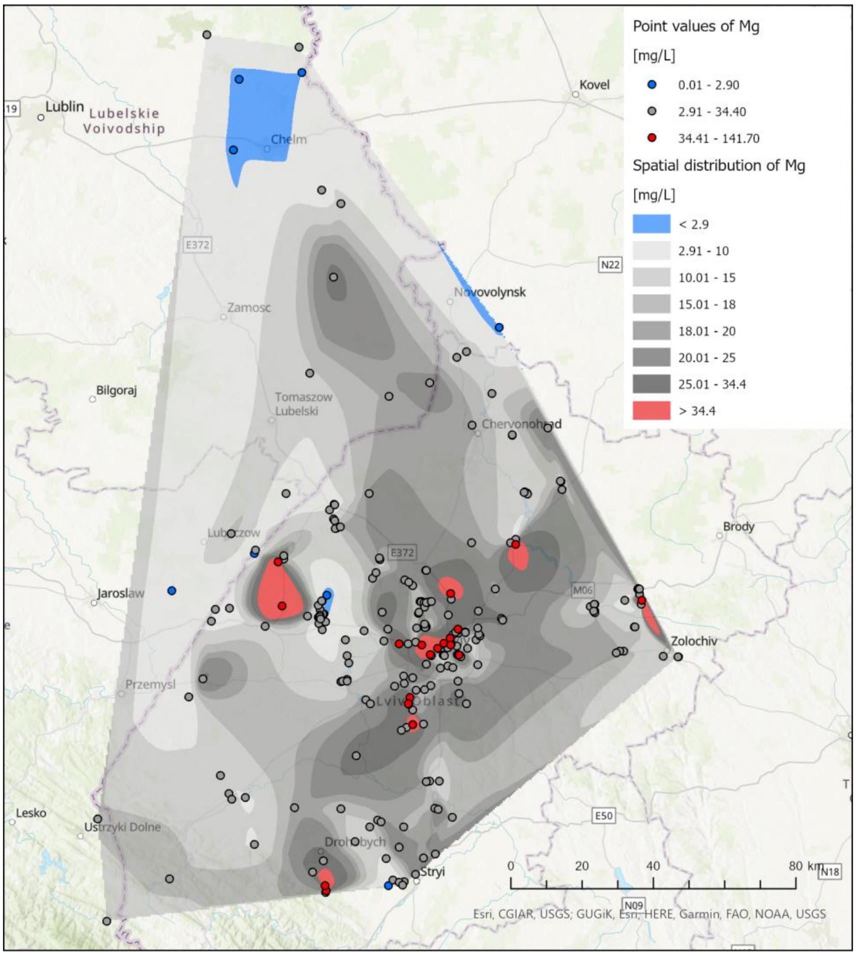


Figure 44. Occurrence of positive (red) and negative (blue) anomalies in magnesium concentration against the background of the spatial trend

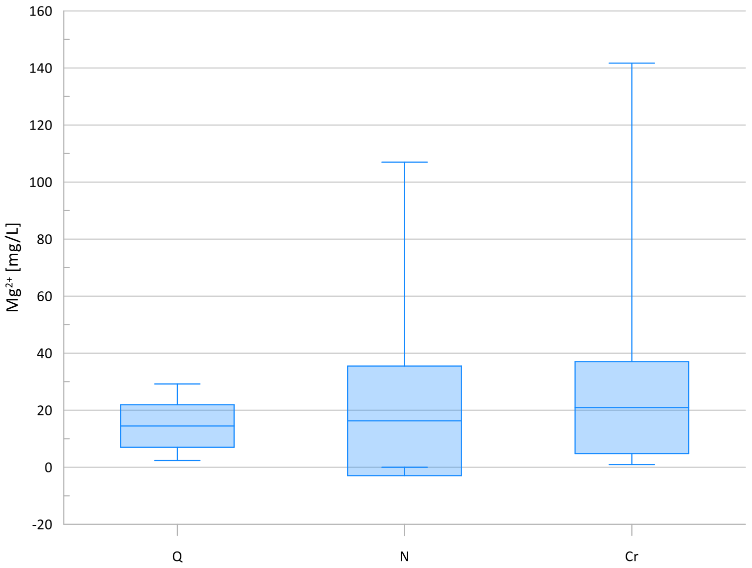


Figure 45. Comparison of empirical distributions of magnesium concentration in groundwater drawn from the Quaternary (Q), Neogene (N) and Cretaceous (Cr) levels
(mean values, a range of one standard deviation around the expected value, and extreme values are plotted on a box-and-whiskers chart).

Table 7. Average calcium concentrations and the range of hydrochemical background in the distribution of aquifers

Aquifer	Mean [mg/L]	Lower background range [mg/L]	Upper background range [mg/L]
Quaternary	14	7	22
Neogene	16	0	35
Cretaceous	21	5	37

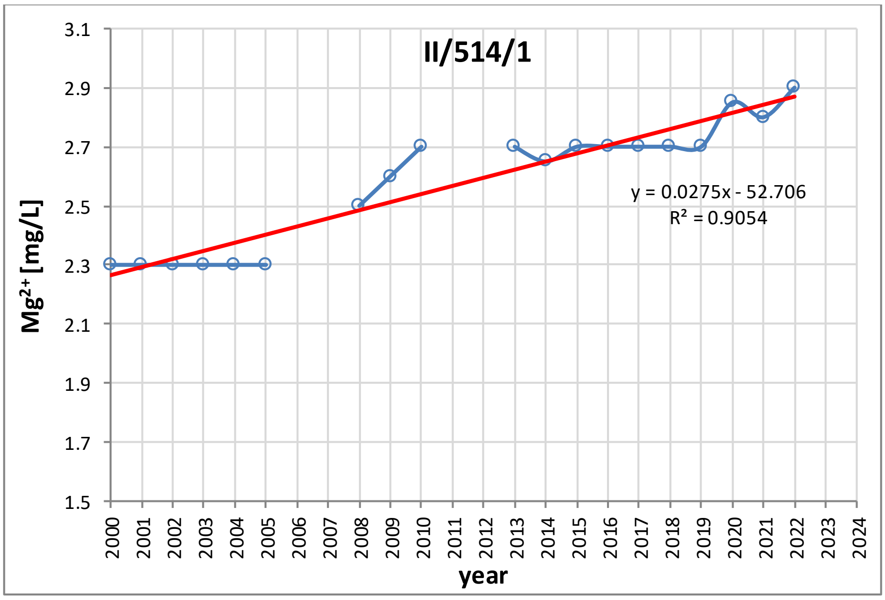


Figure 46. Changes over time in the concentration of magnesium in water taken at monitoring network point No. II/514/1

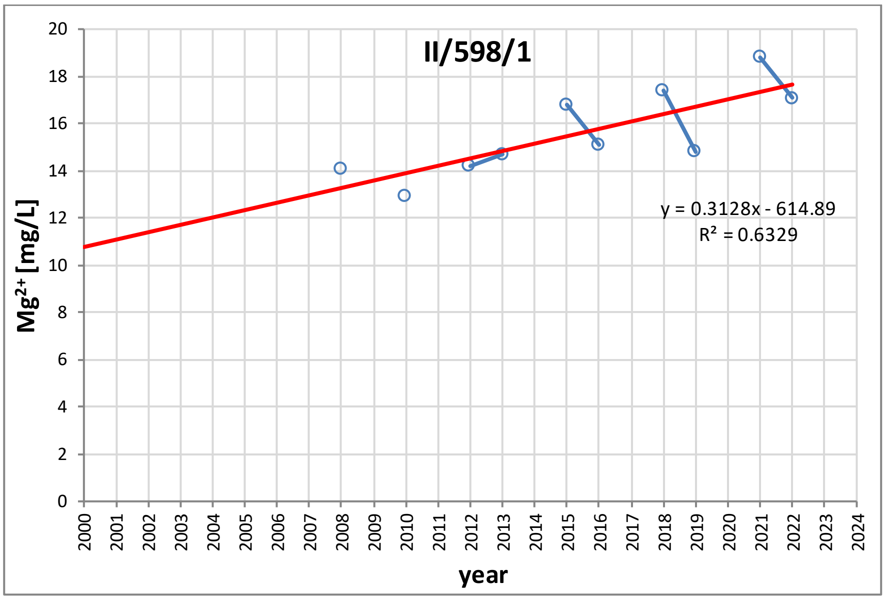


Figure 47. Changes over time in the concentration of magnesium in water taken into monitoring network point No. II/598/1

Sodium and potassium

Since most of the data obtained from the Ukrainian side only included the results of determining the sum of sodium and potassium, these components will be described together. The distribution of the sum of Na^+ and K^+ ion concentrations was analysed based on the results of determinations in water obtained from 224 measurement points. As in the case of sulphate and chloride concentrations, the empirical distribution is clearly asymmetric, with a marked negative skewness, which is why it was decided to logarithmically equalize the normal distribution (Figure 48). On this basis, the hydrochemical background range was determined to be 10 – 94 mg/L. The spatial distribution of the sum of sodium and potassium concentrations was obtained using the Spline method (Figure 49). As in the case of SO_4^{2-} and Cl^- ions, there is also a clear contrast between the Polish and Ukrainian parts for the total content of Na^+ and K^+ ions. Again, all positive anomalies occur on the Ukrainian side, while on the Polish side the concentrations are much lower. The observed spatial differentiation can be interpreted analogously to the previously discussed components. The spatial variability is determined primarily by the different method of development and land cover on both sides of the border, provided that the resulting image may be distorted by the way the measurement network is organized in Poland and Ukraine. The geogenic factor plays an important role in shaping the concentration field of the described components. The empirical distributions of the sum of sodium and potassium concentrations in water taken from the Cretaceous zone indicate higher ranges of values than in the case of the Neogene and Quaternary zones (Figure 50).

On the Polish side of the border, no clear time trends were noted for most research points. The exception is point II/514/1, where both sodium and potassium concentrations show a clear increasing trend (Figure 51, Figure 53). An increasing trend for sodium was also noted in point II/518/1, but in this case, due to the incompleteness of the time series, seasonal changes cannot be ruled out (Figure 52). A similar situation applies to the increasing trend in potassium concentrations recorded in point II/598/1 (Figure 54).

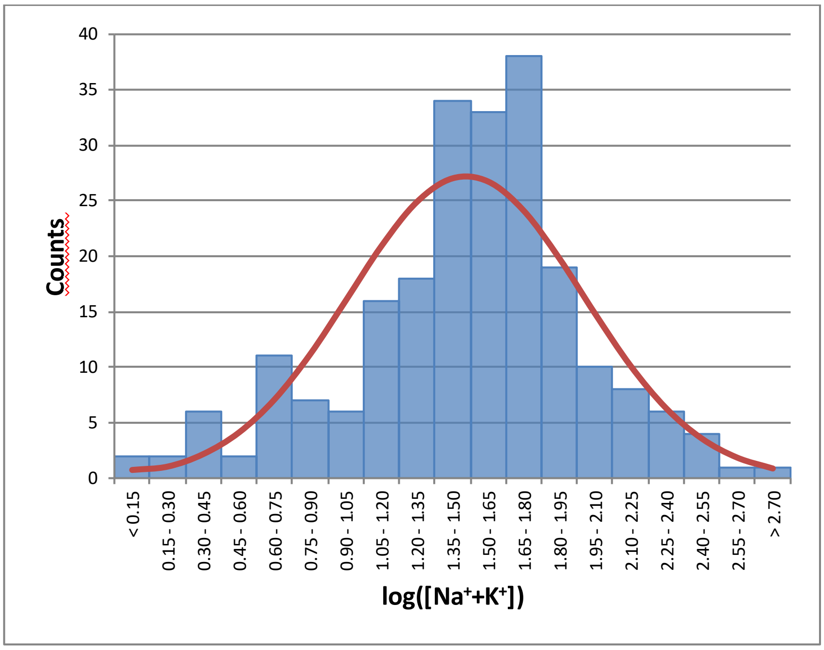


Figure 48. Logarithmically adjusted empirical distribution of the sum of sodium and potassium concentrations in groundwater (N = 224)

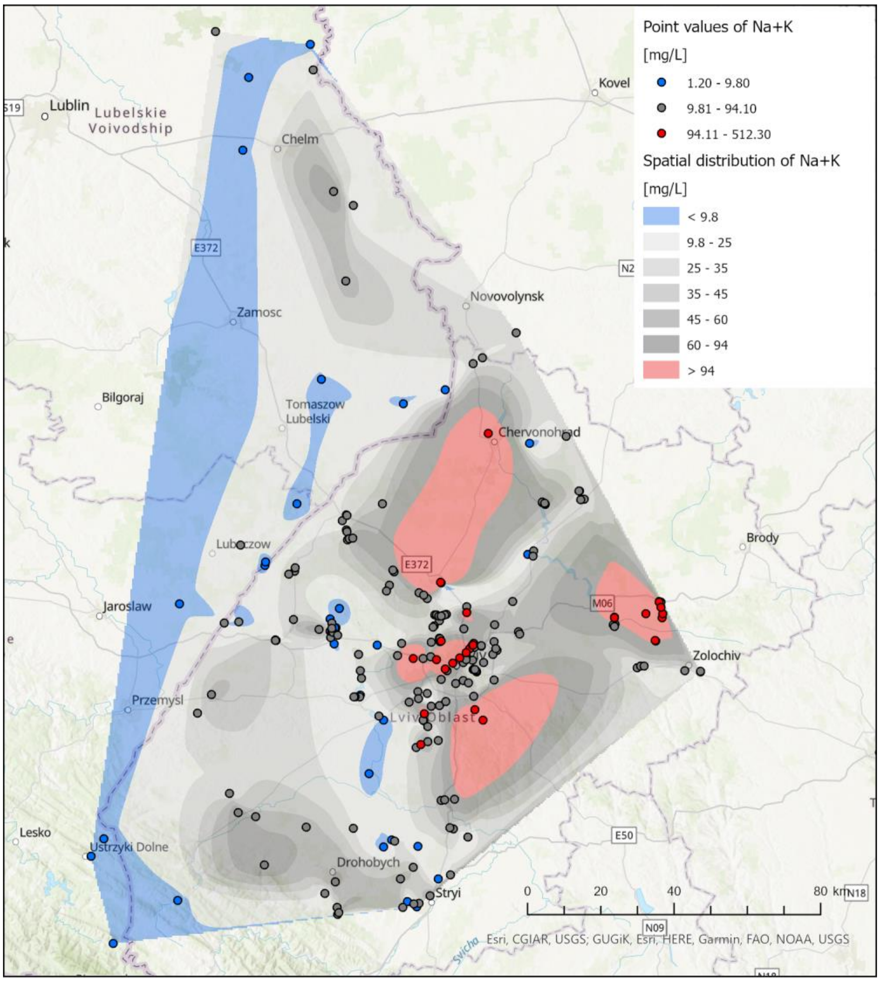


Figure 49. Occurrence of positive (red) and negative (blue) anomalies in the sum of sodium and potassium concentrations against the background of the spatial trend

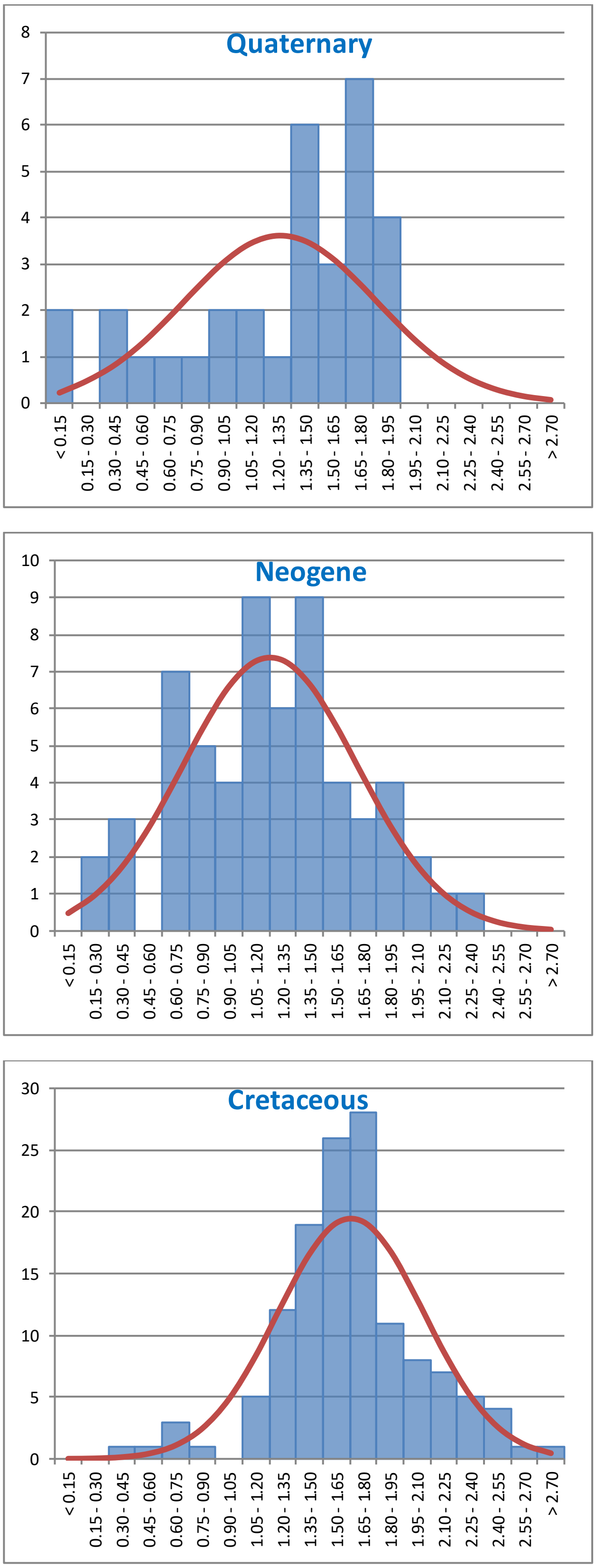


Figure 50. Comparison of logarithmically equalized empirical distributions of the sum of sodium and potassium concentrations in groundwater taken from the Quaternary (N = 32), Neogene (N = 60) and Cretaceous (N = 133) beds

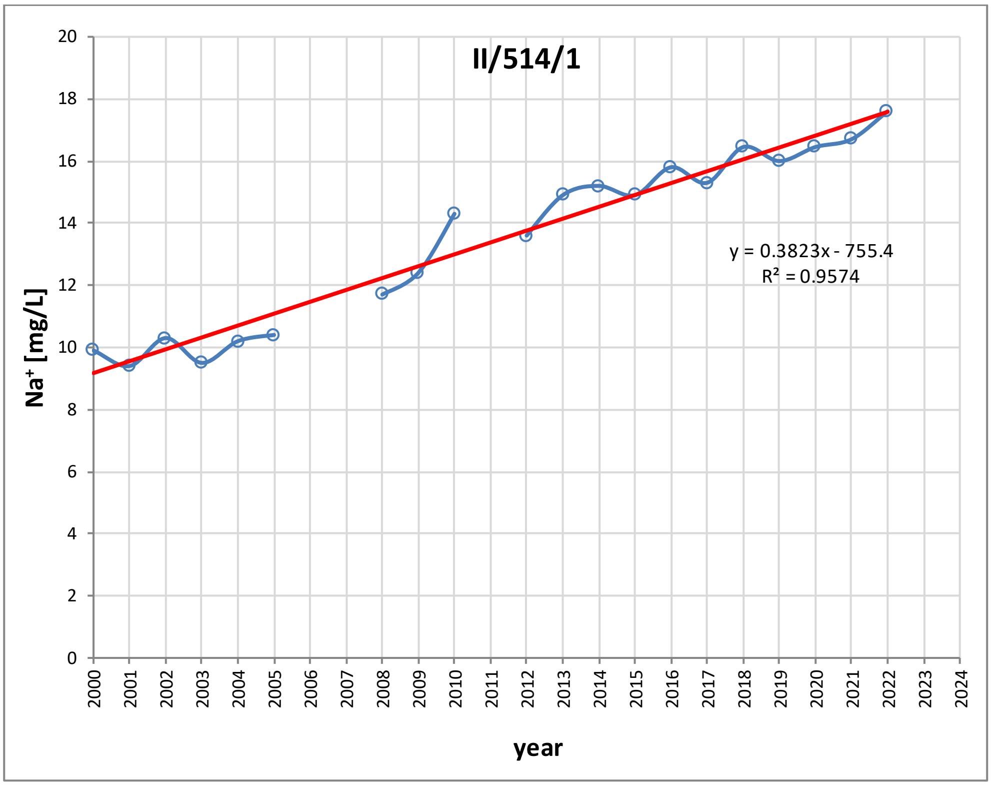


Figure 51. Changes over time in sodium concentration in water taken in monitoring network point No. II/514/1

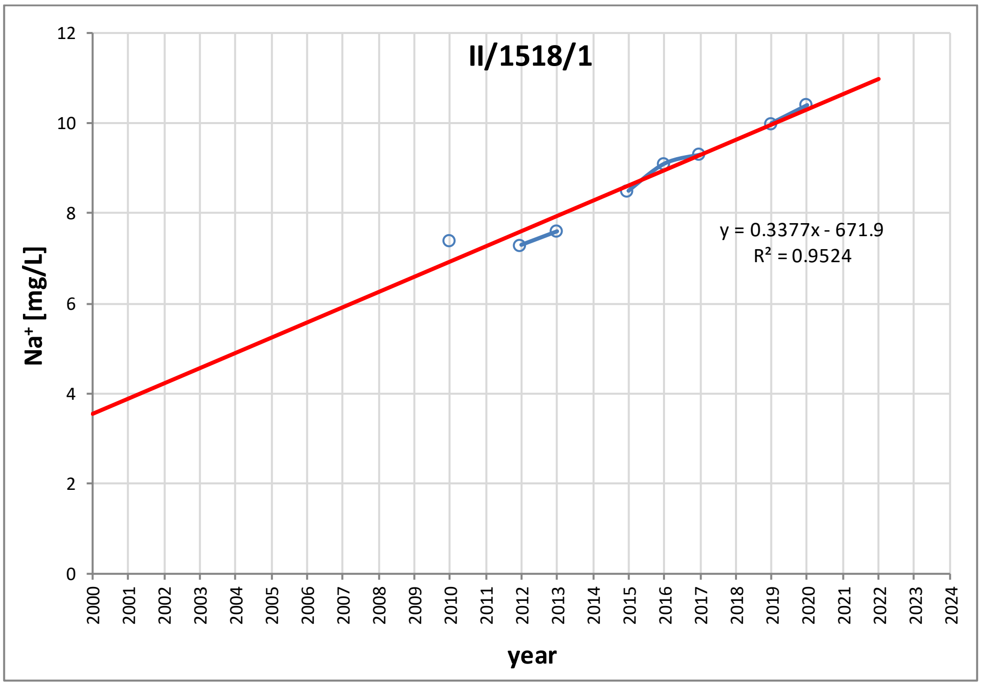


Figure 52. Changes over time in sodium concentration in water taken in monitoring network point No. II/1518/1

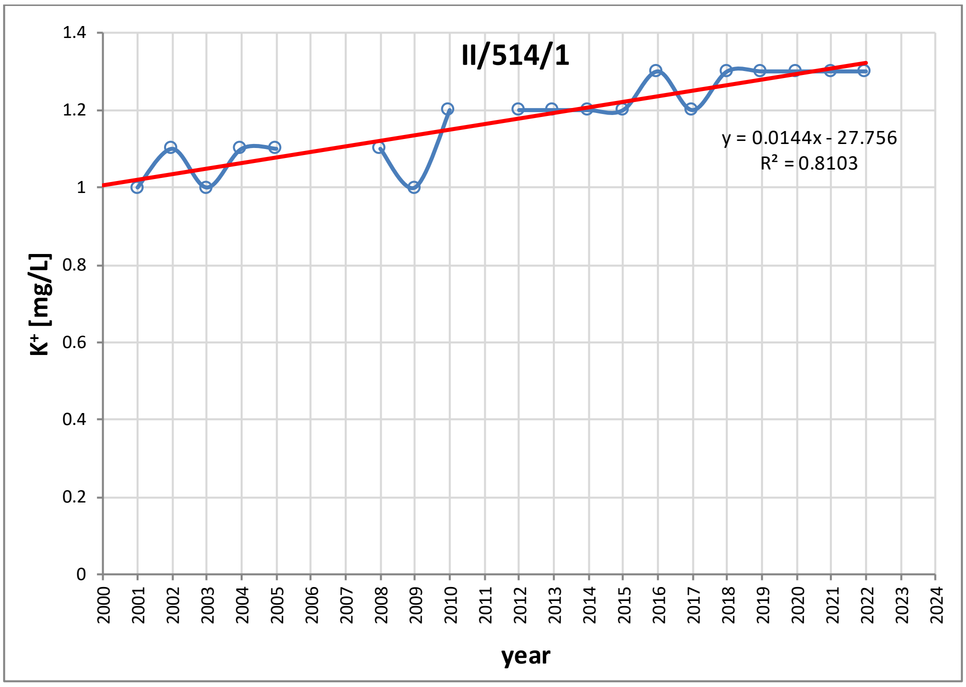


Figure 53. Changes over time in potassium concentration in water taken in monitoring network point No. II/514/1

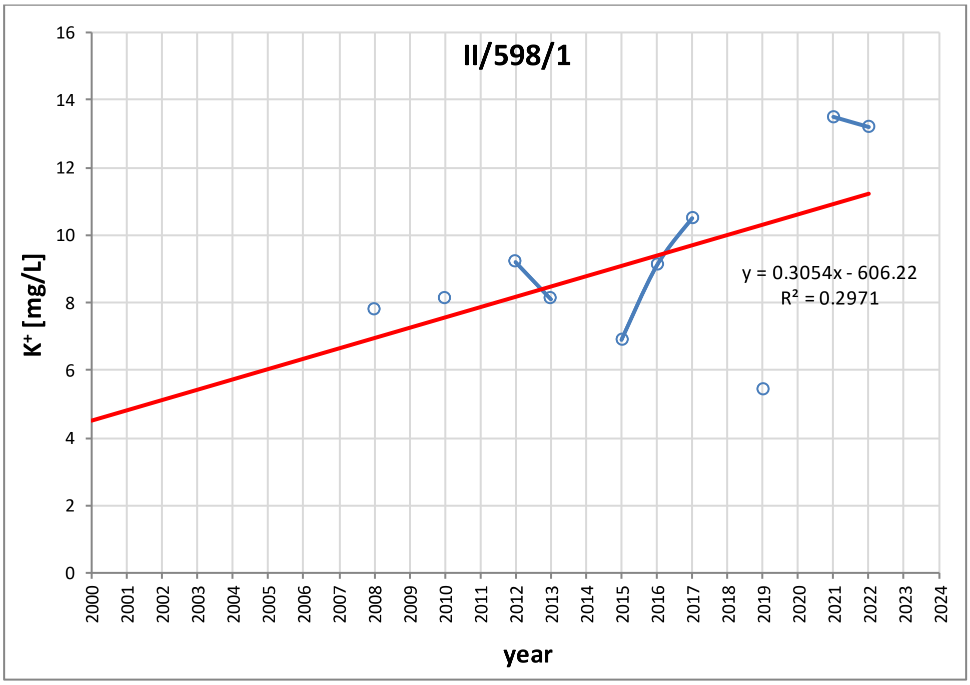


Figure 54. Changes over time in potassium concentration in water taken in monitoring network point No. II/598/1

The presented method of identifying hotspots using the analysis of positive hydrogeochemical anomalies shows adequate effectiveness using some of the analyzed chemical indicators - sulphates, chlorides and sodium. For the remaining indicators - bicarbonates, calcium and magnesium, the poor usefulness in determining hotspots is related to the blurred effect of anthropopressure due to the important role in shaping the field of their concentrations of the geogenic factor - the geochemical composition of the rock medium of aquifers. Areas with positive anomalies of sulphates, chlorides and sodium indicate hotspots where the pressure caused by groundwater pollution manifests itself not only as a threat, but is a fact realized and registered in changes in water chemistry. These areas are mainly located on the Ukrainian side, because on this side of the research area there are large urban centers that do not exist in the part of the Polish border covered by the research or were not covered by the research (a much sparser measurement network). It can be concluded that the spread of areas at increased risk of groundwater contamination is directly related to the method of development and land cover. These areas are located in the vicinity of urban centers, in particular the Lviv agglomeration, and within unreclaimed sulfur and hard coal mining areas. A detailed list of areas is provided in Table 8.

Table 8. List of localities within areas with anthropogenically changed chemical composition of groundwater TAS

Area of anomalous concentrations of chemical indicators of anthropogenic origin	Range	Name of the town
Chloride anomalies	Transboundary	Poland: Horodyszcze, Sulimów, Chochłów. Ukraine: Variazh, Rusyn, Leshkiv, Verbove, Tsebliv, Sebechiv, Murovanne, Vaniv, Hlukhiv, Ostriv, Chervonohrad, Berezhne, Boriatyn, Rudka, Dobriachyn, Bendiuha
	Transboundary	Ukraine: Hrushiv, Nemyriv, Shcheploty, Kolonytsi, Drohomyshl, Zavadiv, Verbliany, Kalytiaki, Horaiets, Poruby, Lypyna, Datski, Khliany, Debri, Koty, Semyrivka, Nahachiv, Chernyliava, Lisok, Stary Yar, Zaluzhzhia
	Regional, national	Ukraine: Zavady, Volia-Vysotska, Hlynsk, Stara Skvariava, Zhovkva, Soposhyn, Matsoshyn, Chystopillia, Blyshchyvody, Zibolky, Hory, Stavnyky, Artasiv, Nahirtsi, Mohyliany, Smerekiv, Peremyvky, Mervychi, Kosteiv, Kulykiv, Hrebintsi, Nove Selo, Vidniv, Sulymiv, Zvertiv
	Regional, national	Ukraine: Pobuzhany, Yablunivka, Novy Ripniv, Rakobovty, Lanerivka, Rokytne, Verbliany, Kupche, Busk, Chuchmany, Humnyska, Kizliv, Zhuratyn, Storonybaby, Utishkiv, Krasne, Petrychi
	Regional, national	Ukraine: Lviv, Riasne-Ruske, Pidriasne, Kozhychi, Zeliv, Domazhyr, Karachyniv, Vorotsiv, Mshana, Rudne, Zymnz Voda, Konopnytsia, Bartativ, Lapaivka
	Regional, national	Ukraine: Zhyrivka, Koviary, Lypnyky, Zagiria
	Regional, national	Ukraine: Velyky Liubin, Maly Liubin
	Regional, national	Ukraine: Truskavets, Stanylia
	Regional, national	Ukraine: Stryi, Dibrova, Dobrivliany, Dobriany
Sodium anomalies	Transboundary	Ukraine: Chervonohrad, Velyke, Dobriachyn, Rudka, Boriatyn, Berezhne, Murovanne, Ostriv, Bendiuha, Hlukhiv, Vaniv, Hirnyk, Mezhyrichchia, Volsvyn, Pozdymyr, Horodyshche, Silets, Sosnivks, Kulychkiv, Borove, Velyki Mosty, Prystan, Butyny, Shyshaky, Dvirtsi, Zarika, Reklynets, Stremin, Pyriatyn, Kazumin Liubelia, Sosnyna, Zalozy, Byshkiv, Besidy, Bobroidy, Halasi, Soroky, Shkoliari, Dibrova, Kuliava, Derevnia, Dobrosyn, Pyly, Pidderevenka, Zamochok, Kachmari, Zaryshche, Hrynchuki, Zavady, Vola-Vysotska, Hlynsl Zhovkva, Borovi, Viazova, Oplitna, Chystopillia, Turynka, Sarnivka, Lisove, Vereny, Blyshchyvody, Soposhyn, Stara Skvariava, Vidrodzhennia
	Regional, national	Ukraine: Zavodske, Pidstavky, Bolozhyniv, Zabolotne, Verbliany, Rokytne, Busk, Chuchmany, Humnyska, Yanhelivka, Ozhydiv, Pidlyssia, Voluiky, Havarechchyna, Bilyi Kamin, Buzhok, Cheremoshnia,Pochapy, Honcharivka, Rozvazh,

		Petrychi, Utishkiv, Storonybaby
	Regional, national	Ukraine: Lviv, Malyniaky, Malekhiv, Soroky-Lvivski, Riasne-Ruske, Pidriasne, Kozhychi, Karachyniv, Vorotsiv, Palanky, Rudne, Zymna Voda, Lapaivka, Konopnytsia
	Regional, national	Ukraine: Tarasivka, Pecheniia, Kurovychi, Turkotyn, Solova, Mykolaiv, Horodyslavychi, Chyzhykiv, Hai, Hlukhovychi, Zvenyhorod, Kotsuriv, Pidiarkiv, Romaniv, Selytska, Pidhorodyshche, Hryniv, Mostyshche, Vidnyky, Stare Selo, Sholomyn, Honchary, Dmytrovychi, Davydiv, Cherepyn, Budkiv, Pidmonastyr, Shpylchyna, Volove, Bobrka, Voloshchyna, Velyki Hlibovychi, Vilkhovets, Lopushna Selysko, Tovshchyv, Myliatychi, Zhyrivka, Zahiria, Kuhaiv, Pidtemne, Rakovets, Novosilka, Krasiv, Brodki, Poliana, Sukhodil, Berezyna, Hlukhivets, Mala Volia, Velyka Volia, Stilsko, Trostianets
Sulphate anomalies	Transboundary	Ukraine: Stary Yar, Zaluzhzhia
	Regional, national	Ukraine: Chervonbohrad, Ostriv, Rudka
	Regional, national	Ukraine: Halasi, Shkoliari, Soroky, Dibrova, Kuliava, Dobrosyn, Kachmari, Zaryshche, Pyly, Pidderevenka, Zamochok, Borovi, Viazova, Turynka, Bir Kunynski, Hrynchuki, Zavady, Volia-Vysotska, Oplitna, Chystopillia, Soposhyn, Zhovkva, Stara Skvariava, Nova Skvariava, Skvariava, Hlynsk
	Regional, national	Ukraine: Kosteiv, Kulykiv, Zashkiv, Velyky Doroshiv, Maly Doroshiv, Kosheliv, Sytykhiv, Stroniatyn, Nove Selo, Vidniv, Hrebintsi, Nadychi
	Regional, national	Ukraine: Chuchmany, Humnyska, Busk, Storonybaby, Krasne, Utishkiv, Petrychi
	Regional, national	Ukraine: Lviv, Malekhiv, Riasne-Ruske, Pidriasne, Kozhychi, Zeliv, Domazhyr, Karachyniv, Vorotsiv, Malchytsi, Mshana, Palanky, Rudne, Zymna Voda, Konopnytsia, Bartativ, Obroshyne, Basivka, Sknyliv, Hlynna, Sokilnyky, Zubra, Horishni, Pasiky-Zubrytski, Berezhany, Volytsia, Vynnychki, Dmytrovychy, Honchary, Davydiv, Krotoshyn, Zhyrivka, Myliatychi, Tovshchiv, Cherepyn, Sholomyn, Zvenyhorod, Hlukhovychi, Hai, Horodyslavychi, Kotsuriv, Hryniv, Mostyshche, Volove, Shpylchyna, Pidmonastyr, Vidnyky, Stare Selo, Budkiv, Selysko, Lopushna, Vilkhovets, Voloshchyna, Velyki Hlibovychi, Sukhodil, Malechkovychi, Nahoriany, Porshna, Koviari, Lypnyky Zahiria, Kuhaiv, Berehy, Viniavy, Derevach, Pidtemnr, Rakovets, Khorosno, Novosilky, Krasiv, Brodky, Lypivka, Dobriany, Ternopillia, Pisky, Semenivka, Shchyrets, Odynoke, Nykonkovychi, Sokolivka, Soroky, Humenets, Lany, Popeliany, Dmytre, Lypivka Brodky, Poliana, Hlukhivets, Mala Vola, Trostianets, Velyka Volia, Stilsko

Identification of the extent of groundwater occurrence in the TAS aquifer with reduced water quality (hotspots) allows for the identification of areas requiring immediate attention. These include areas with identified cross-border anomalies. In addition, areas that have been recognized as having national hotspots should also be taken into account in joint groundwater protection programs, as transboundary migration of pollutants here does not occur directly with groundwater as in the above case, but through the river network.

4. Identification of areas at risk of a deficit of groundwater resources within the Polish-Ukrainian Transboundary Aquifer System

The volume of groundwater resources is influenced by two key groups of factors:

- hydrogeological conditions of the considered system,
- natural and environmental constraints determining what part of the waters in the system in question may constitute resources. This group includes all administrative decisions regarding various protection zones, in particular those that directly translate into restrictions on changes in hydrogeological conditions, for example limiting the lowering of the water table..

Resources are a function of hydrogeological conditions and any change in conditions results in a change in resources. When considering the issue of the impact of changes in hydrogeological conditions on changes in resources, it should be emphasized that not all good quality water contained in the underground circulation in the system under consideration constitutes resources. Contrary to the hydrological concept, in hydrogeology it is only that part of groundwater that can be exploited without violating specific environmental constraints. Not only a change in hydrogeological conditions, but also a change in the limiting criteria expressing the requirements for environmental protection may significantly affect the change in groundwater resources. The ratio of water constituting groundwater resources to the total amount of water in a given hydrogeological system depends on the criteria limiting these resources. For example, establishing a protected area in the immediate vicinity of the system entails imposing a strict limit on the amount of groundwater level decline within the area, and often also in its vicinity. Another example is the determination of new baseflow rates in rivers, which constitute a drainage system for the hydrogeological system under consideration.

The identification of areas at risk of groundwater resources deficits in the Polish-Ukrainian TAS was based on the results of the analysis of the spatial distribution of the amount of groundwater level reduction at the forecasted level of exploitation. The magnitude of groundwater level decline is determined using a numerical model of the groundwater filtration field, described in detail in the EU-Waterres report entitled "Transboundary impacts as a result of exploitation of groundwater resources in Polish-Ukrainian and Estonian-Latvian pilot areas."

The procedure consisted of calibrating and verifying the model based on data describing the "current" situation, and then a series of simulations of the "future" situation were carried out, in which the spatial distribution of water consumption was assumed to be the same as the current one, but the consumption was proportionally increased at all points. It was assumed that the level of forecast exploitation for municipal and industrial intakes operating on the basis of water and legal permits will correspond to the approved exploitation resources. However, for individual intakes it was not possible to apply a similar approach, because in this case the intake is not subject to obtaining permits and any reporting, and there is no location database. In this situation, it was assumed, with some approximation, that the water demand per capita is 0.4 m3/d/person, which is approximately twice as high as the maximum recorded consumption in both the Polish and Ukrainian parts of the area (excluding Horyniec Zdrój). Unfortunately, the individual consumption amount obtained according to the above methodology could not be used directly in the filtration field model. This was due to the fact that in the case of some administrative units, the model area covered only a fragment of their area, and the collection data concerned the entire unit. Therefore, it was necessary to estimate what part of the intake falls on the part of the unit that falls within the limits of the model. For this purpose, it was assumed that the consumption from individual intakes is distributed evenly over the entire area of the administrative unit. The obtained abstraction amount was then divided into abstraction points, which could be represented in the model using the Well condition. It was assumed that the collection would be concentrated primarily in the vicinity of towns forming the settlement network of the area. Thanks to the applied methodology, the obtained distribution of intake from individual intakes takes into account population density and the structure of the settlement network. The simulation results of the decline of the groundwater level at the predicted level of exploitation assuming the above-discussed criteria for individual, municipal and industrial intakes are presented in Figure 55.

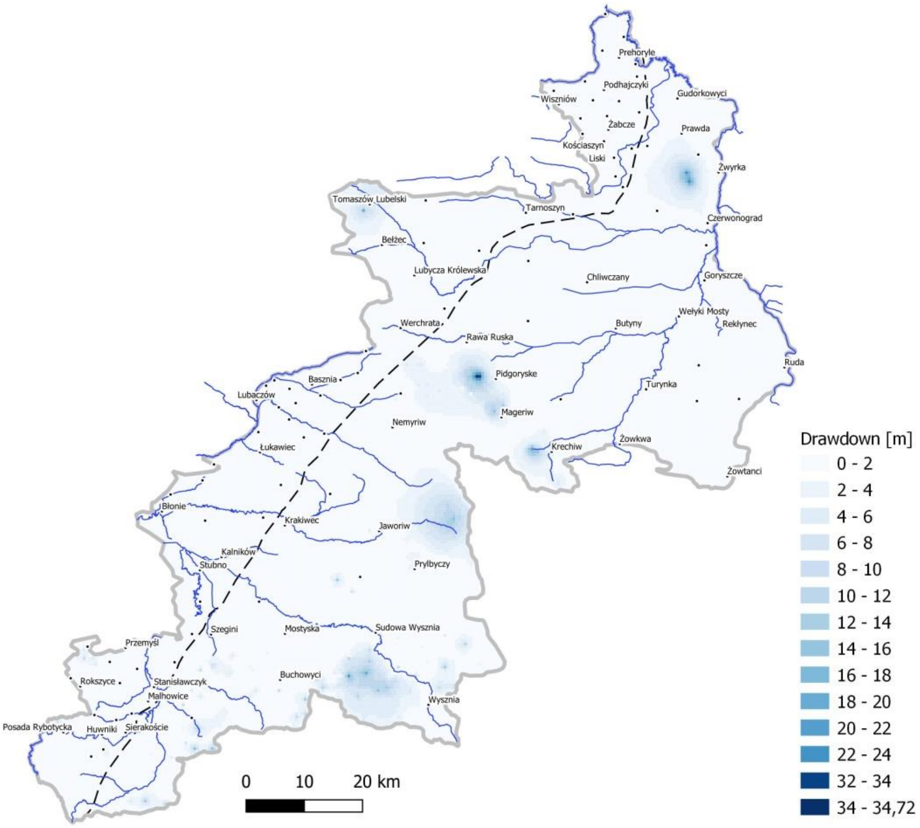


Figure 55. Decline of groundwater level in TAS at the predicted level of exploitation

Identification of areas at risk of a deficit of water resources was based on the criterion of a 2 m decrease in the groundwater level in the TAS. This practice is already implemented in the Upper Pannonian transboundary basin between Austria, Hungary, Slovakia, Slovenia and Croatia. The results of identifying these areas, with an indication of the towns within them, are presented in Table 9.

Table 9. List of towns located in the area at risk of significant reduction of the groundwater level in the TAS as a result of the predicted exploitation

Area	Poland	Ukraine
Agglomeration Tomaszów Lubielski	Tomaszów Lubielski, Dąbrowa Tomaszowska, Rogóźno-Kolonia, Rogóźno, Ławki, Jeziernia, Rabinówka, Łaszczówka-Kolonia, Wieprzowe Jesioro, Majdanek, Irenówka, Pardasówka, Sabaudia, Majdan Górny, Lipka, Podbór, Pasieki, Cieplachy	

Area of group intakes for the agglomeration of Chervonograd-Sokal		Hatkivka, Boianychi, Huta, Savchyn, Sebechiv, Berezhne, Boriatyn, Rudka, Leshkiv, Opilsko,
Area of group intakes for the agglomeration of Lviv		Klebany, Yonychi, Stare Selo, Dubrivka, Lutsyky, Monastyrok, Zamok, Poharysko, Vysich, Dumychi, Pidlissia, Kamiana Hora, Dumychi, Maheriv, Luh, Zubeiky, Hirky, Hirkany, Zarubany, Prynada, Kapeliukh, Huta Obedynska, Mali Dolyny, Velyki Dolyny, Losyny, Chornii, Deviatyr, Sorochi Lozy Tsytulia, Ruda Krekhivska, Krekhiv, Kozulka, Majdan, Papirnia
Agglomeration Shklo-Novoiavorivsk		Novyi Yar, Vola Starytska, Starychi, Shklo, Solyty, Novoiavorivsk, Kohuty, Stadniki, Akademichne, Steni, Lis, Kertyniv, Cholhyni, Prilbychy, Ternovytsia
Agglomeration Sudova-Vyshnia		Dmytrovychi, Kulmatychi, Volostkiv, Dydiatychi, Voronche, Vovchyshchovychi, Velyka Dibrova, Mala Dibrova, Shyshorovychi, Makuniv, Bertsi, Orkhovychi, Zelenyi Hai, Voshchantsi, Rozdilne, Kupnovychi, Mali Mokriany, Velyki Mokriany, Kostylnyky, Topilnytsia, Pidlisky, Vyshenka, Mystychi, Yaremkiv, Sheptychi, Chyzhevychi, Ostrozhets, Khlypli, Volia-Sadkivska, Vladypil

The adopted criteria for identifying areas at risk of resource deficit may seem quite a "strict approach", but it is practiced in the EU for TAS. Moreover, this approach differs from those used in Poland based on the degree of use of groundwater resources available for management, where the limit value is set at a quite drastic level of 90%. In Ukraine, there are no similar limits or even assessments of available groundwater resources for water and economic units. Therefore, only the possible solution discussed above, common to both countries, was used.

5. Assessment of the risk of cross-border migration of pollutants in the area of the Polish-Ukrainian Transboundary Aquifer System

The aim of the analysis was to assess the risk of transboundary transformations of the hydrogeochemical field in the Polish-Ukrainian TAS zone. It should be noted that the TAS area does not include the northern section of the state border between Poland and Ukraine, which runs along the Bug river bed. This river is the main axis of groundwater drainage in this area, which is why it constitutes a natural barrier to the transfer of both hydrodynamic and hydrogeochemical influences.

The TAS area stretches along the border from Kosmów (Poland) in the north to Katyna (Ukraine) in the south. Regionally, this area runs from the north and south through the Volhynia-Podolia Upland, the Lublin-Lviv Upland, the Northern Podkarpacie Province, the Eastern Beskids and includes parts of the left bank of the Bug catchment and the right bank of the San catchment. The course of the border line in this section does not refer to natural hydrodynamic zones, which makes it a zone potentially open to impact transfer. Quantitative assessment of this phenomenon required recognition of the filtration field and analysis of mass transport in groundwater in both spatial and temporal terms. The results of model calculations carried out as part of the first stage of the EU-Waterres project were used to quantitatively assess the filtration field. A numerical model of groundwater flow was then developed using the finite difference method. The tared model allowed for mapping the current hydrodynamic state of the aquifer system. At the current stage of work, it was decided to use the results of these calculations to develop a regional model of mass transport in the advective-dispersive stream. For this purpose, advection calculations were performed using the *Modpath* program built into the *Groundwater Vistas* software package. On this basis, the course of stream lines indicating the directions of the underground flow to the border line was determined in a time interval of 25 years. Then, the pollution injection points were selected, on the basis of which the migration of the conservative component in the advection-dispersion stream was examined. For this purpose, a numerical mass transport model was developed in the *MT3DMS* program, which is also part of the *Groundwater Vistas* package. The finite difference method was used to approximate the solution of the advection–dispersion equation. The calculations were of a simulation nature and their aim was to identify zones potentially exposed to the risk of transboundary impact transfer as a result of mass transport in groundwater. For the purposes of the calculations, a time interval of 100 years was discretized into forcing periods of one year, each of which was divided into 10 time steps of equal length. Due to the simulation nature of the model tests, the most unfavorable parameters and variables were used for calculations, i.e. those most favorable to the transfer of substances in the advection-dispersion stream:

- groundwater flow directions and hydraulic gradient values were obtained on the basis of the spatial distribution of the hydraulic gradient, which is the result of the numerical model of the filtration field,
- to calculate the average actual flow rate, the filtration coefficient values obtained at the taring stage of the groundwater flow model and the effective porosity values of 0.1 within the fissure massifs (Carpathians, Lublin-Lviv Upland) and 0.15 in the pore medium (Quaternary layer in the remaining area) were used,
- the dispersion of the substance was described using longitudinal dispersion constants at the 50 m level, and horizontal and vertical dispersion constants being 0.1 and 0.01 of this value, respectively,
- the calculations omitted the delay effect associated with the diffusion of the solute into the rock matrix in rocks with double porosity,
- the calculations were carried out with respect to the conservative component, i.e. they ignored interactions with the rock matrix as a result of sorption interactions, and it was assumed that this component was not subject to decay and biodegradation reactions.

According to the classical approach to the problem of mass transport, the chloride ion is assumed to be the component closest to the conservative component. Also, as part of the work carried out, this component was treated as an indicator for the analysis of the transfer of substances as a result of advection and dispersion processes. The high solubility of chlorides also allowed for the formulation of appropriately strong signals related to the injection of the substance into the tested system. This injection was mapped using a type I boundary condition, assigning a constant concentration value of 360 g/L to selected points in space (continuous injection), which corresponds to the chloride concentration for saturated brine. Calculations were carried out in two variants of the spatial distribution of injection points. In the first variant, the points were located on both sides of the state border in the space between the border line and the 25-year isochrone of advective inflow to this line (Figure 566 - Figure 733). This allowed for the assessment of the time of arrival of the first portions of pollution to the state border. In the second variant, points were located on the boundary line to identify the maximum spatial extent of transboundary influence transfer as a result of mass transport in groundwater (Figure 74 - Figure 91).

Division of the PL-UA TAS area into tributary zones to the border line (state border)

For this purpose, the capabilities of the Modpath program were used, which allows determining the trajectory of movement of particles specified by the user based on a previously prepared model of the filtration field. This involves using an array of numbers representing the spatial distribution of hydraulic head to determine the flow direction and hydraulic gradient. Then, based on the value of the filtration coefficient set in the flow model and the assumed value of effective porosity, it is possible to determine the position of the particle after a specified time. By connecting the points defining the subsequent positions of the particle, its theoretical motion trajectory (pathline) can be determined. In the case of the described research, it was decided to distribute the particles along the entire section of the boundary line covered by the model calculations. The particles were placed near the lower boundary surface of the tested system, which allowed the determination of the maximum particle path, taking into account the vertical component of motion. On this basis, it was possible to identify in which zones the flow to the border line comes from the territory of Ukraine and in which from the territory of Poland.

The calculation results indicate significant spatial diversity in the direction and rate of groundwater flow, and three areas can be distinguished, which differ significantly due to these values: 1) the Bug catchment area, 2) the San catchment area within the Carpathian foredeep, 3) the San catchment area within the eastern Beskids.

1) The northern area (A) of the PL-UA TAS covers mainly the laft bank of the Bug catchment area. In this zone, the water flow takes place from the watershed zone in Poland towards the drainage axis defined by the beds of the Bug and its tributaries. Hence, on the majority of the border line, groundwater flows from the territory of Poland to the territory of Ukraine. The isochrone of the 25-year-old tributary is located at a maximum of 6 km from the border line. In the southern part of area A, the water flow takes place from the watershed zone along the elevation of the Lublin-Lviv Upland and is approximately co-shaped with the border line.

2) The central part (B) of the PL-UA TAS area covers a fragment of the right bank of the San catchment in the area of the Carpathian Foredeep. This area is characterized by a high density of the river network, which results in the development of numerous local watershed zones. This causes a high variability of flow directions, and as a result, underground flow to the border line comes from both Ukraine and Poland. Low hydraulic gradients combined with low water permeability of the matrix in the area of old glacial highlands mean that the isochrone of the 25-year-old inflow is located at a maximum distance of 3 - 4 km from the border line, i.e. much closer than in area A. The exception is the Lublin - Lviv edge

zone Upland, where due to the high values of the hydraulic gradient combined with the high water permeability of the medium, the isochrone is located about 10 km from the border.

3) The southern part (C) of the PL-UA TAS area covers a fragment of the eastern Beskids. The aquifer here is primarily fissure, and the water permeability of the rocks is generally low. As a result, despite the high values of the hydraulic gradient, the water flow is relatively slow, and the isochrone of the 25-year inflow is located at a maximum of 1.5 - 2 km from the state border. In the southern part of area C, the underground flow to the border line comes mainly from the Polish side, while in the northern part from the Ukrainian side.

Assessment of the risk of transboundary migration of pollutants from potential hotspots located away from the border at a distance not exceeding the 25-year isochrone of groundwater inflow (variant 1).

Injection points (potential pollution hotspots) were located on both sides of the border in such a way that they were located in the direction of groundwater flow to this line at a distance not exceeding the isochrone of the 25-year inflow. The assumption was that this would allow for the assessment of the time of arrival of the first portions of pollution to the state border, and this time the calculations took into account the dispersion of the substance as a result of hydrodynamic dispersion. The injection of the ingredient was point-like in space and continuous in time. The injection process was mapped using the Dirichlet condition by assigning a constant concentration to selected points in space. The concentration of the conservative component was assumed for the calculations at 360 g/L, which corresponds to the concentration of chlorides in a solution saturated with respect to halite. This allowed the simulation to include the most unfavorable conditions due to the high concentration gradients created in this way around the injection points (at all points in the discrete space, a chloride concentration of 0 g/L was assumed as the initial condition). When interpreting the calculation results, a threshold concentration value of 0.25 g/L was adopted, which corresponds to the permissible chloride content in drinking water. The results of the calculations in a regional perspective are presented in Figure 56 - Figure 73 in the form of maps of the spatial distribution of chloride concentrations after 1, 5, 10, 25, 50 and 100 years from the start of the pollution injection. The resulting image is consistent with the advective transfer model in terms of mass transport directions. In the northern part of the TAS (A) area, the dominant movement of polluting substances is from the territory of Poland to the territory of Ukraine. At the same time, the substance is strongly dispersed as a result of hydrodynamic dispersion. As a result, the threshold concentration value is recorded locally near the state border already **10 years after** the contamination injection. In the central part of the TAS area (B), substances are transferred from the territory of Ukraine to Poland on the majority of the border line. Here, too, the threshold concentration value in the vicinity of the state border is exceeded locally as early as **10 years after** the initiation of the injection. This applies especially to the edge zone of the Lublin-Lviv Upland. In the southern part of the TAS area (C), there is a clear contrast between the Carpathian thrust zone and the Carpathian foredeep. In the Carpathian flysch area, the dominant flow of substances is from Poland to Ukraine. However, due to the low water permeability of the medium, the substance migrates much slower, and the permissible chloride concentration in the vicinity of the border line is exceeded only **15 years after** the start of injection.

Four injection points were located in the northern area of PL-UA TAS (A), including three on the Polish side and one on the Ukrainian side. The points on the Polish side were located near local watershed zones, which are relatively close to local drainage zones. As a result, strong dispersion of the substance and its rapid movement towards the drainage zones were usually observed around these points (Figure 56 - Figure 61). At the same time, it is worth noting that the upper sections of rivers in this area constitute a significant barrier to the migration of pollutant clouds. Over time, the cloud contours determined by the 0.25 g/L concentration isoline gradually expand towards the river beds and are usually reached 25 to 50 years after the start of injection. Importantly, in most cases, water pollution occurs on both sides of the border, and in most areas the concentrations of substances within the cloud range from 0.25 to 5 g/L. The transformations of the concentration field occur most intensively within the first 50 years from the moment of injection. After this time, the area of increased concentrations stabilizes in the inter-river area, and changes over the next 50 years are relatively minor. After 100 years from the moment of injection, the effect of exceeding hydrodynamic barriers is visible locally. This is due to the spatial nature of the stream and the dispersion of substances as a result of mechanical dispersion and molecular diffusion. The southernmost injection point in area A was located on the Ukrainian side in the morphologically elevated zone of the Lublin-Lviv Upland. In this area, the streamlines run almost parallel to the state border. As a result, the spread of the pollution cloud was observed on both sides of the border, with the center of mass within the cloud located on the Ukrainian side. The lateral dispersion of substances is clearly visible here, and this is the effect of both lateral dispersion and the advection factor (water flow from the local watershed zone towards the surrounding river beds).

In the central area of PL-UA TAS (B), the dominant groundwater flow is from the Ukrainian side to Polish territory. For this reason, all injection points were located in Ukraine (Figure 62 - Figure 67). In the northern part of the area, the injection point was located near the edge zone of the Lublin-Lviv Upland. High hydraulic gradient values are recorded in this zone, which, combined with the good water permeability of the medium, translates into high groundwater flow rates. As a result, a rapid movement of the pollution cloud was observed in this zone, which, despite the distance of the injection point from the border, penetrates deep into the territory of Poland. This is the effect of both the advection factor and the strong dispersion of substances as a result of longitudinal dispersion. However, the lateral dispersion of substances is relatively small, which results from the existence of hydrodynamic barriers in this area in the form of deeply incised river beds. In the case of the other two injection points located in the southern part of area B, the migration of substances occurs much slower. This is due to the lower hydraulic gradients recorded in this part of the area. At the same time, the lateral dispersion of substances is more visible here, which, in addition to the lateral dispersion, is also influenced by the hydrodynamic system of the stream (advective flow of substances away from the watershed zone).

In the southern part of the PL-UA TAS (C) area, four injection points were located, including three in Poland and one in Ukraine. All points on the Polish side were located in the area of the Carpathian overthrust. The point on the Ukrainian side is located in the area of the Carpathian Foredeep. In the case of points located on the Polish side, the migration of substances was very slow (Figure 68 - Figure 73). In the two southernmost points, the first exceedances of the permissible chloride concentration in the vicinity of the state border were observed only 15 years after the injection. After this time, the spread of pollution clouds is very slow, and at the same time there is a strong transverse dispersion of the substances (mainly due to the advection factor). As a result, even 100 years after the injection, increased chloride concentrations on the Ukrainian side cover a zone only 2-3 km wide from the state border. A slightly different situation was observed in the case of the injection point located the northernmost on the Polish side. In this case, mass transport initially occurs in a fractured medium with low water permeability and is very slow. The situation changes 10 years after the injection, when the first portions of the pollution reach the river valleys developed in the area of the Carpathian Foredeep. The high water permeability of sand and gravel alluvium means that from that moment on, one can observe the rapid movement of the cloud front towards the drainage zones. In the case of the point located on the Ukrainian side, the migration of substances takes place entirely within the aquifer formed in sand and gravel sediments. The good water permeability of the sediments means that migration occurs much faster here than in the Carpathians, and the cloud quickly moves to the Polish side and migrates towards the San river bed, which it reaches 20 years after injection.

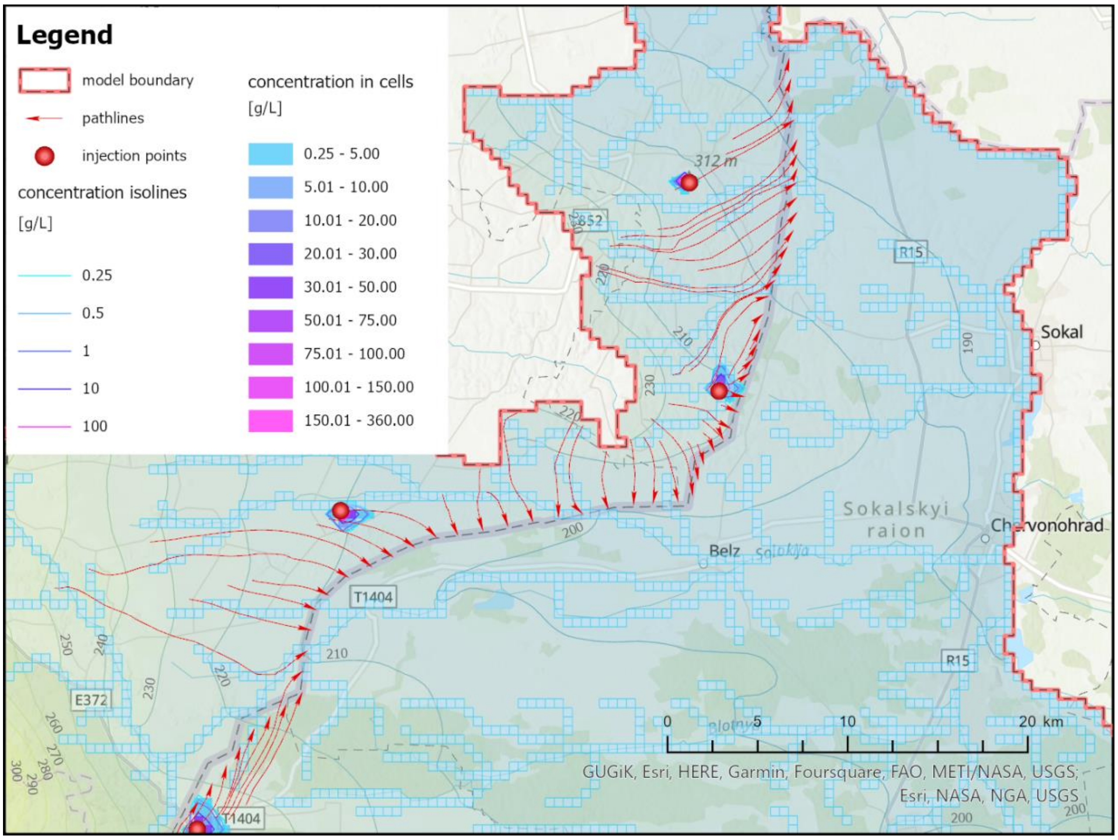


Figure 56. Calculated concentration field in the northern part of the PL-UA TAS area (A) one year after the start of continuous injection of the conservative substance

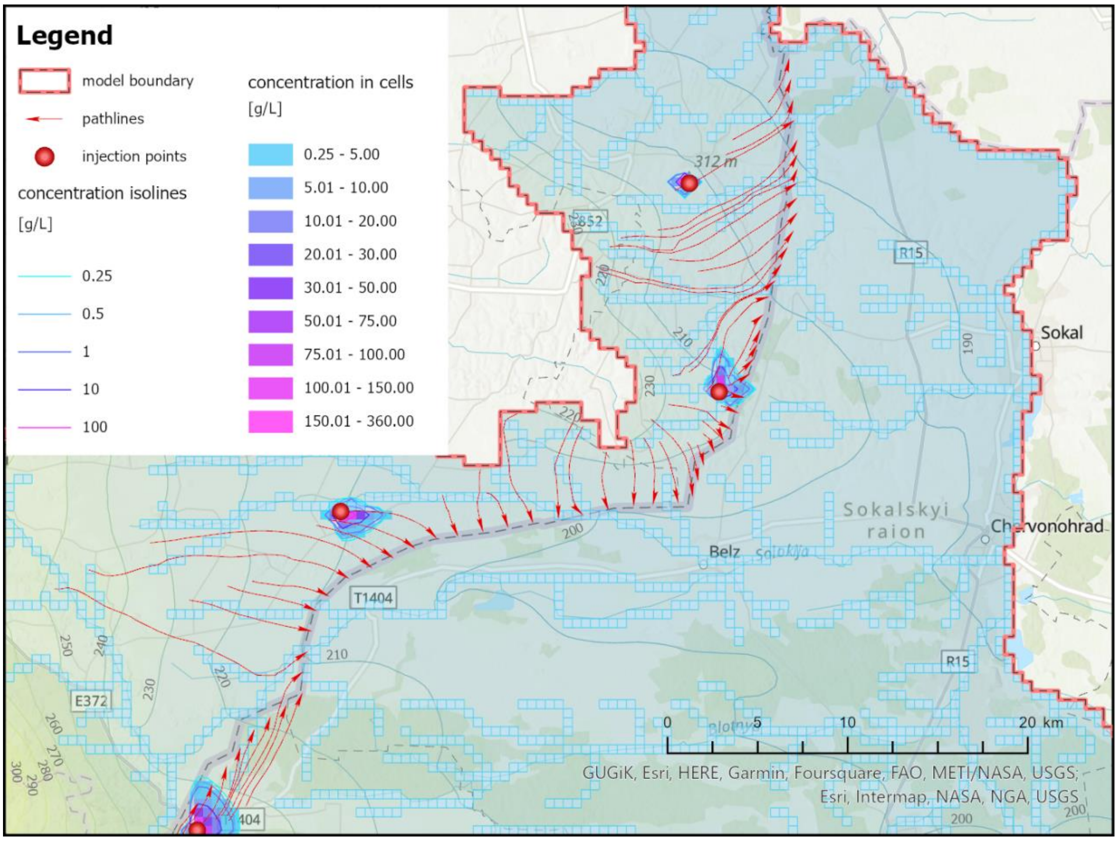


Figure 57. Calculated concentration field in the northern part of the PL-UA TAS area (A) 5 years after the start of continuous injection of the conservative substance

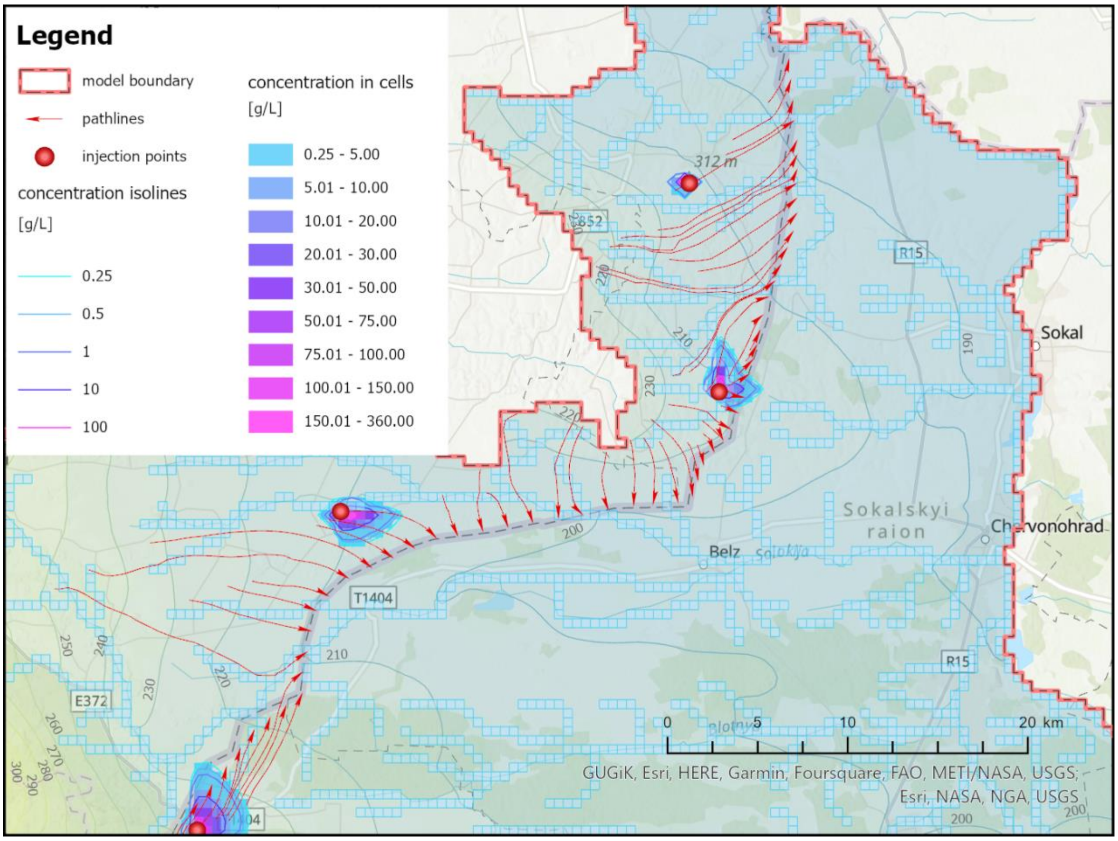


Figure 58. Calculated concentration field in the northern part of the PL-UA TAS area (A) 10 years after the start of continuous injection of the conservative substance

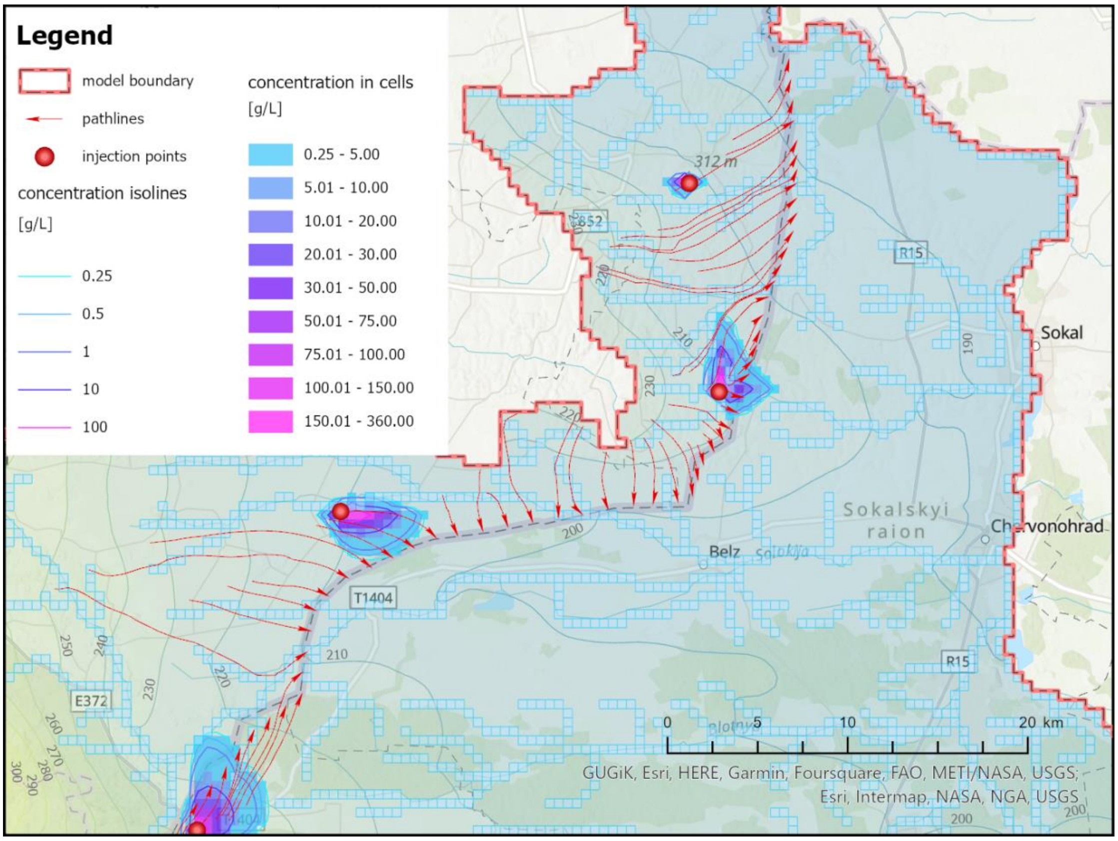


Figure 59. Calculated concentration field in the northern part of the PL-UA TAS area (A) 25 years after the start of continuous injection of the conservative substance

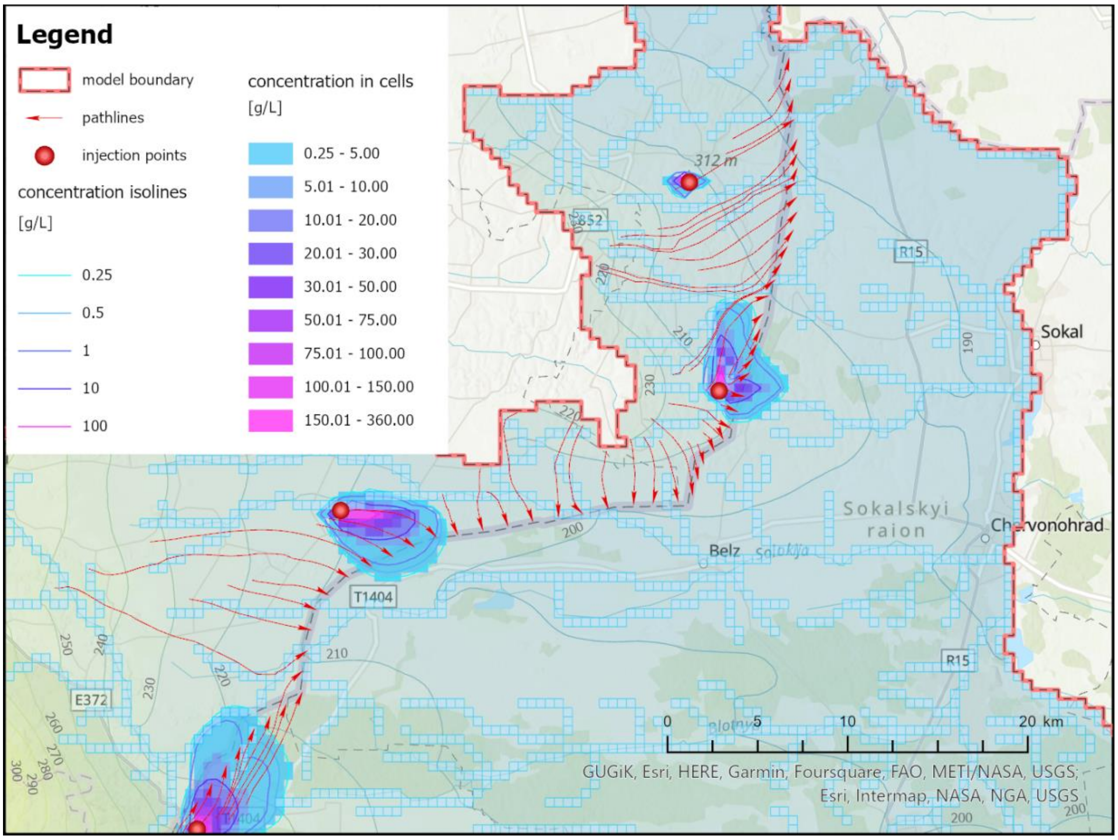


Figure 60. Calculated concentration field in the northern part of the PL-UA TAS area (A) 50 years after the start of continuous injection of the conservative substance

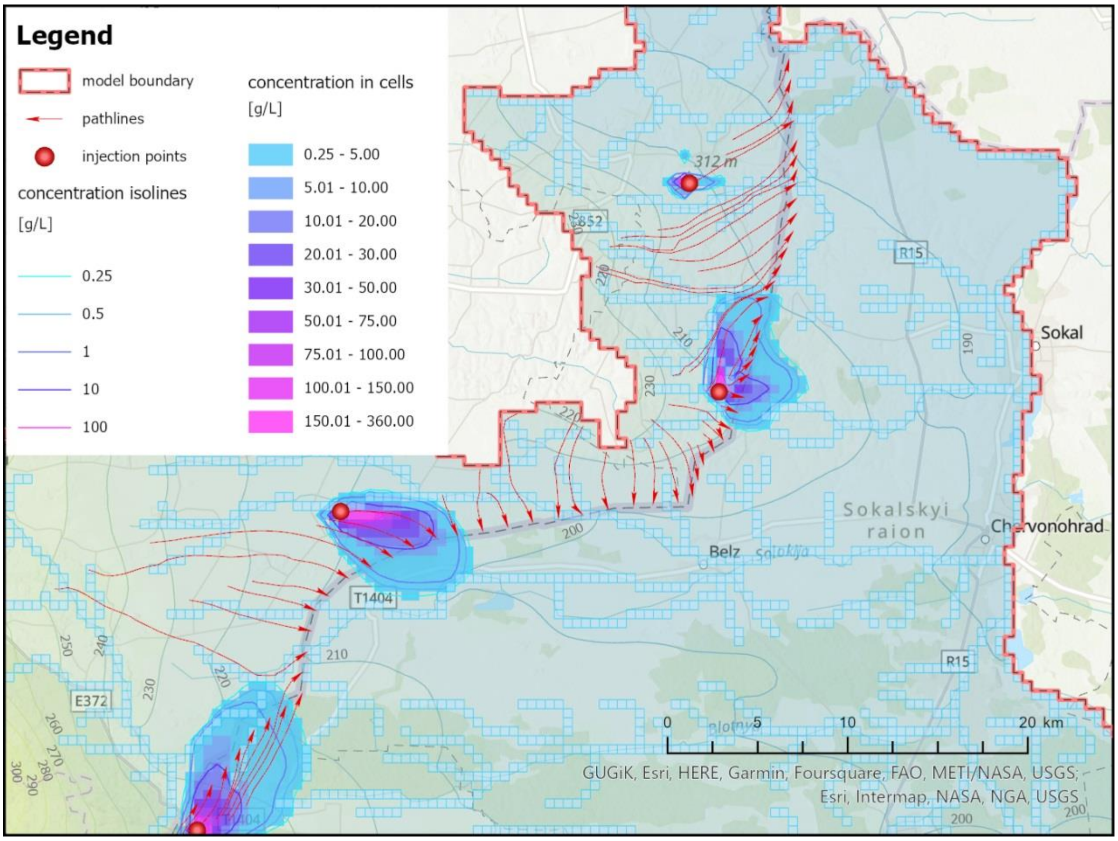


Figure 61. Calculated concentration field in the northern part of the PL-UA TAS area (A) 100 years after the start of continuous injection of the conservative substance

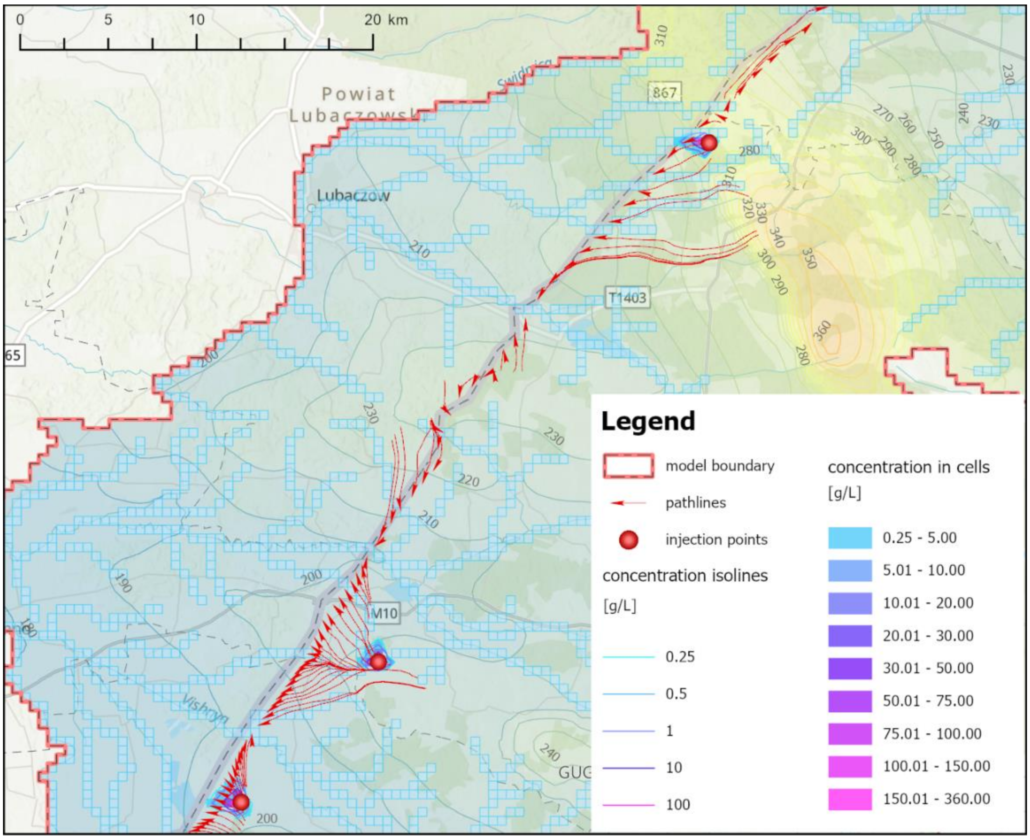


Figure 62. Calculated concentration field in the northern part of the PL-UA TAS area (B) one year after the start of continuous injection of the conservative substance

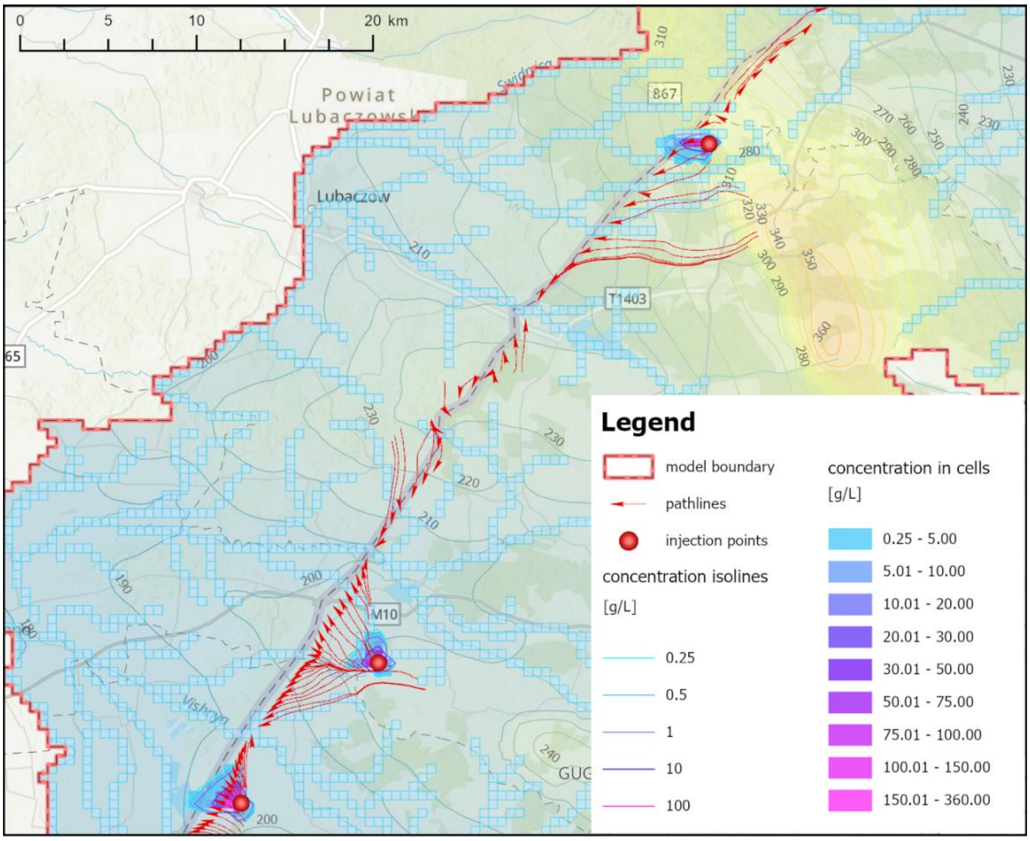


Figure 63. Calculated concentration field in the northern part of the PL-UA TAS area (B) 5 years after the start of continuous injection of the conservative substance

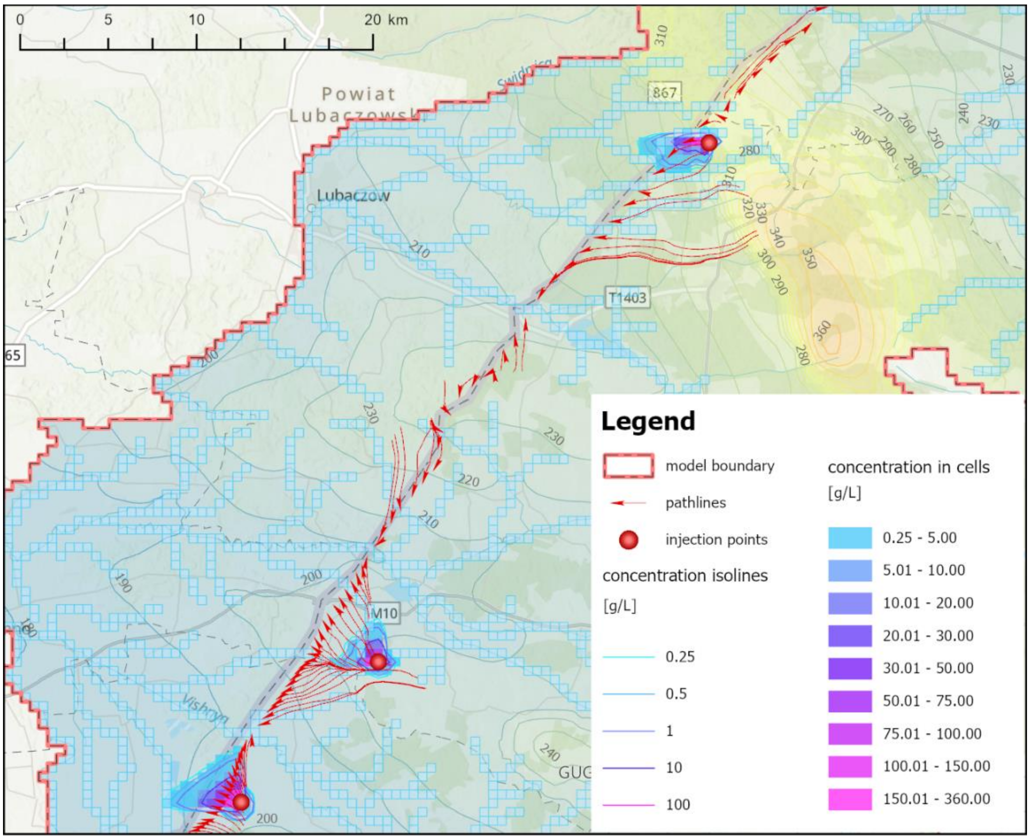


Figure 64. Calculated concentration field in the northern part of the PL-UA TAS (B) area 10 years after the start of continuous injection of the conservative substance

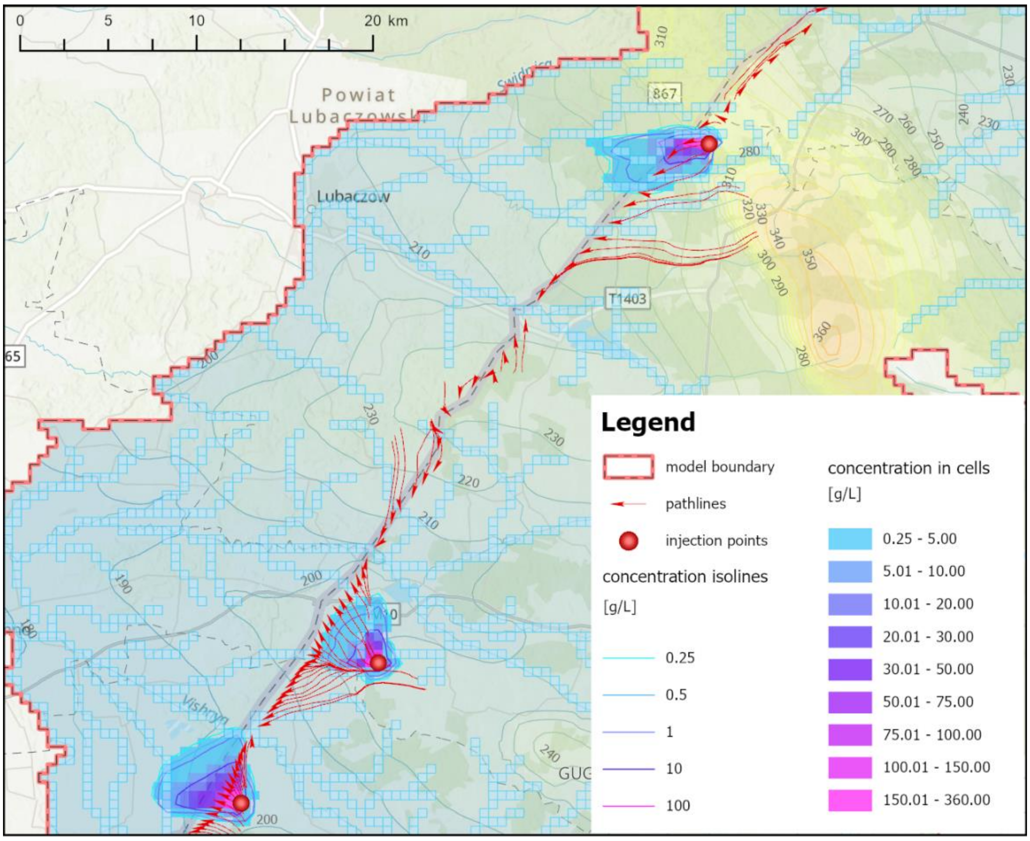


Figure 65. Calculated concentration field in the northern part of the PL-UA TAS (B) area 25 years after the start of continuous injection of the conservative substance

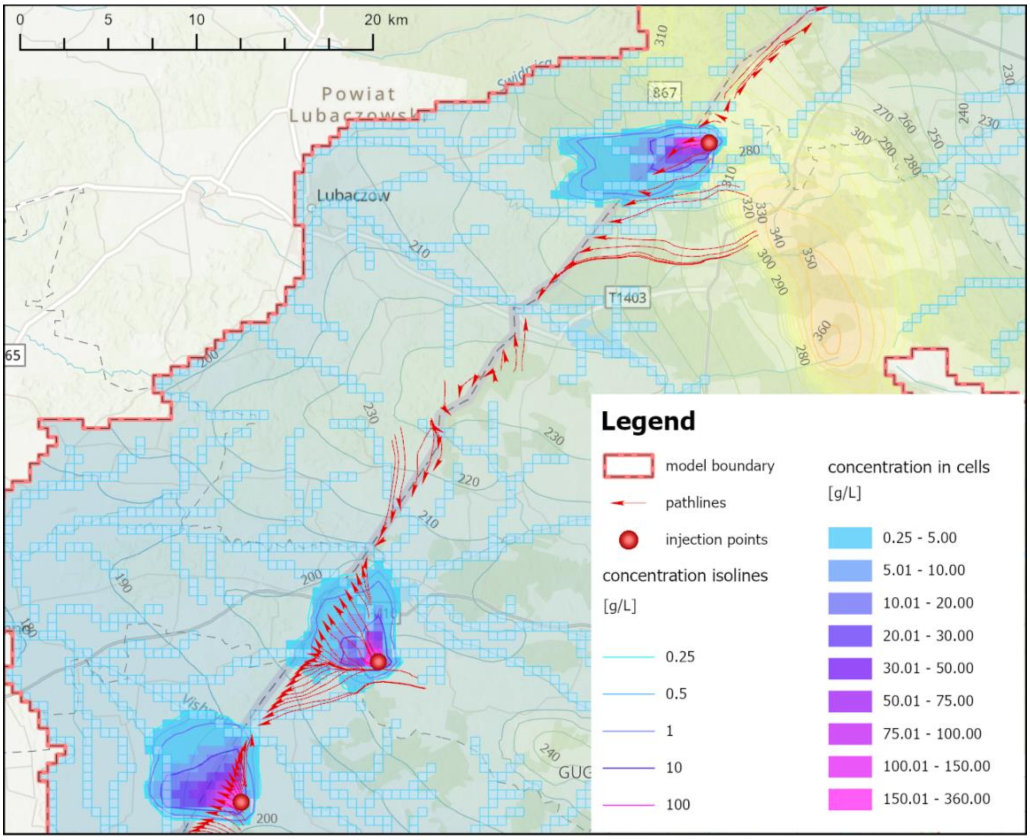


Figure 66. Calculated concentration field in the northern part of the PL-UA TAS (B) area 50 years after the start of continuous injection of the conservative substance

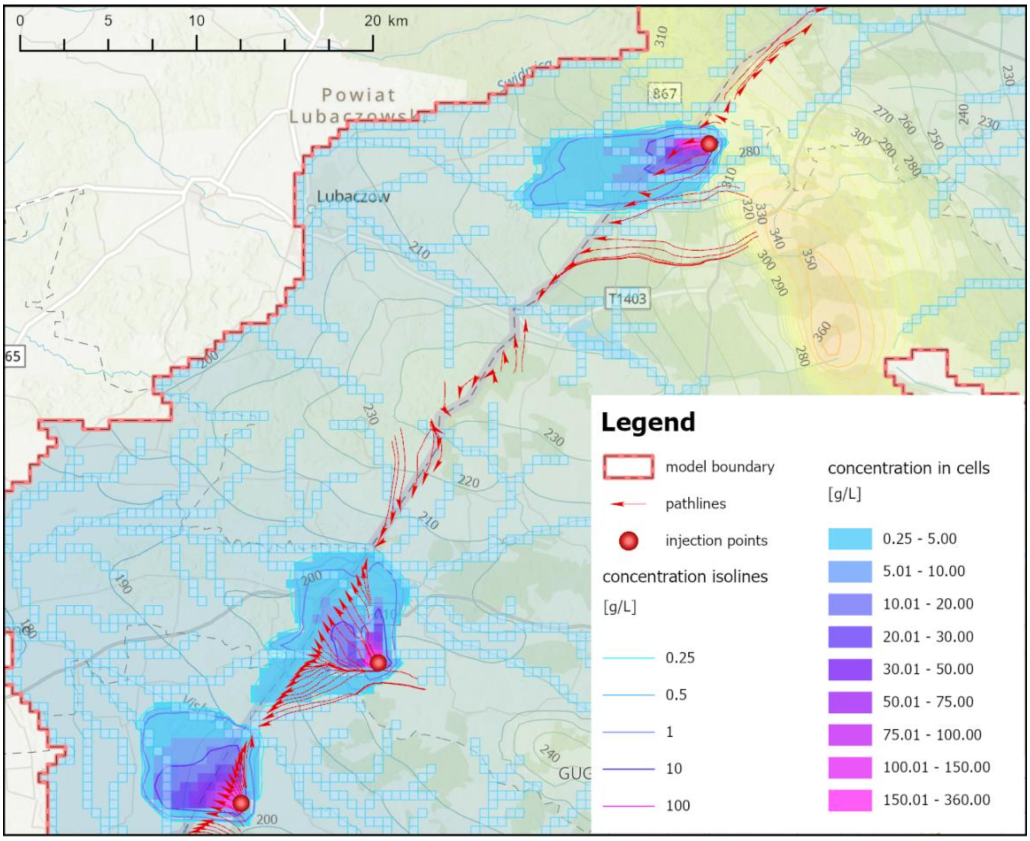


Figure 67. Calculated concentration field in the northern part of the PL-UA TAS area (B) 100 years after the start of continuous injection of the conservative substance

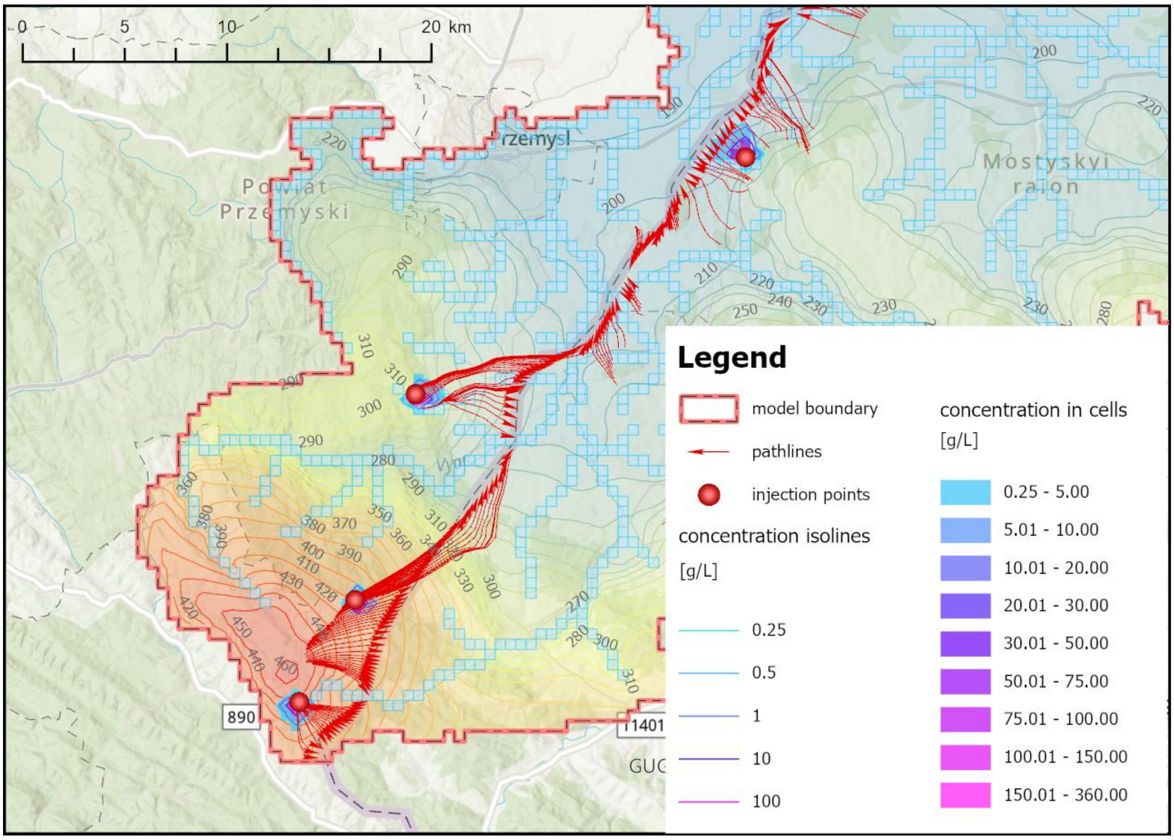


Figure 68. Calculated concentration field in the northern part of the PL-UA TAS area (C) one year after the start of continuous injection of the conservative substance

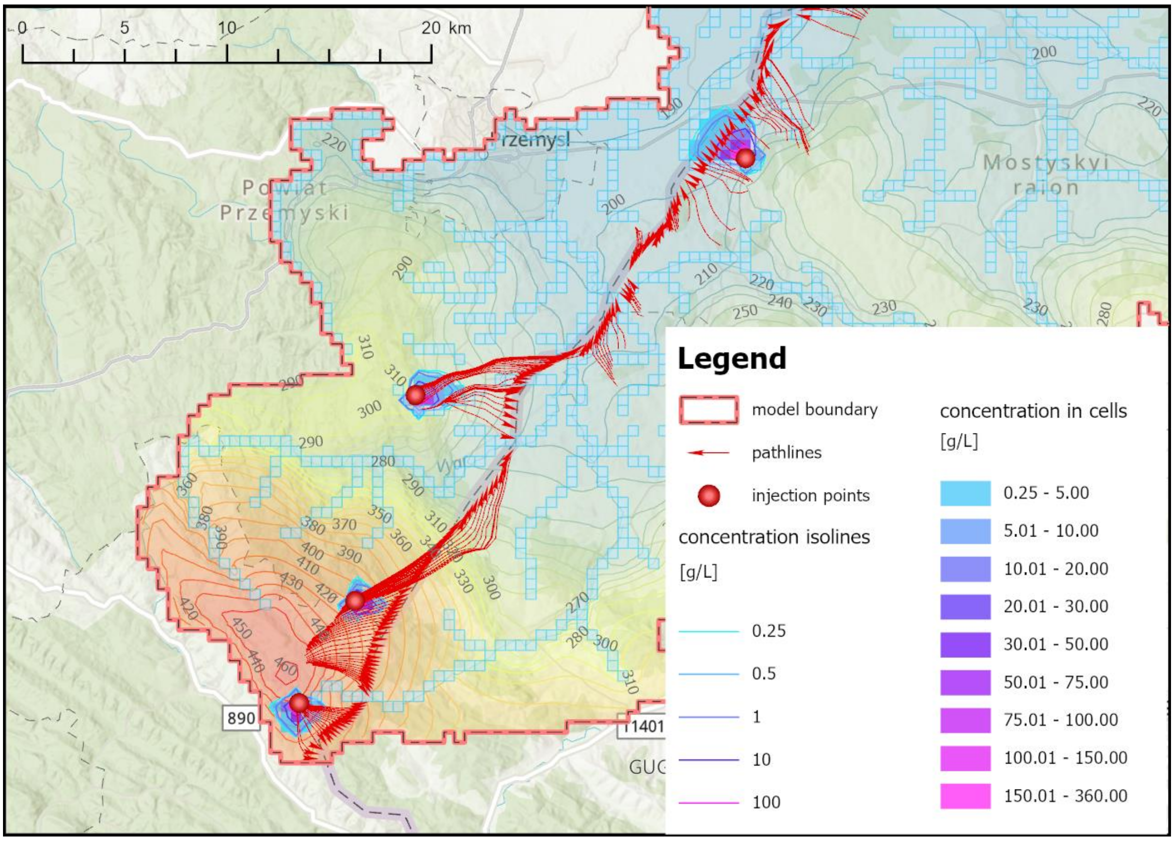


Figure 69. Calculated concentration field in the northern part of the PL-UA TAS area (C) after 5 years from the start of continuous injection of the conservative substance

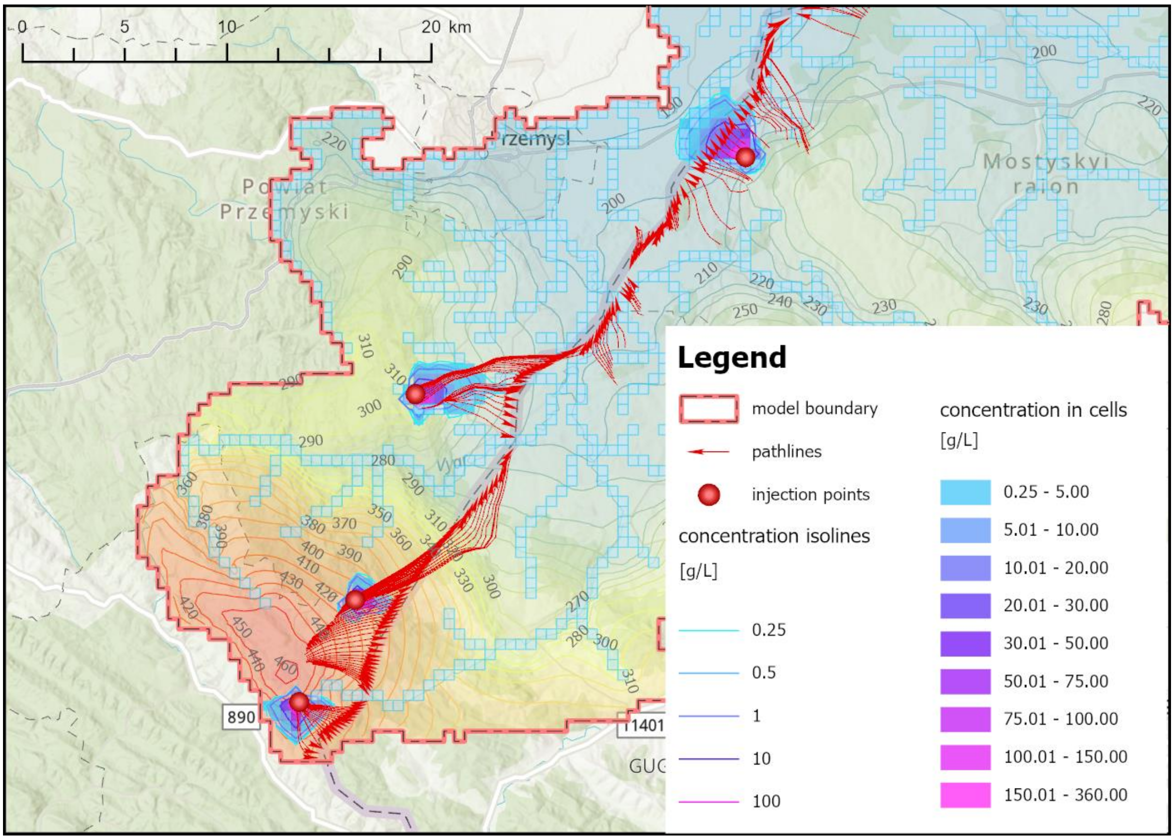


Figure 70. Calculated concentration field in the northern part of the PL-UA TAS area (C) 10 years after the start of continuous injection of the conservative substance

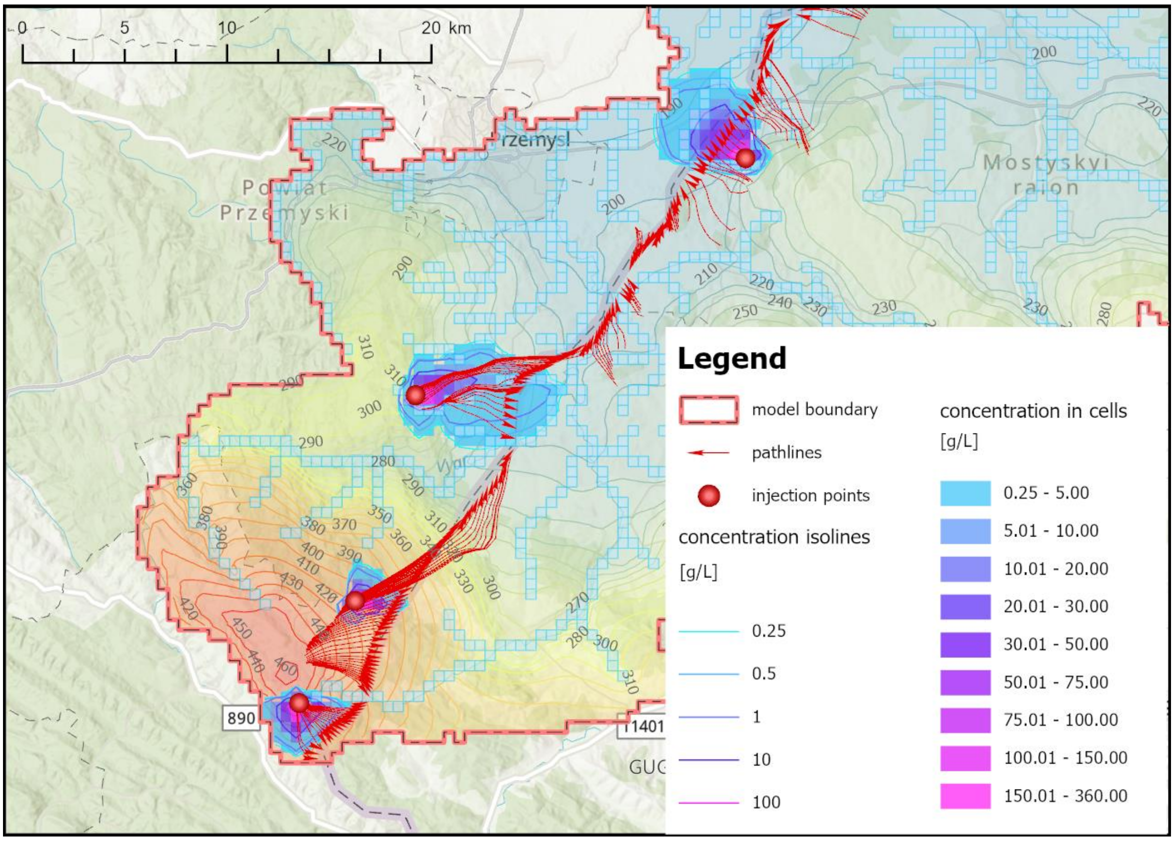


Figure 71. Calculated concentration field in the northern part of the PL-UA TAS area (C) 25 years after the start of continuous injection of the conservative substance

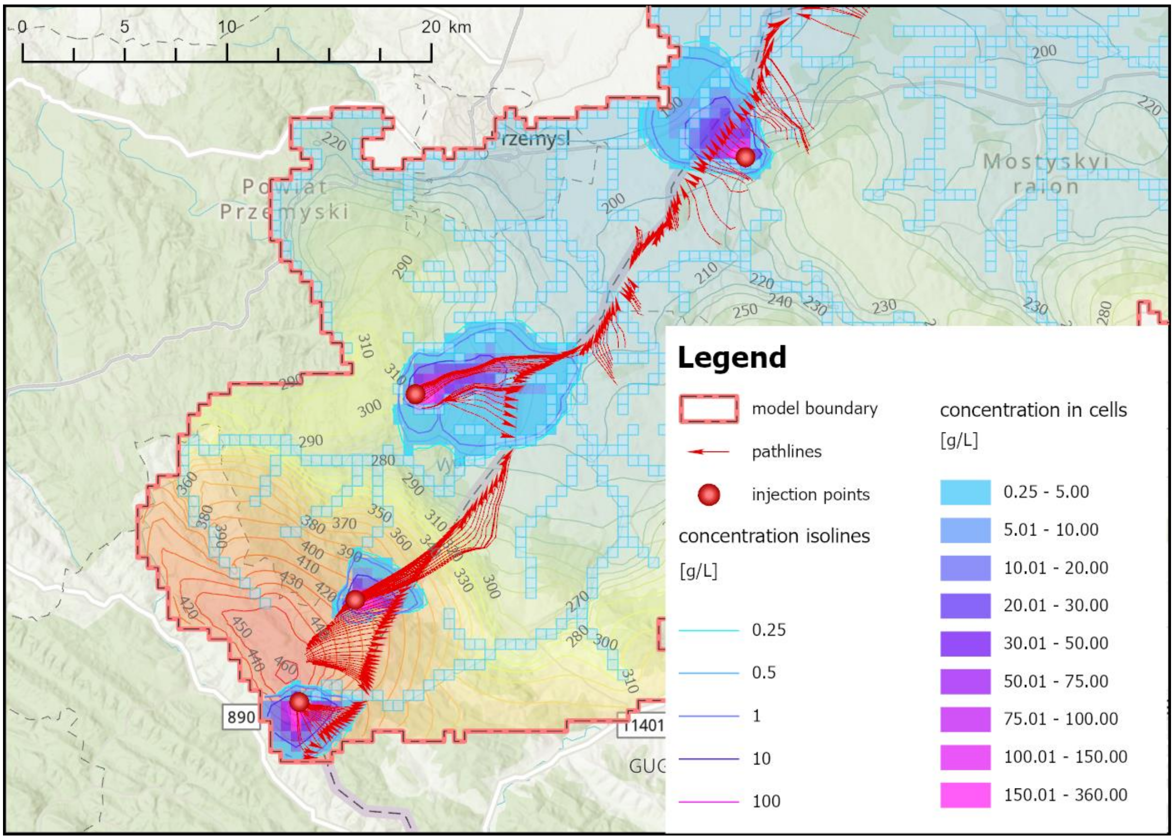


Figure 72. Calculated concentration field in the northern part of the PL-UA TAS area (C) 50 years after the start of continuous injection of the conservative substance

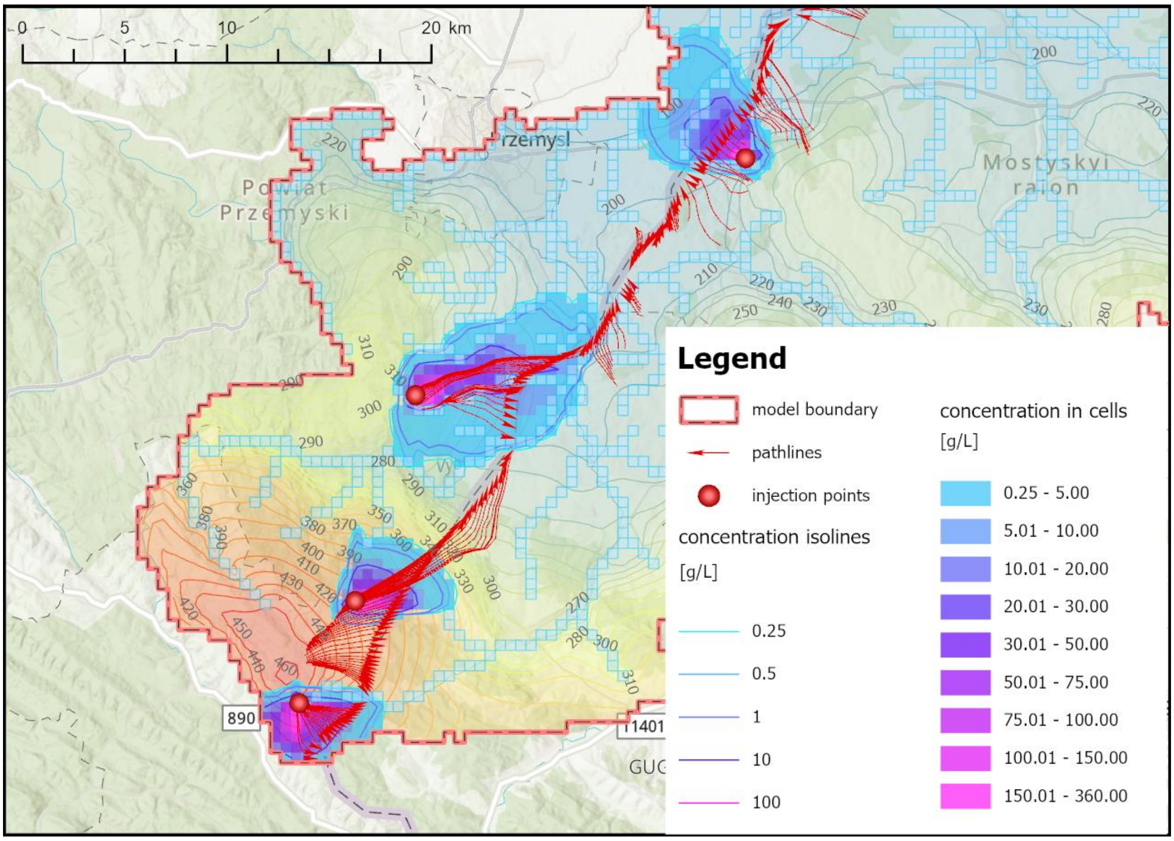


Figure 73. Calculated concentration field in the northern part of the PL-UA TAS area (C) 100 years after the start of continuous injection of the conservative substance

Assessment of the risk of cross-border migration of pollutants from potential hotspots located at the state border (variant 2)

The second variant of the calculations was carried out to assess the potential cross-border transfer of impacts as a result of mass transport, and this time the most unfavorable spatial distribution of injection points was considered. In order to recognize the maximum extent of impact on the territory of a neighboring country, all injection points were located in the immediate vicinity of the state border. The remaining assumptions regarding both the groundwater flow model and the mass transport model remained unchanged in relation to the first variant. The injection of the pollutant over time was continuous and was mapped on the model using a type I boundary condition, assigning a conservative component concentration value of 360 g/L to selected points in space. Similarly to the first variant, calculations were carried out for a time period ranging from 1 to 100 years.

The results of the calculations from a regional perspective are generally consistent with those presented in the first variant of the mass transport model. In the northern area (A), covering a part of the left-bank catchment of the Bug River, mass transport from the border line to the territory of Ukraine dominates. In this area, the location of potential pollution hotspots in the immediate vicinity of the state border leads to significant transformations of the hydrochemical field, and the formed pollution clouds may migrate over the course of a century deep into the territory of Ukraine to a distance of up to **5 - 7 km** (Figure 74 - Figure 79). In the morphologically elevated area of the Lublin-Lviv Upland, underground flow occurs approximately parallel to the border, and the injected mass is dispersed both in Poland and Ukraine. In the central part of the PL-UA TAS area (B), covering a fragment of the right bank of the San catchment, the mass flow dominates in the territory of Poland. This is determined by the regional groundwater circulation system and the fact that the San river bed determines the main drainage axis here. However, the migration of substances is also largely determined by the presence of lower-level watercourses, which create hydrodynamic barriers limiting the spread of substances dissolved in groundwater. As a result, in the area of the Carpathian Foredeep, the extent of the transboundary impact zone usually **does not exceed 10 km** from the state border. The exception is the edge zone of the Lublin-Lviv Upland, where due to high flow velocities this value may be exceeded. In the area of the Eastern Beskids (area C), the stream lines around some of the injection points run approximately parallel to the state border. As a result, the mass introduced at these points is dispersed on both sides of the boundary line. The exception is the southernmost point, from which the mass is transported only to the territory of Ukraine. Analysis of the results on a larger scale and with higher time resolution confirms the conclusions presented above. In area A, the migration of the substance injected into the system along the border line occurs primarily in the territory of Ukraine (Figure 74 - Figure 79). Point injection of a conservative component causes the formation of clouds of pollution, which gradually migrate towards the drainage zones marked by river beds. The dispersion of substances in the advection-dispersion stream causes intensive transformations of the concentration field, and exceedances of the permissible chloride concentration value for drinking water are gradually recorded in an increasingly larger area. The growth of pollution clouds is not evenly distributed over time. The process is most dynamic in the first five decades from the moment of injection. In the next fifty years, the changes are no longer so dynamic and the concentration field tends to a steady state. This is due, on the one hand, to the method of injection of the substance, which is administered continuously at a constant concentration. On the other hand, there is a draining role of streams, which take the mass of the conservative component outside the studied system. A similar situation can be observed in area B, covering the central part of the PL-UA TAS (Figure 80 - Figure 85). Here, clouds created as a result of point injection of chlorides migrate westwards to finally stabilize in the area of local interfluvial areas. An interesting situation can be observed by analyzing mass transport in the southern part of the PL-UA TAS - area C (Figure 86 - Figure 91). Here, the injection of the conservative component was made through four points located directly on the Polish-Ukrainian border. The migration of pollution clouds from each of these points had a slightly different course. The northernmost point is located in the area of the Carpathian Foredeep, so the migration of pollutants here is similar to the neighboring area B. In turn, at the southernmost point, an interesting situation occurs when the mass is initially transferred to the territory of Ukraine and then takes place a change in the direction of transport, and the substance is dispersed again into Poland. Ultimately, the cloud stabilizes here in the local interfluvial area on both sides of the border, with the center of mass remaining on the Ukrainian side. An equally interesting situation can be observed at a point located further south (the third one from the north). Here, the spread of the pollution cloud is initially slow, which results from low flow velocities in the fractured medium developed in the Carpathian flysch rocks. However, from the moment the cloud front enters the area of alluvial aquifers, it begins to grow dynamically, and due to the low density of the river network, its spatial extent 100 years after the start of injection is definitely the largest. In the case of the southernmost point, migration occurs only in flysch rocks, so it is slow, and the cloud stabilizes a short distance from the injection point. This is due to the small distance of the injection point from the edge surface, which means that the mass can be moved outside the PL-UA TAS.

To sum up, using the example of the conservative component - chlorides, the migration of the cloud of contaminants with groundwater was determined in time and space using the mass transport model in the advection-dispersion stream. For two variants, the extent of transboundary impact transfer as a result of mass transport in groundwater was tested. In the first variant, potential hotspots were located on both sides of the border in such a way that they were located in the direction of groundwater flow to this line at a distance not exceeding the isochrone of the 25-year inflow. The second variant assumed the location of pollution hotspots in the immediate vicinity of the border. The modeling results show that the migration process of pollutants in both scenarios is slow and the cloud of pollutants grows within 50 years from the moment of injection, then the changes are no longer so dynamic and the concentration field tends to a steady state. Within the Busko part of PL-UA TAS, clouds of pollutants formed on the Polish-Ukrainian border, regardless of which side of the border, are transported deep into Ukraine to a distance of up to 5 - 7 km. In the San catchment, within the Carpathian foredeep, the dominant mass flow is in the territory of Poland. High hydraulic gradient values are recorded in this zone, which, combined with the good water permeability of the medium, translates into high groundwater flow rates. As a result, the scope of the cross-border impact zone reaches its maximum size here - up to 10 km deep into Poland. In the Carpathian part of PL-UA TAS, migration takes place in flysch rocks, which is why it is slow, and the cloud stabilizes a short distance from the pollution center, only 2 - 3 km from the state border.

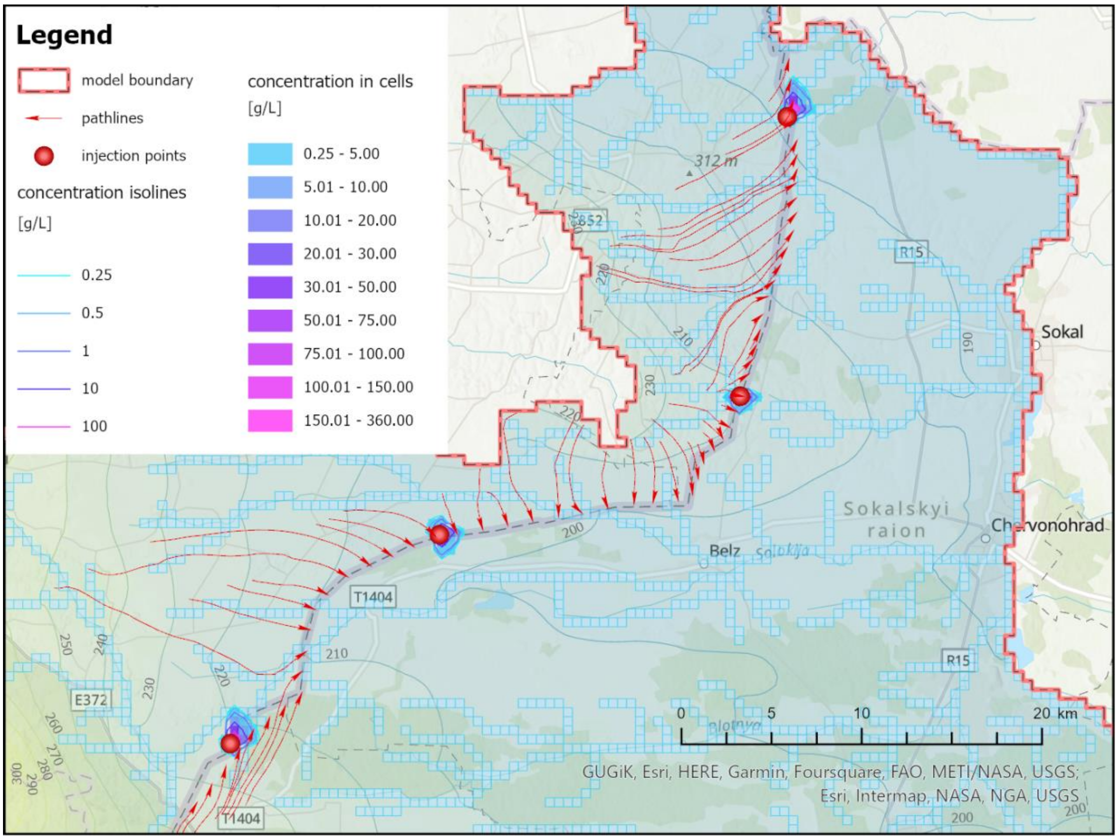


Figure 74. Calculated concentration field in the northern part of the PL-UA TAS area (A) one year after the start of continuous injection of the conservative substance (variant 2)

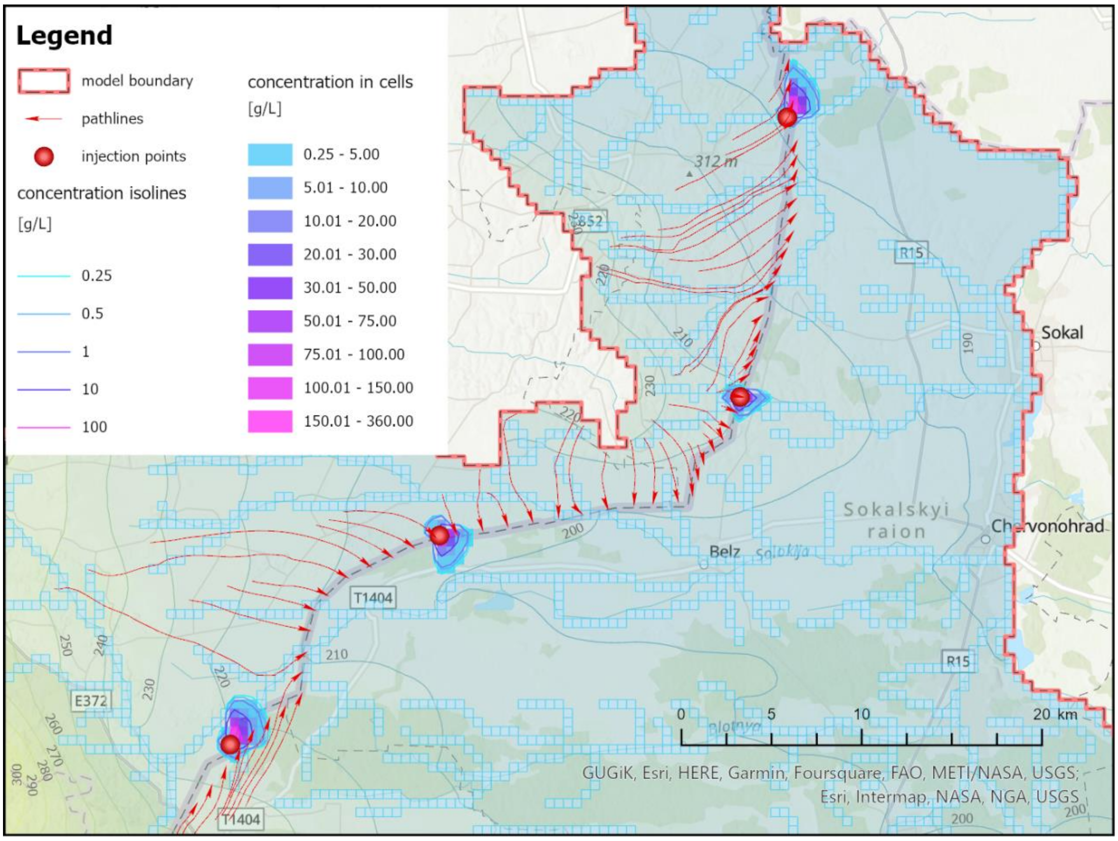


Figure 75. Calculated concentration field in the northern part of the PL-UA TAS area (A) after 5 years from the start of continuous injection of the conservative substance (variant 2)

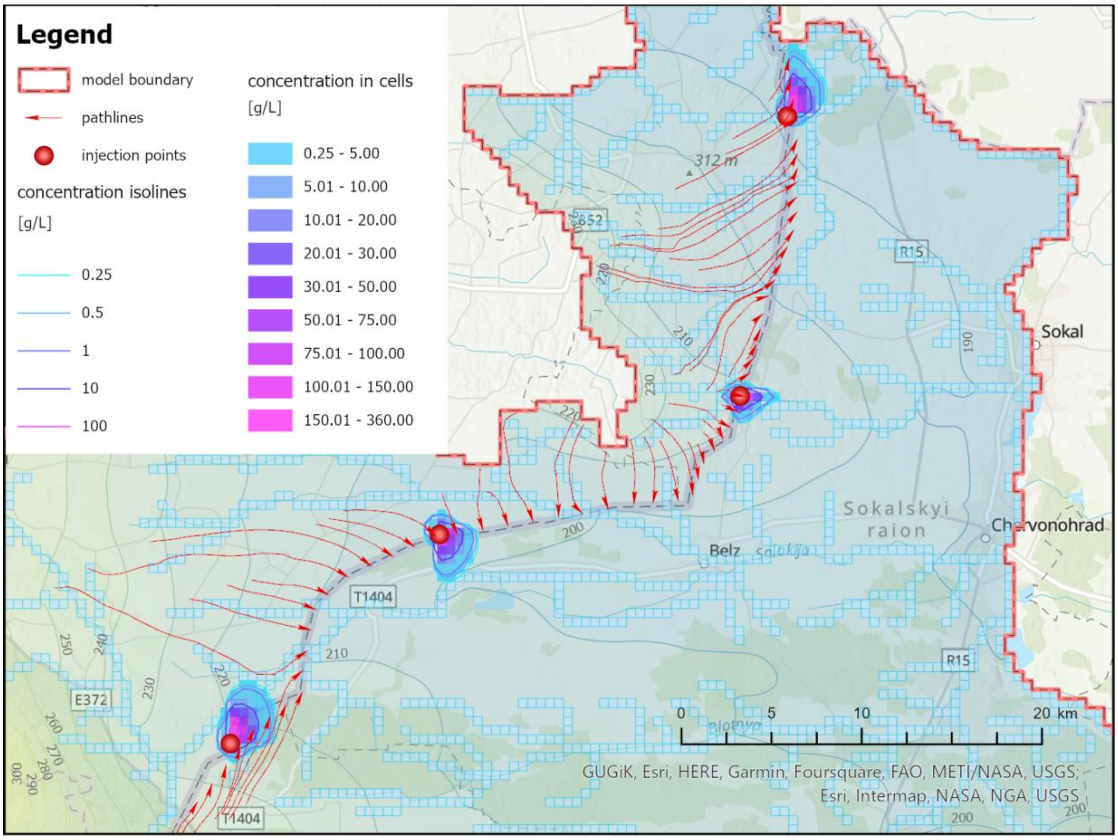


Figure 76. Calculated concentration field in the northern part of the PL-UA TAS area (A) 10 years after the start of continuous injection of the conservative substance (variant 2)

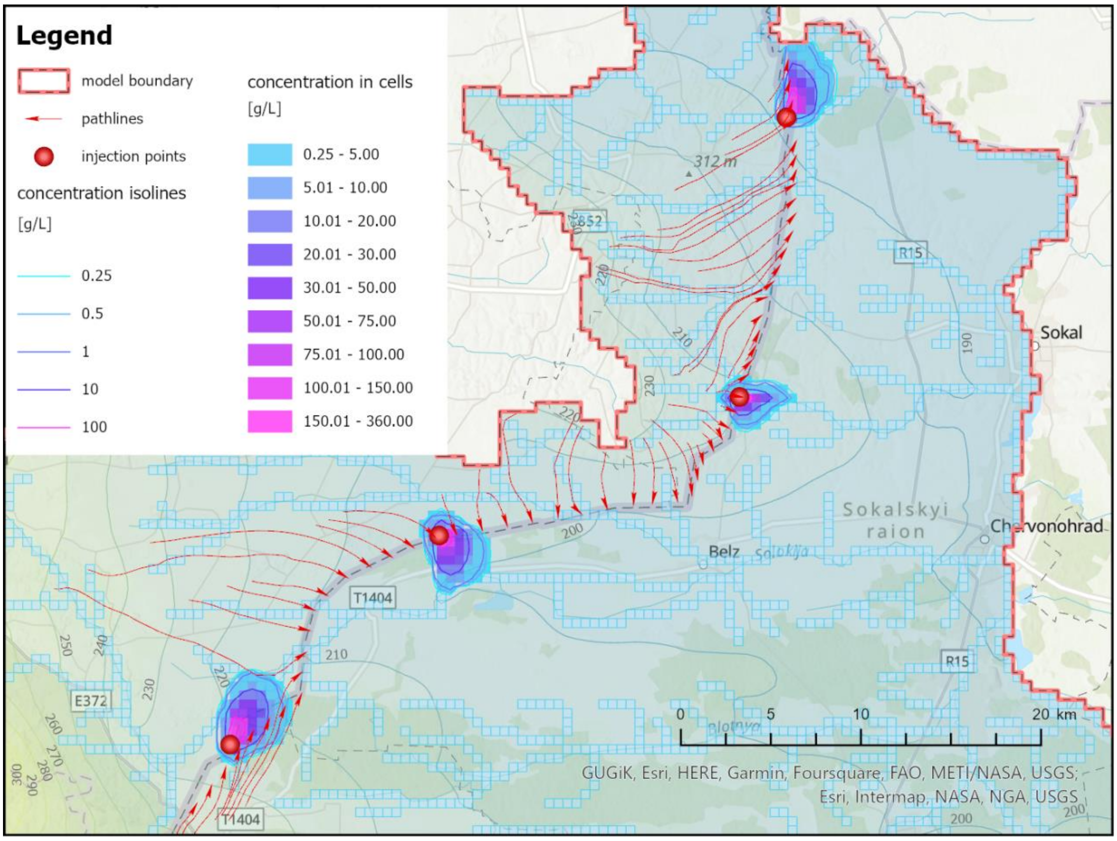


Figure 77. Calculated concentration field in the northern part of the PL-UA TAS area (A) 25 years after the start of continuous injection of the conservative substance (variant 2)

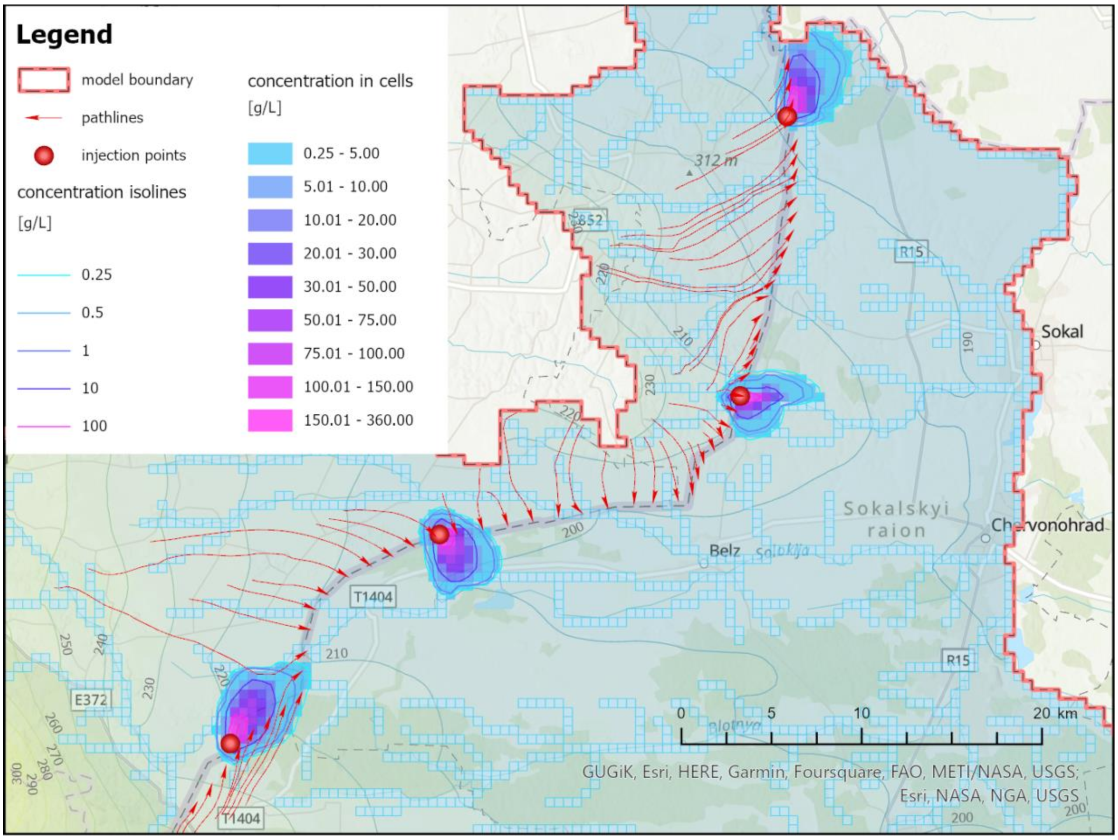


Figure 78. Calculated concentration field in the northern part of the PL-UA TAS area (A) 50 years after the start of continuous injection of the conservative substance (variant 2)

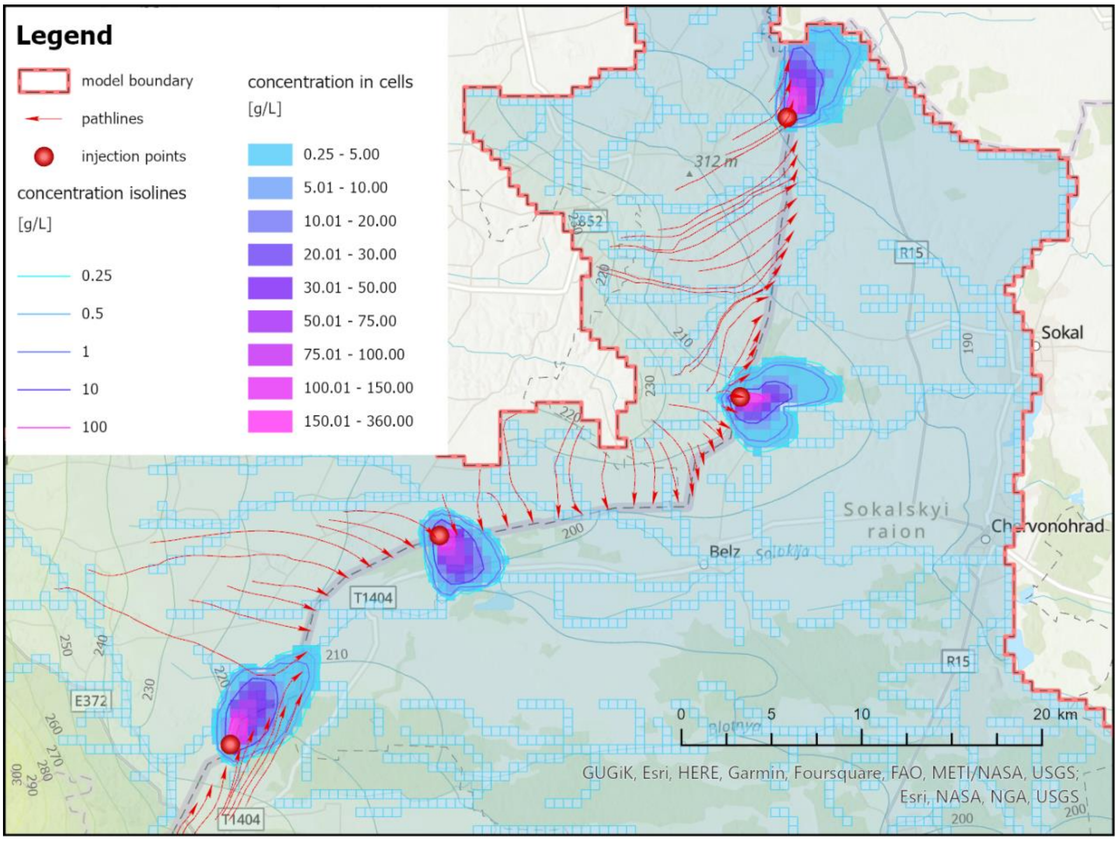


Figure 79. Calculated concentration field in the northern part of the PL-UA TAS area (A) after 100 years from the start of continuous injection of the conservative substance (variant 2)

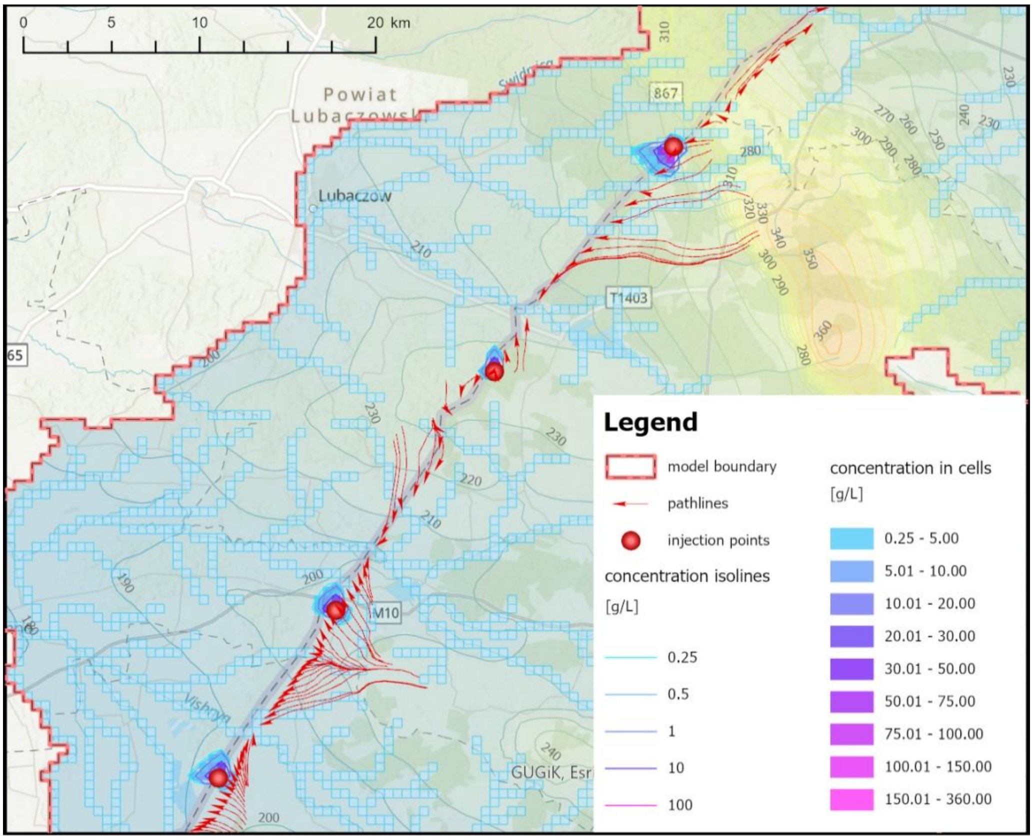


Figure 80. Calculated concentration field in the northern part of the PL-UA TAS area (B) one year after the start of continuous injection of the conservative substance (variant 2)

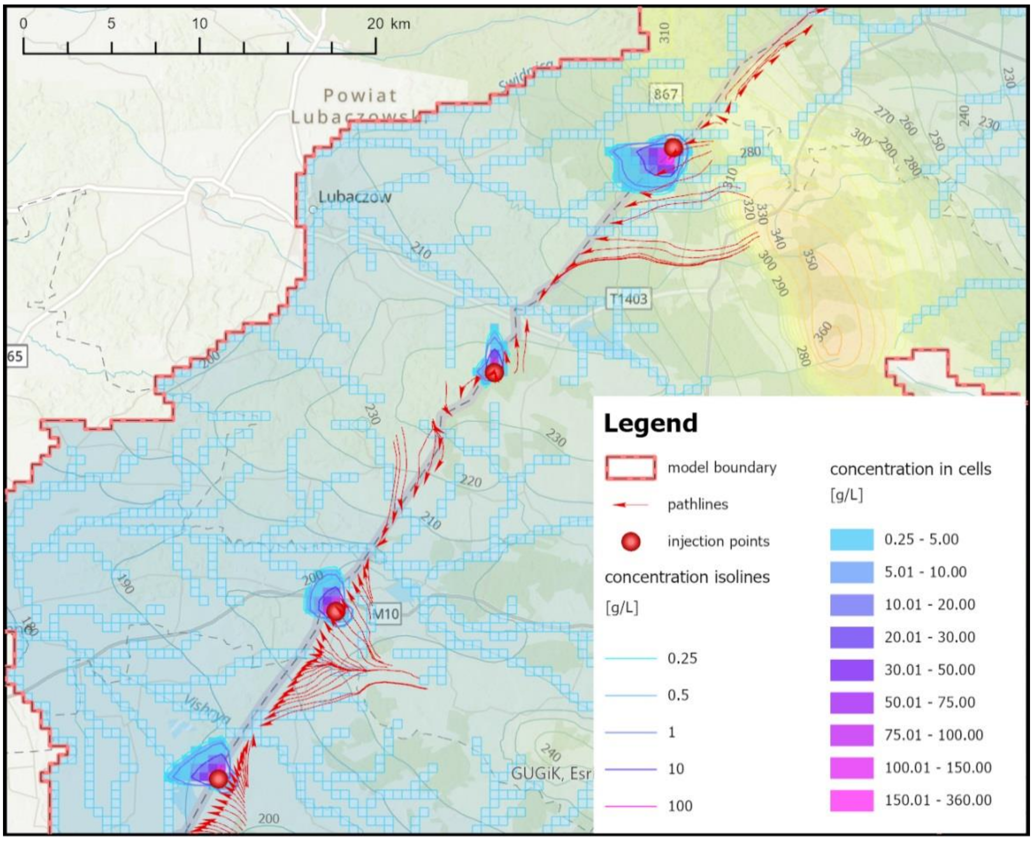


Figure 81. Calculated concentration field in the northern part of the PL-UA TAS area (B) after 5 years from the start of continuous injection of the conservative substance (variant 2)

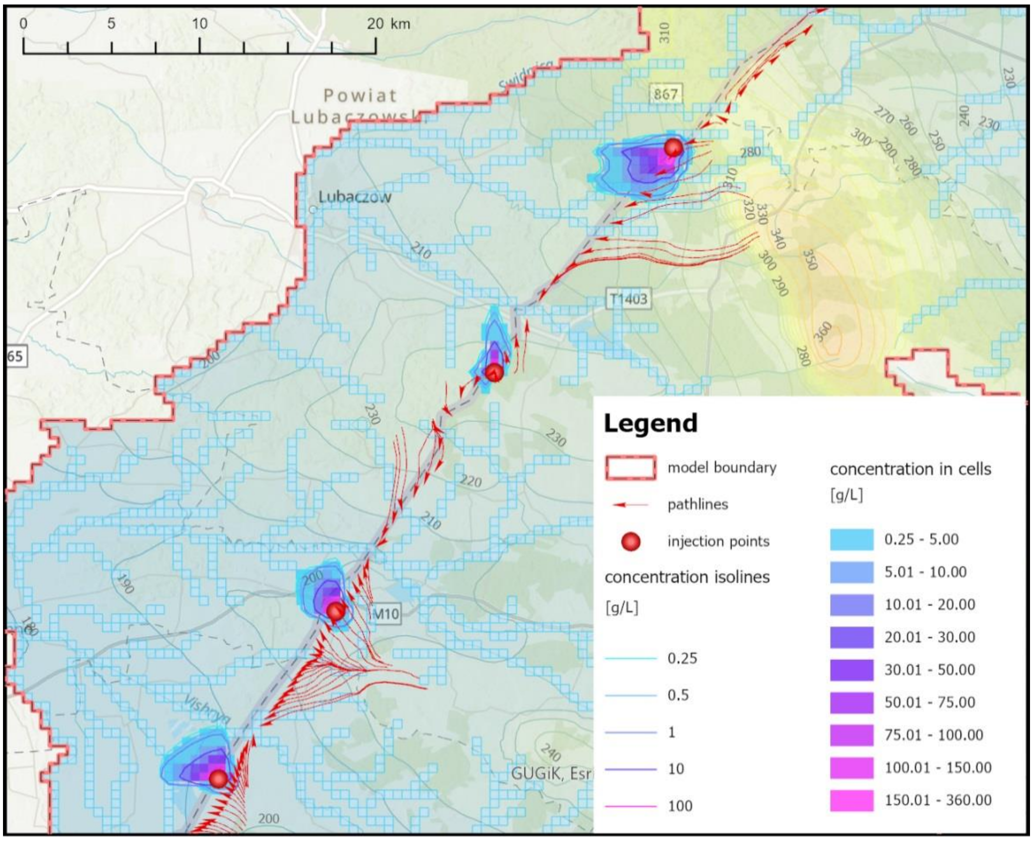


Figure 82. Calculated concentration field in the northern part of the PL-UA TAS area (B) 10 years after the start of continuous injection of the conservative substance (variant 2)

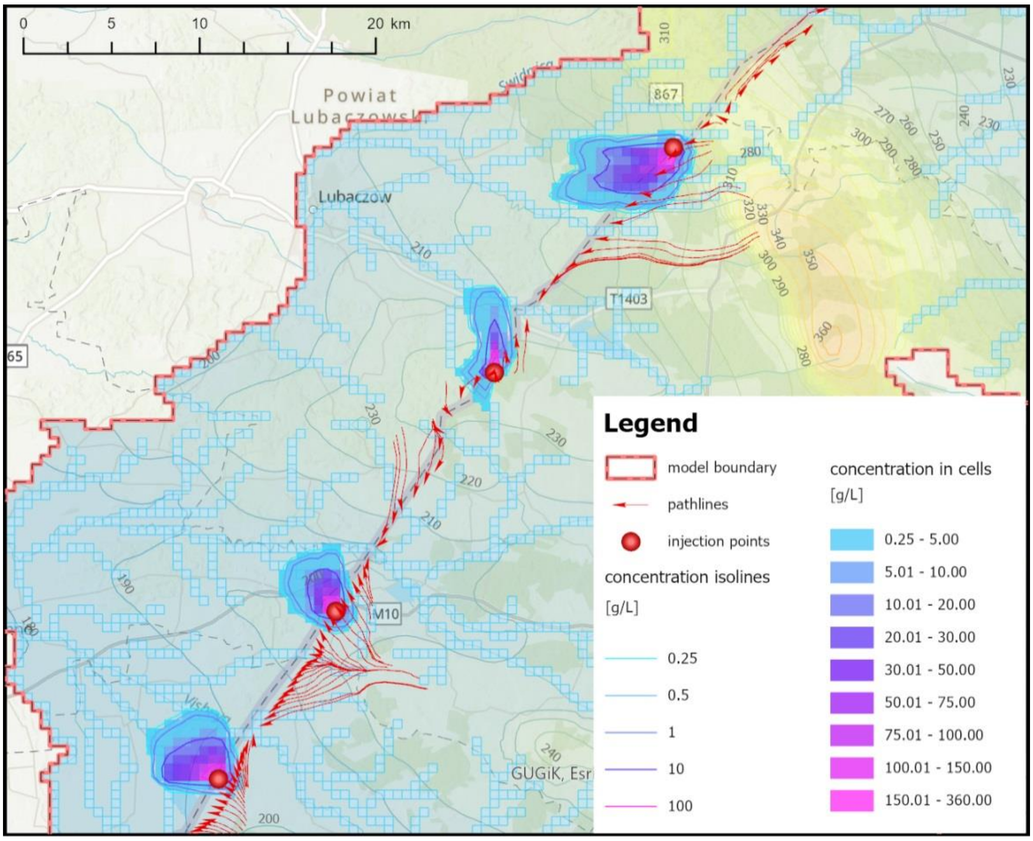


Figure 83. Calculated concentration field in the northern part of the PL-UA TAS area (B) 25 years after the start of continuous injection of the conservative substance (variant 2)

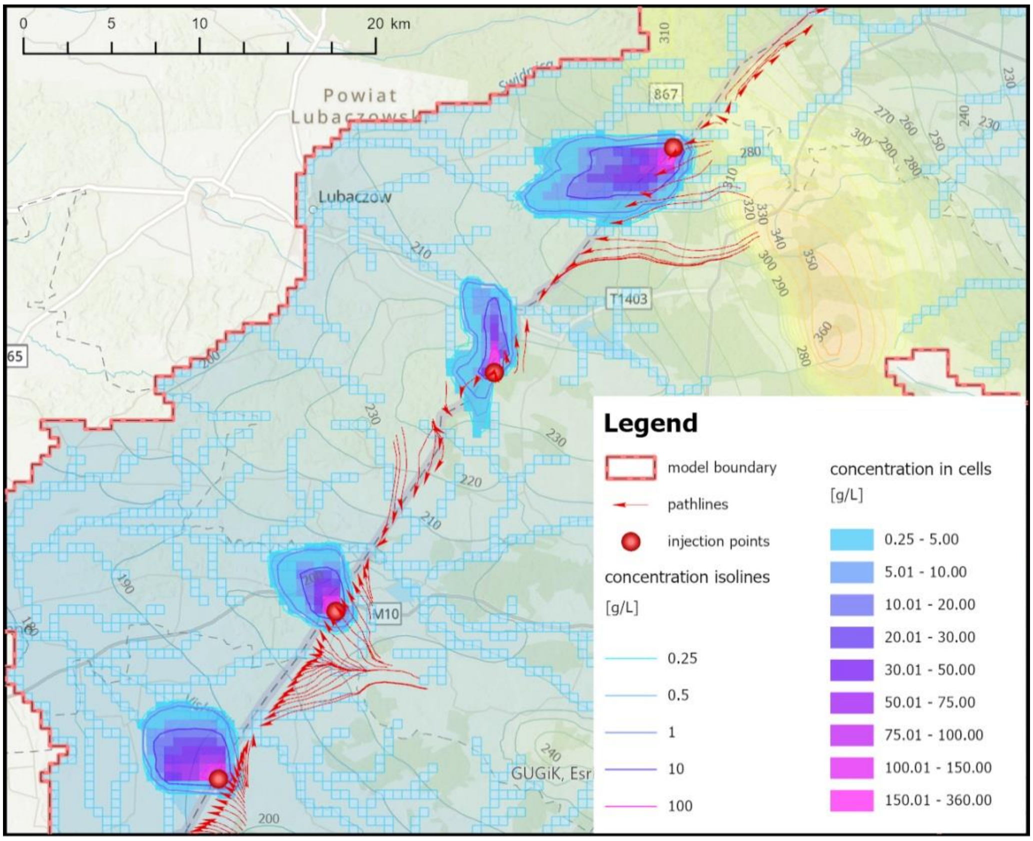


Figure 84. Calculated concentration field in the northern part of the PL-UA TAS area (B) 50 years after the start of continuous injection of the conservative substance (variant 2)

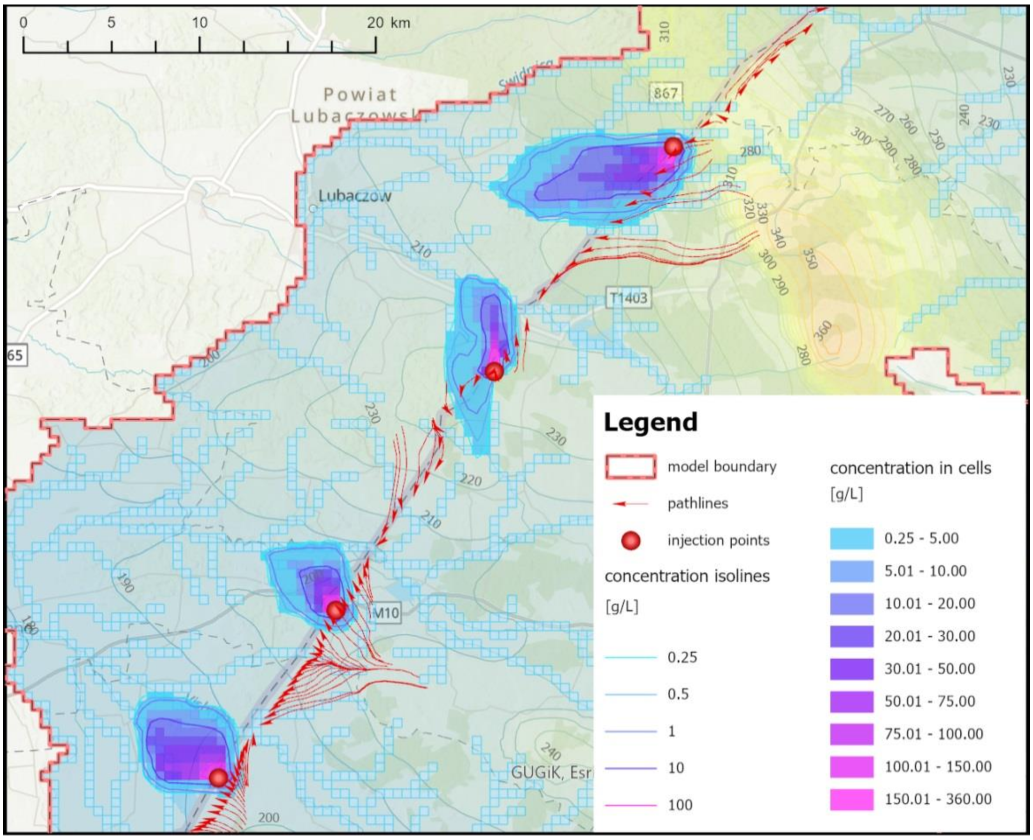


Figure 85. Calculated concentration field in the northern part of the PL-UA TAS area (B) after 100 years from the start of continuous injection of the conservative substance (variant 2)

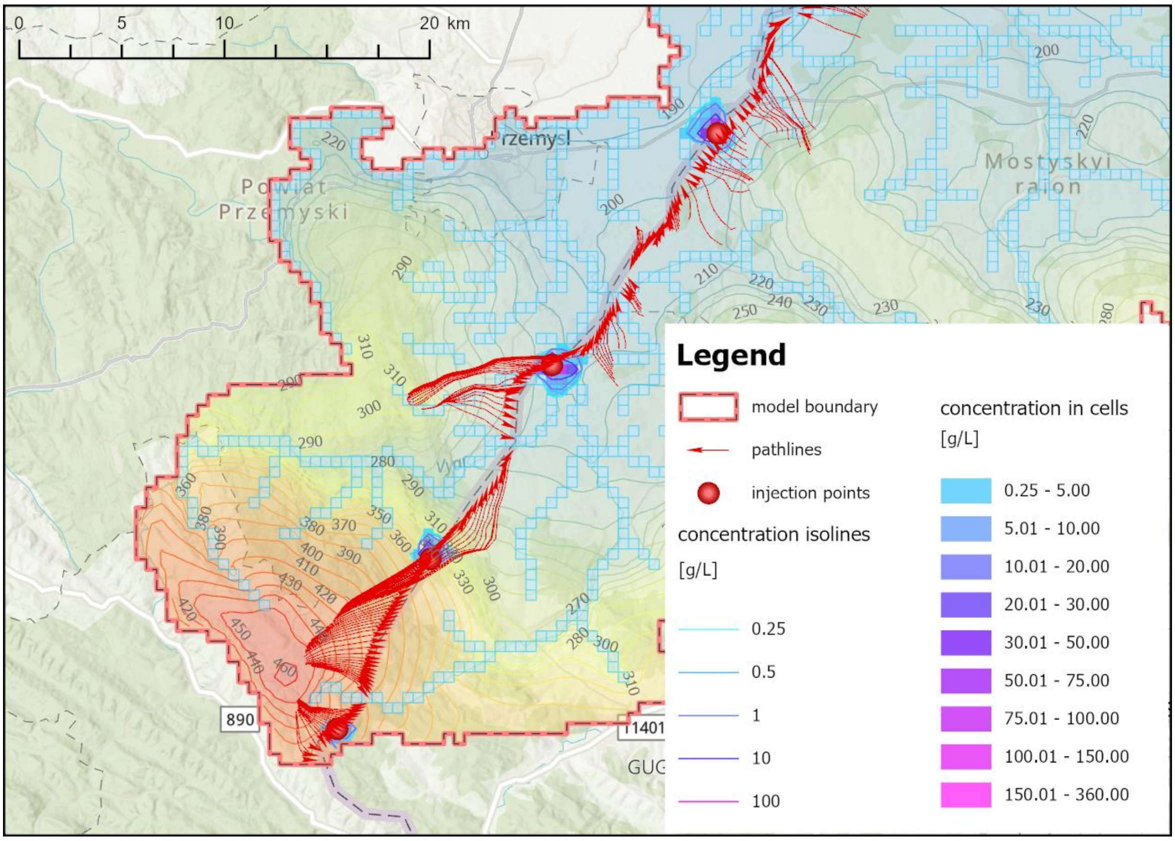


Figure 86. Calculated concentration field in the northern part of the PL-UA TAS area (C) one year after the start of continuous injection of the conservative substance (variant 2)

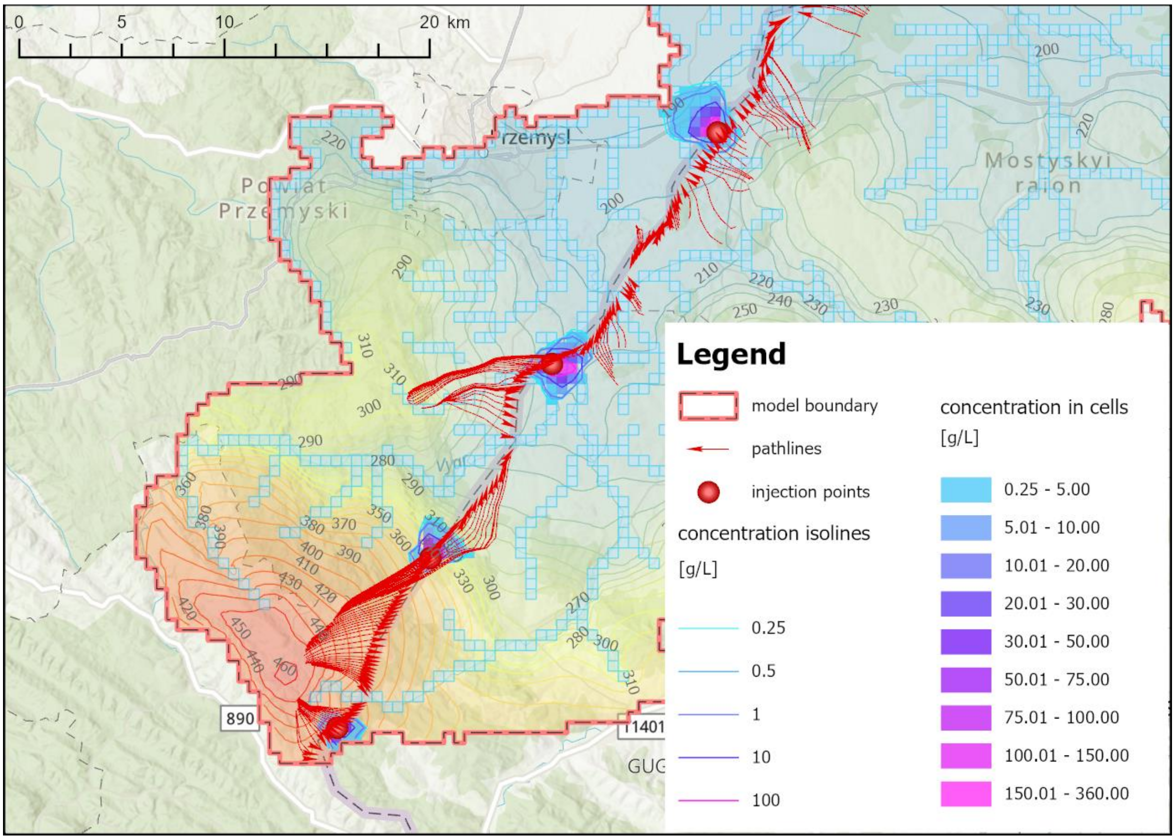


Figure 87. Calculated concentration field in the northern part of the PL-UA TAS area (C) after 5 years from the start of continuous injection of the conservative substance (variant 2)

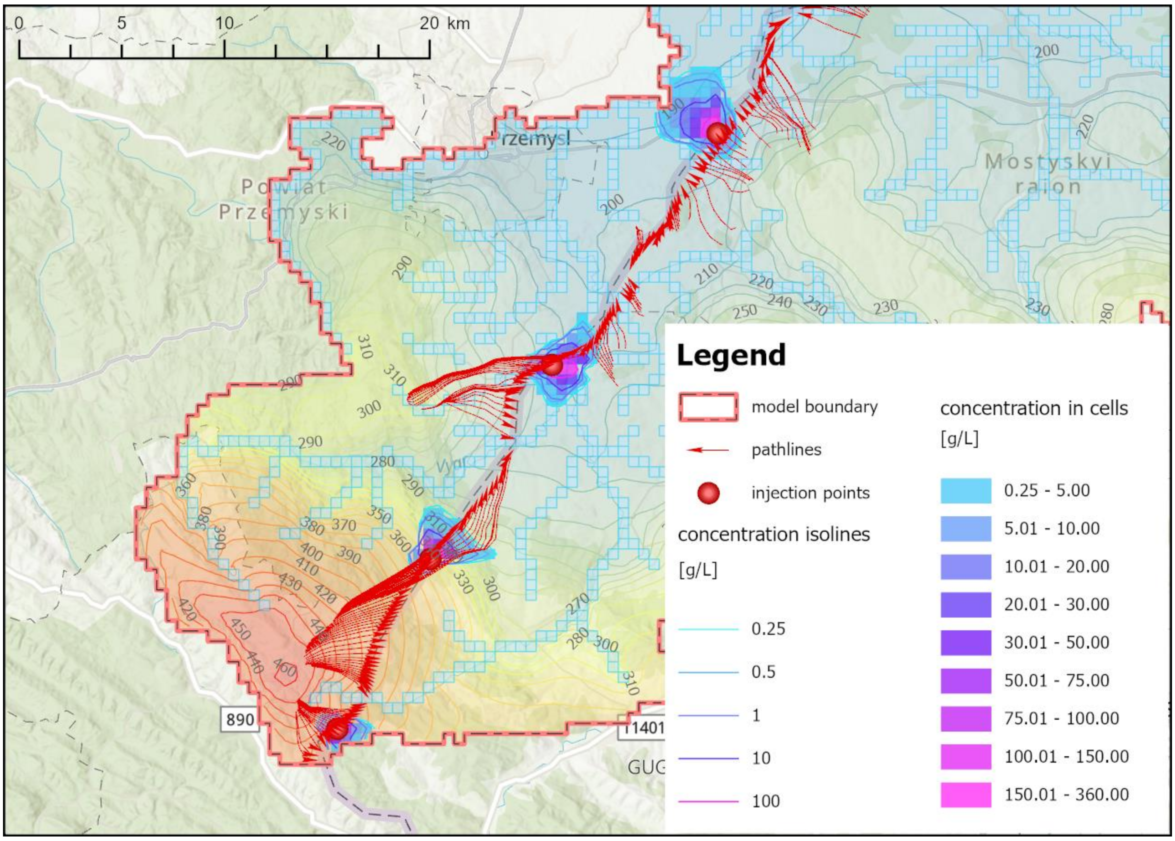


Figure 88. Calculated concentration field in the northern part of the PL-UA TAS area (C) 10 years after the start of continuous injection of the conservative substance (variant 2)

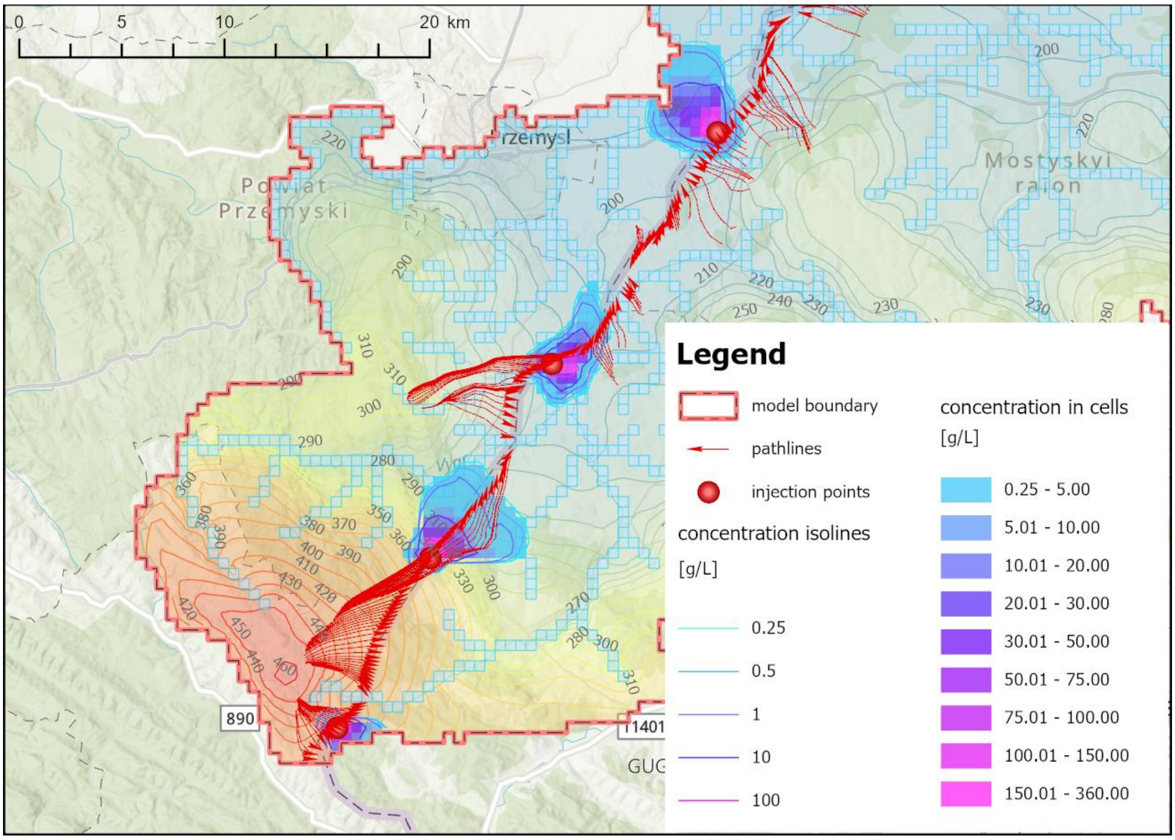


Figure 89. Calculated concentration field in the northern part of the PL-UA TAS area (C) 25 years after the start of continuous injection of the conservative substance (variant 2)

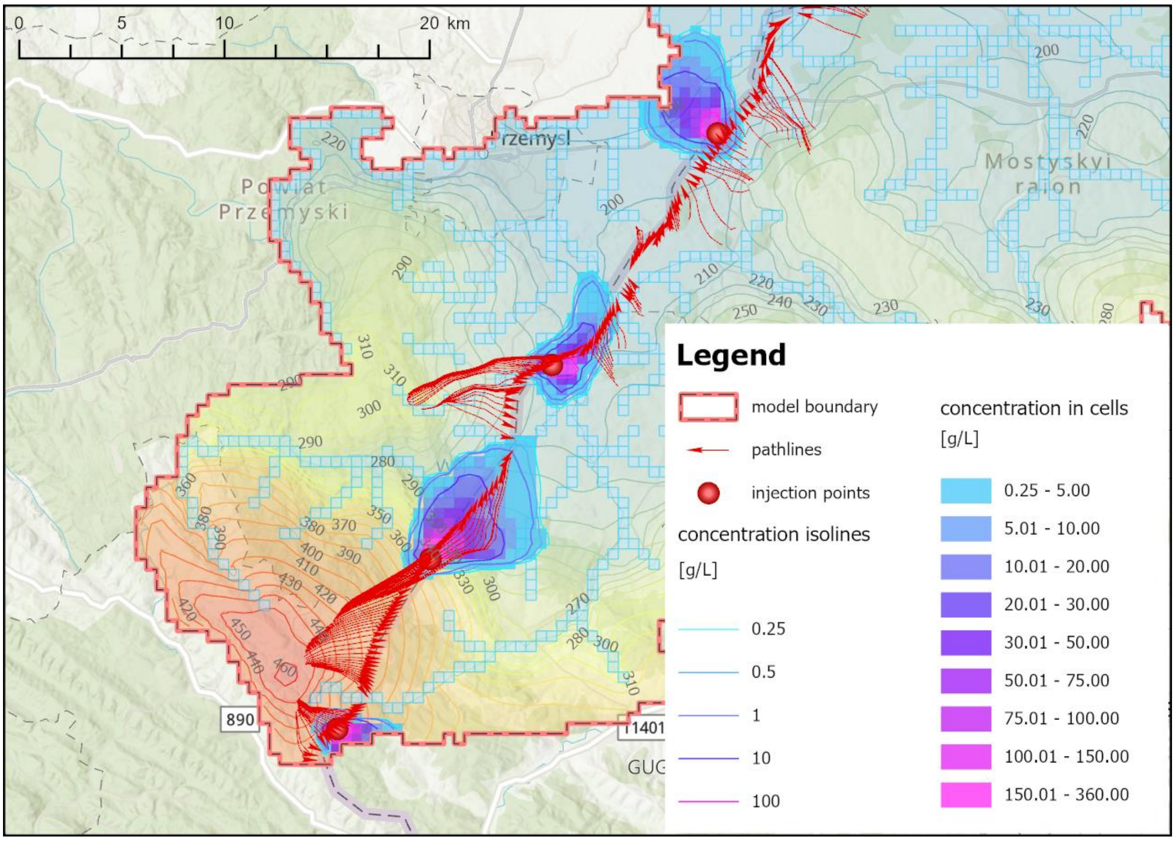


Figure 90. Calculated concentration field in the northern part of the PL-UA TAS area (C) 50 years after the start of continuous injection of the conservative substance (variant 2)

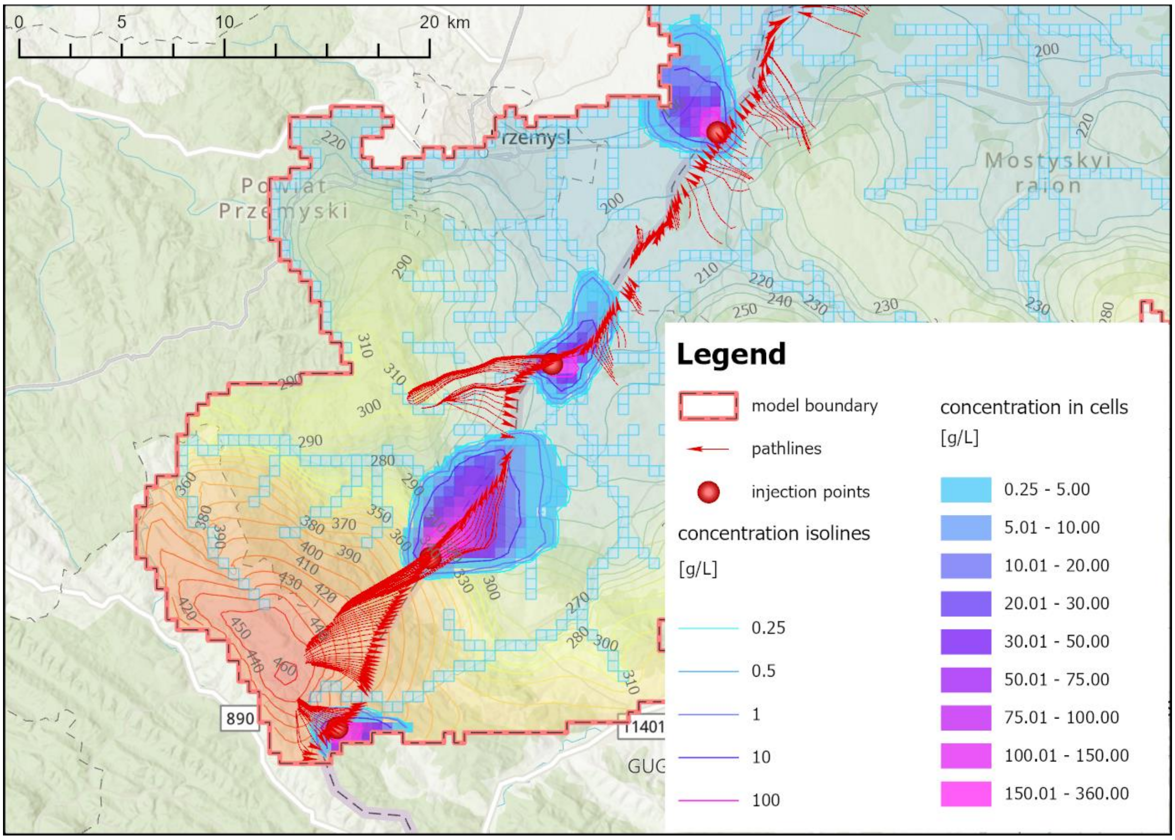


Figure 91. Calculated concentration field in the northern part of the PL-UA TAS area (C) after 100 years from the start of continuous injection of the conservative substance (variant 2)

6. Program for quantitative protection of groundwater in the Polish-Ukrainian Cross-border Aquifer System

This is the first scientific study comprehensively discussing the possibilities and necessary directions of action in the field of protection of common groundwater resources of PL-UA TAS. Considering that this program should be complementary to other planning documents in the field of water management - water management plans, flood risk management plans, drought effects counteracting plan, the proposed solutions are slightly ahead of the events, because for the PL-UA TAS none of the above planning documents have been developed yet.

In accordance with the WFD, each Member State shall ensure the establishment of a program of measures (measures) for all river basin districts and parts of international river basin districts lying on its territory, taking into account the results of the analyzes required by Art. 5 WFD (including a review of the impact of human activities on the environment and an economic analysis of water use). The action program should be aimed at achieving environmental objectives for surface waters, groundwater and protected areas.

The main objective of the Polish-Ukrainian TAS quantitative protection program for groundwater is to prevent the depletion of resources of transboundary aquifers (ensuring the balance between abstraction and recharge of these waters so as to achieve their good condition) and to take corrective actions and to increase water retention. The main objective is to be supported by specific objectives:

- Indication and implementation of activities related to the construction of an integrated TAS management system;
- Creating conditions for sustainable use of groundwater resources;
- Strengthening public awareness of the need to save water.

Planned activities should contribute to achieving the program objectives. The basis for their determination is to carry out analyzes of the deficits of groundwater resources in the TAS area, to determine the current and future demand for water, as well as to analyze the retention status. Protective measures can be broadly divided into soft and hard. Soft includes educational, informational and promotional activities related to strengthening public awareness of the need to retain and save water. Administrative and economic instruments based on the national regulations of both countries should play a key role in the implementation of the Program. In Poland and Ukraine, water resources management instruments include:

1. planning in water management;
2. water permits;
3. fees and charges in water management;
4. water cadastre;
5. water management control.

The planning process for water management in Poland is carried out based on the Water Management Plan for the river basin area, which is updated every 6 years. Taking into account the location of the PL-UA TAS area, the document that directly affects this area is the Water Management Plan in the Vistula River Basin Area, which was updated on November 4, 2022.

Ukraine currently has the status of an associated country with the European Union and is undergoing administrative reform in the field of water resources management. In the context of the above, WFD implementation is ongoing in Ukraine, in particular the obligation to develop water management plans and other planning documents resulting from the WFD provisions has been introduced. Currently, draft Water Management Plans for 9 river basins have been developed and public consultations are ongoing. Approval of Water Management Plans is planned by the end of 2024. For the Vistula river basin area, where the PL-UA TAS is located, the first part of the draft Water Management Plan has already been developed, containing information on the GWB list and the monitoring system in relation to groundwater. Other key elements are still missing, such as: 1) identification of significant anthropogenic impacts and assessment of their impact on the status of groundwater, 2) environmental goals for GWB, 3) actions to implement the principle of cost recovery for water services, 4) actions to implement environmental goals and requirements related to water supply, 5) information regarding water law permits, 6) information about permits to introduce pollutants directly into groundwater, 7) actions to eliminate the concentrations of priority substances, 8) information about the method of carrying out water maintenance activities.

The water management plan in the Vistula river basin area in Poland and Ukraine, in accordance with the legal framework, is an important tool for the protection of water resources through the impact of its provisions on procedures related to determining spatial development, issuing water permits and decisions on environmental conditions. The plans constitute the basis for making decisions shaping the state of water resources in river basin areas and the principles of their management in the future. In addition, they serve, among others, to coordinate activities aimed at achieving or maintaining at least good status of waters and water-dependent ecosystems, improving the condition of water resources, improving the possibilities of using water, reducing the amount of substances introduced into water or land that may have a negative impact on water.

On the Polish side, PGW WP is responsible for the implementation of the Water Management Plans in the PL-UA TAS area, in particular RZGW WP in Rzeszów and Lublin and ZZ WP in Przemyśl. These bodies also cooperate with the Marshal's Office of the Lublin Voivodeship and the Regional Directorate for Environmental Protection in Lublin. On the Ukrainian side, water management in the study area is the responsibility of the Catchment Management Board of Water Resources in Lviv, which is subordinated to the State Agency for Water Resources of Ukraine, in cooperation with the Management Board of the Bug and San Catchments.

The assumption of the PL-UA TAS groundwater protection plan is to implement protective measures regarding GWB within a given area resulting from the Vistula Water Management Plan as obligatory and supplementary, recommended on the basis of assessments carried out as part of the EU-Waterres project.

The program of protective measures, as an integral element of the Water Management Plan, was developed only for the Polish part of the TAS area. In Ukraine, it is difficult to expect the development of this program in the near future, at least due to the lack of preceding documents - assessment of the state of the GWB, assessment of pressure on the state of the GWB, environmental goals for the GWB. However, the basic actions resulting from the Polish Vistula Water Management Plan can be largely transferred to the Ukrainian part of the TAS area, because these actions are referred to as minimum requirements and therefore their scope is very wide.

Mandatory quantitative protection measures for the Polish part of the TAS resulting from the Vistula Water Management Plan

The measures have been selected and assigned to GWB individually and their implementation within the indicated GWB is obligatory regardless of their current status or the risk of failure to achieve environmental goals.

In the PL-UA TAS area, there are a total of 23 GWB on both sides of the border (Table 10). The condition of all PL GWB is good in terms of chemical and quantitative status. The pressure analysis did not reveal any threats in any of the PL GWB, and accordingly there is no risk of failure to achieve environmental goals. For the UA GWB, a formal condition assessment, risk analysis and definition of environmental objectives have not yet been carried out. However, the EU-Waterres project developed a pilot program of quantitative protection activities for cross-border GWB of the Ukrainian part of the Vistula catchment area, which is discussed in the following part of this chapter.

Table 10. GWB within the PL-UA TAS

Poland	Ukraine
Bug catchment	
PLGW200067 PLGW200091 PLGW2000121	UAA6.6.1.01Q100 UAA6.6.1.02Q100 UAA6.6.1.02Q200 UAA6.6.1.01N100 UAA6.6.1.01K100 UAA6.6.1.02K100 UAA6.6.1.01D100
San catchment	
PLGW2000136 PLGW2000154 PLGW2000168	UAA6.6.2.03Q100 UAA6.6.2.03Q200 UAA6.6.2.03N100 UAA6.6.2.03K100
Dniestr catchment	
PLGW2000169	UAM5.2.0.01Q100 UAM5.2.0.01Q200 UAM5.2.0.01Q300 UAM5.2.0.01N101 UAM5.2.0.01K101

Each mandatory measure developed for the Polish part of the TAS below is characterized by information regarding (Table 11):

- name of the measure along with the specification of the implementation schedule for the given one,
- description of measure,
- determining the type of pressure that the measure is aimed at reducing (quantitative pressures or quantitative and chemical pressures),
- designation of units responsible for its implementation.

Table 11. Mandatory GWB quantitative protection measures for the Polish part of TAS

GWB number	Name of the measures, implementation schedule	Description of measure	Type of pressure that the measure is aimed at	Unit responsible for implemetnation
PLGW2000136 PLGW2000154 PLGW2000168	Verification of available groundwater resources, by 2024	Preparation of hydrogeological documentation determining the available resources for the upper Wisłok and San catchment areas below Sanok within the Flysch Carpathians	Quantitative pressure	Polish Hydrogeological Survey
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Groundwater abstraction control, continuous measure	Inventory of boreholes up to 30 m deep for the purpose of constructing groundwater intakes for the purposes of groundwater abstraction in an amount not exceeding 5 m^3/day, not requiring the preparation of a geological works project	Quantitative pressure	Communes, Regional Water Management Board
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Environmental impact assessment, continuous measure	Obligation to conduct a cross-border environmental impact assessment for projects for which a significant cross-border impact has been identified	Chemical and quantitative pressure	The investor in the scope of submitting an application for a decision on environmental conditions, the authority competent to issue a decision on environmental conditions, the Chief Directorate for Environmental Protection
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Registration activities, continuous measure	Obligation to include groundwater reservoirs, water intake protection zones and inland water reservoirs protection areas in spatial planning acts	Chemical and quantitative pressure	Authorities competent in matters of spatial planning + authorities competent to issue decisions on development conditions and land development
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Water permits, continuous measure	Obligation to obtain a water law assessment for investments and activities that may affect the ability to achieve environmental goals	Chemical and quantitative pressure	An entity planning to implement investments or activities that may affect the ability to achieve environmental goals
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Water permits, continuous measure	Obligation to obtain water permits	Chemical and quantitative pressure	Entity using water services
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Groundwater monitoring, continuous measure	Conducting monitoring of the GWB in terms of quantitative and chemical status, maintaining and developing the groundwater observation and research network	Chemical and quantitative pressure	Polish Hydrogeological Survey
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Improving natural retention, continuous measure	Implementation of measures included in the plan to counteract the effects of drought in terms of improving natural retention	Quantitative pressure	Entities indicated in the plan to counteract the effects of drought as implementing agencies

The vast majority of mandatory measures are non-technical in nature. These measures are mainly focused on additional review of water permits and verification of available groundwater resources and operational groundwater intakes. In addition, they include monitoring groundwater and developing a research monitoring program for the state of groundwater in areas subject to significant anthropopressure, for example in the area of mining activities, and developing a drainage water management program.

Technical measures are related to the construction/modernization of retention facilities and the implementation of other methods of retention and management of rainwater in agriculture, as well as slowing down or stopping the outflow of water from the catchment area and increasing the retention capacity of the catchment area, including increasing retention in urbanized areas.

Mandatory quantitative protection measures for the Ukrainian part of TAS

Uncontrolled exploitation of groundwater can lead to its depletion, i.e. to such a decrease in levels that makes it impossible to further use the aquifer to meet the needs of the public through traditional technical means. Integrated management of transboundary water resources involves the sustainable rational use of available water resources based on the long-term protection strategy, constant control over the extraction, and monitoring the impact on the quantitative state of groundwater.

Quantitative protection of transboundary groundwater in the Polish-Ukrainian border area can be ensured by complying with the legislation in the field of water use and protection; regulating all types of economic and any other activities that effect the state of groundwater; monitoring the state of groundwater, in particular at water intake sites and in the vicinity of industrial and agricultural facilities to establish any discrepancies and deviations in the predicted levels of environmental impact of the facilities.

Assessment of the provision of transboundary aquifers with a uniform required network of monitoring points and justification of additional points arrangement within the model area was carried out for here-located groundwater bodies. The following main parameters were analyzed and taken into account:

1) directions of transboundary groundwater flows;
2) the presence of zones sensitive to water withdrawal;
3) number and location of existing monitoring points.

A quantitative assessment of flows at the level of groundwater resources available for management within the Polish-Ukrainian cross-border area was performed in the first phase of the EU-WATERRES project. For this purpose, a digital hydrodynamic model was created and described in detail in the report "Assessment of the resources of transboundary groundwater reservoirs for the 2 pilot areas" (https://eu-waterres.eu/wp-content/uploads/2021/12/Output-1.Assessment-of-the-resources-in-2-pilot-areas.pdf).

The identified transboundary groundwater flows were the basis for selecting transboundary monitoring sites (Figure 92).

The study of the impact of water abstraction on groundwater level changes using simulation modeling conducted at the project previous stage made it possible to classify the model area into zones of different sensitivity:

- low sensitivity - decrease in groundwater level by 0.5-1 m
- significant sensitivity - a decrease in the groundwater level by 1-2 m;

- high sensitivity - a decrease in the groundwater level by more than 2 meters.

More details are described in the report "Transboundary impacts as a result of the exploitation of groundwater resources in Polish-Ukrainian and Estonian-Latvian pilot areas" (https://eu-waterres.eu/nextcloud/index.php/s/BrzJf829oymGZFe). High sensitivity zones are indicators of the risk of depression cones occurrence. Their location allows us to justify the placement of additional monitoring points.

The main tool for quantitative groundwater protection in the Polish-Ukrainian transboundary aquifer system is monitoring.

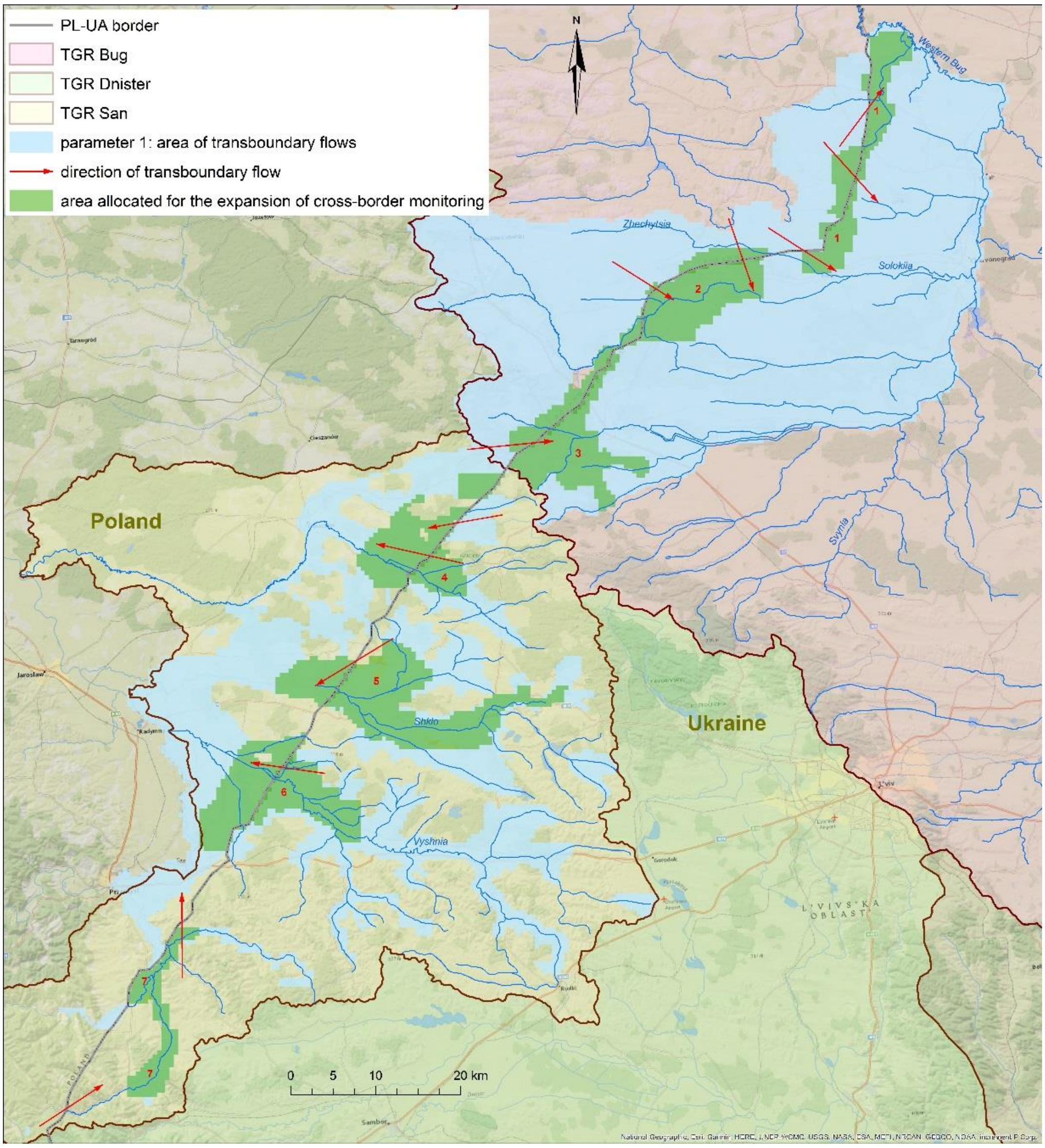


Figure 92. Directions of transboundary flows and designated sites for transboundary monitoring

Over the Polish-Ukrainian cross-border territory within the model area, which is part of the Vistula River basin, the following groundwater bodies have been identified on the Ukrainian side:

- UAA6.6.1.01Q100, UAA6.6.2.03Q100 groundwater bodies in alluvial Quaternary sediments
- UAA6.6.2.03Q200 groundwater body in fluvioglacial Quaternary deposits;

- UAA6.6.1.01N100, UAA6.6.2.03N100 groundwater bodies in the Miocene aquifers;
- UAA6.6.1.01K100, UAA6.6.2.03K100 groundwater bodies in the Upper Cretaceous aquifer.

The UAA6.6.1.01Q100 unconfined groundwater body, allocated in alluvial Quaternary sediments, is spatially located in the Western Bug River basin (Figure 93). As can be seen from the figure, the horizon groundwater is not used by large water intakes. Most likely, water is used only by private households and is not significantly affected by its abstraction. However, it may be hydraulically connected with the underlying Upper Cretaceous pressure aquifer and may be its partial supply source. Therefore, it is undoubtedly necessary to monitor groundwater levels in the UAA6.6.1.01Q100 groundwater body. As of today, there are 3 (the required minimum number of monitoring points per groundwater body) monitoring points for this aquifer. In addition, one monitoring point for the alluvial Quaternary aquifer within the project has recently been equipped with an automatic level measurement device. Formally, it is located outside the allocated body, but taking into account strict criteria for the allocation of groundwater body in terms of the capacity and water supply, and having additionally analyzed geological and hydrogeological maps, we understand that the monitoring point contains waters from the alluvial Quaternary horizon, but of lower capacity. Therefore, we assume that this monitoring point can be used to control the quantitative state of the UAA6.6.1.01Q100 groundwater body.

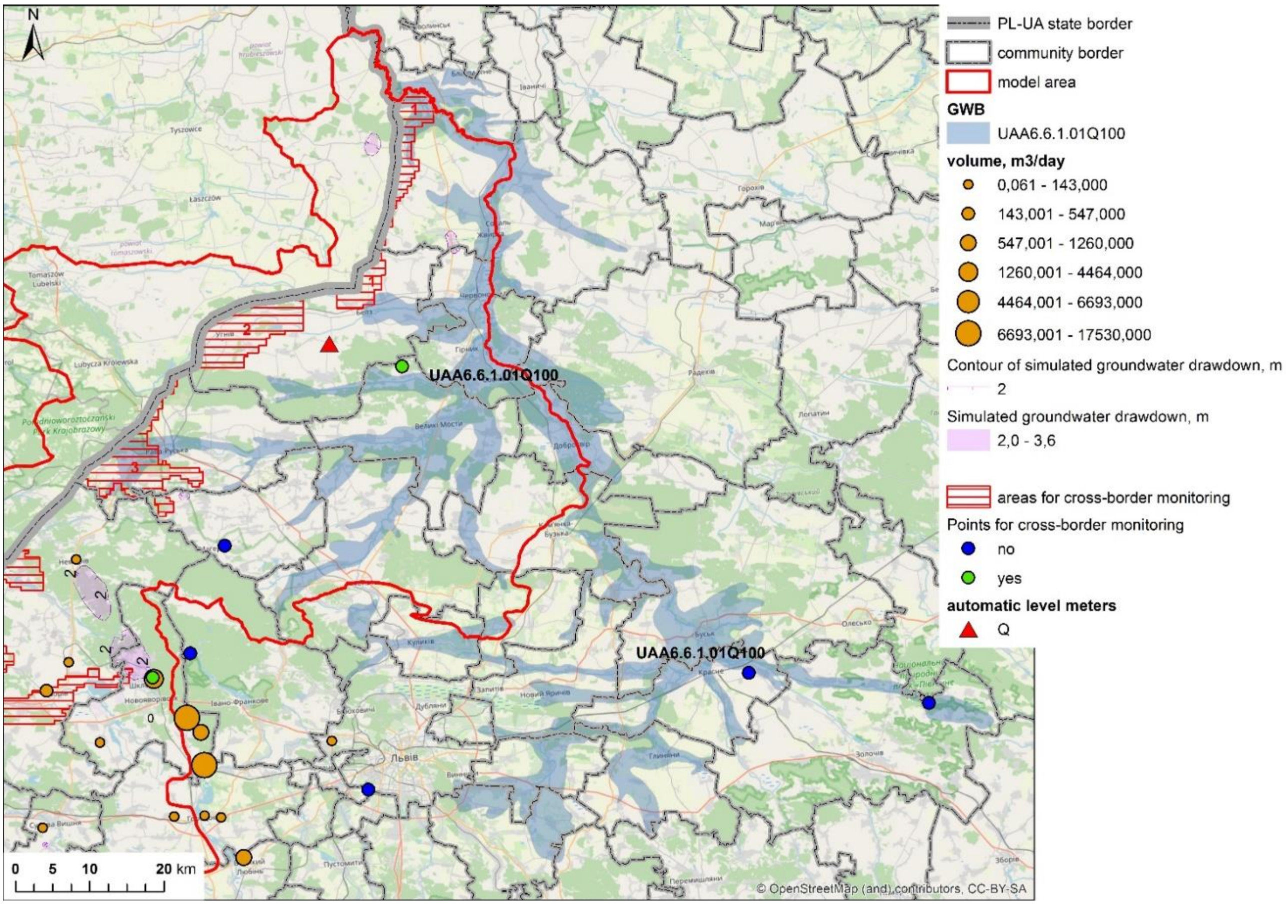


Figure 93. Status of monitoring of the UAA6.6.1.01Q100 groundwater body in Quaternary sediments

The UAA6.6.2.03Q100 unconfined groundwater body, allocated in alluvial Quaternary sediments, is spatially located in the San River basin. As can be seen from the figure (Figure 94), the horizon groundwater is used to meet the water supply needs of the population living within the territory due to the lack of distribution of powerful artesian groundwater horizons here. However, water intakes are not characterized by high capacity (up to 100 m^3/day or 326 m3/day if hydraulically connected with the Quaternary aquifer and underlying local Lower Neogene aquifer, which in both cases is significantly less than the maximum allowable withdrawal rate). In this case, the groundwater body is transboundary and, accordingly, requires quantitative monitoring as part of transboundary monitoring system. At present, there is no necessary monitoring network for this body. Only within the allocated area No. 6 (Mostyska – TC (Territorial Community)) there are 2 monitoring points, one of which is equipped with an automatic level gauge. Therefore, it is recommended to equip 3 additional monitoring points within the designated cross-border areas No. 4 (Nemyriv in Yavoriv TC), No. 5 (Krakivets in Yavoriv TC) and No. 7 (Nyzhankovychi in Dobromyl TC), one point for each.

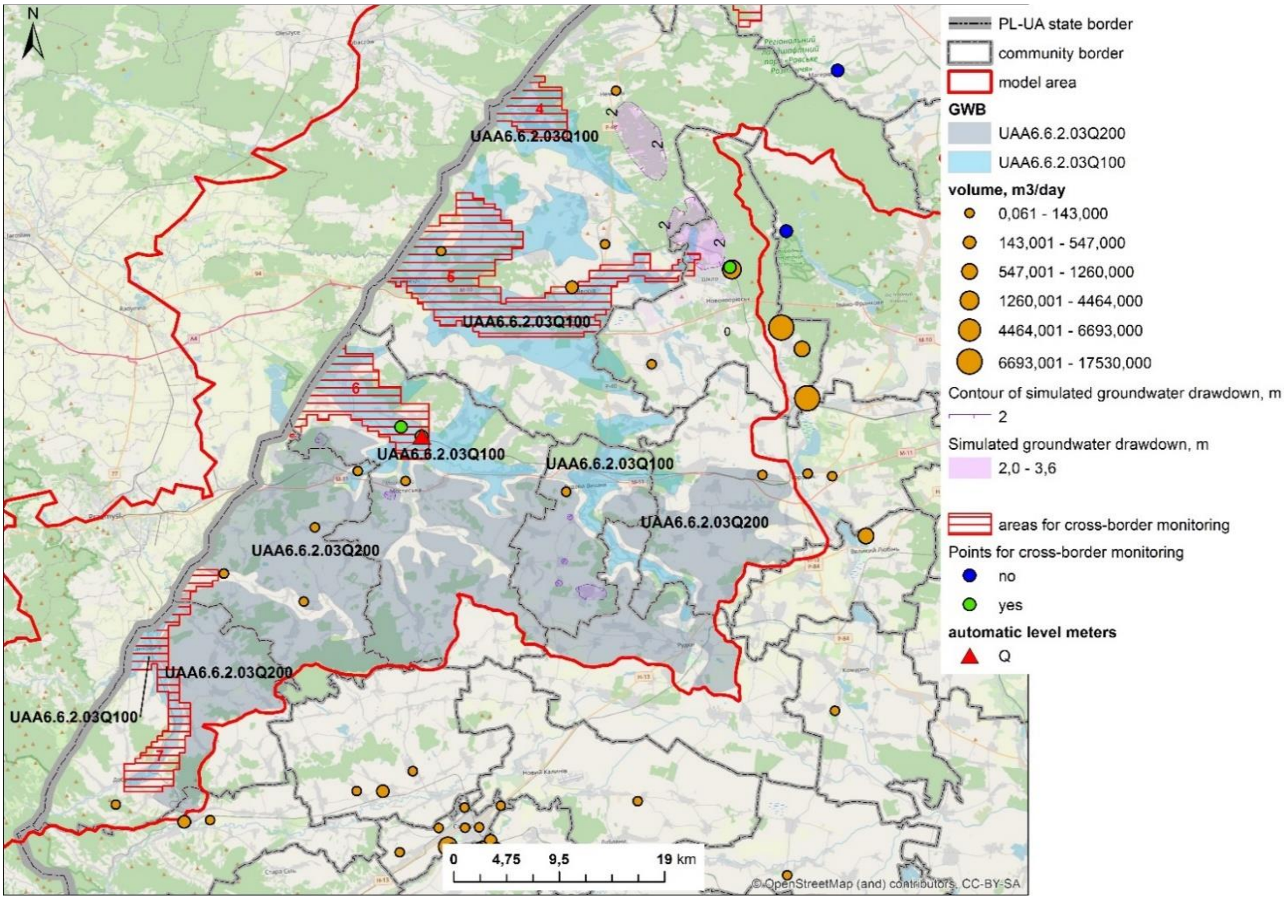


Figure 94. Status of monitoring of UAA6.6.2.03Q100, UAA6.6.2.03Q200 groundwater bodies in Quaternary sediments

The UAA6.6.2.03Q200 unconfined groundwater body, allocated in Quaternary fluvioglacial sediments, is spatially located in the San River basin (Figure 94). The groundwater of the horizon is of local importance and is used to meet the water supply needs of the population, as it is the main useful aquifer for this area. However, the existing water intakes are of low capacity (1-3 m^3/day).

Even though individual intakes operate with low efficiency, in total they produce a cumulative effect on the quantitative state of groundwater. Therefore, when studying the impact of water withdrawal on groundwater level changes using simulation modeling within the UAA6.6.2.03Q200 body, areas with high sensitivity to groundwater level drops (by more than 2 m) were identified, which could lead to the occurrence of real depression cone. Two small areas with high sensitivity to groundwater level decline are located in the south of Mostyska TC (Zaverkhy village), one near Mostyska town, and four within Sudovovyshnyanska TC (villages of Dmytrovychi, Didiatychi, Shyshorovychi, Makuniv).

At the moment, the groundwater body is not provided with monitoring points, so it is recommended to arrange 3 monitoring points for the quantitative state of groundwater in areas with high sensitivity to groundwater level decline, namely near villages of Zaverkhy, Mostyska and Makuniv.

The UAA6.6.1.01N100 confined groundwater body, allocated in Miocene sediments, is spatially located in the watershed part of the Western Bug and San river basin, but belongs to the Western Bug basin (Figure 95). Large centralized water intakes do not exploit it but it is of local importance. The only registered water intake near the village of Maidan (Zhovkivska TC) operates with a capacity of 143 m^3 / day, which is less than the permissible withdrawal rate. There are no monitoring points here. To observe the quantitative state of the groundwater body three monitoring points should be arranged. It is proposed to establish two points within the model area: one point in area No. 3, allocated for transboundary monitoring, near the village of Kovali, and the second - near the village of Maidan to control water intake. The third monitoring point is proposed to be set up directly within the city of Lviv, where the UAA6.6.1.01N100 groundwater body is distributed.

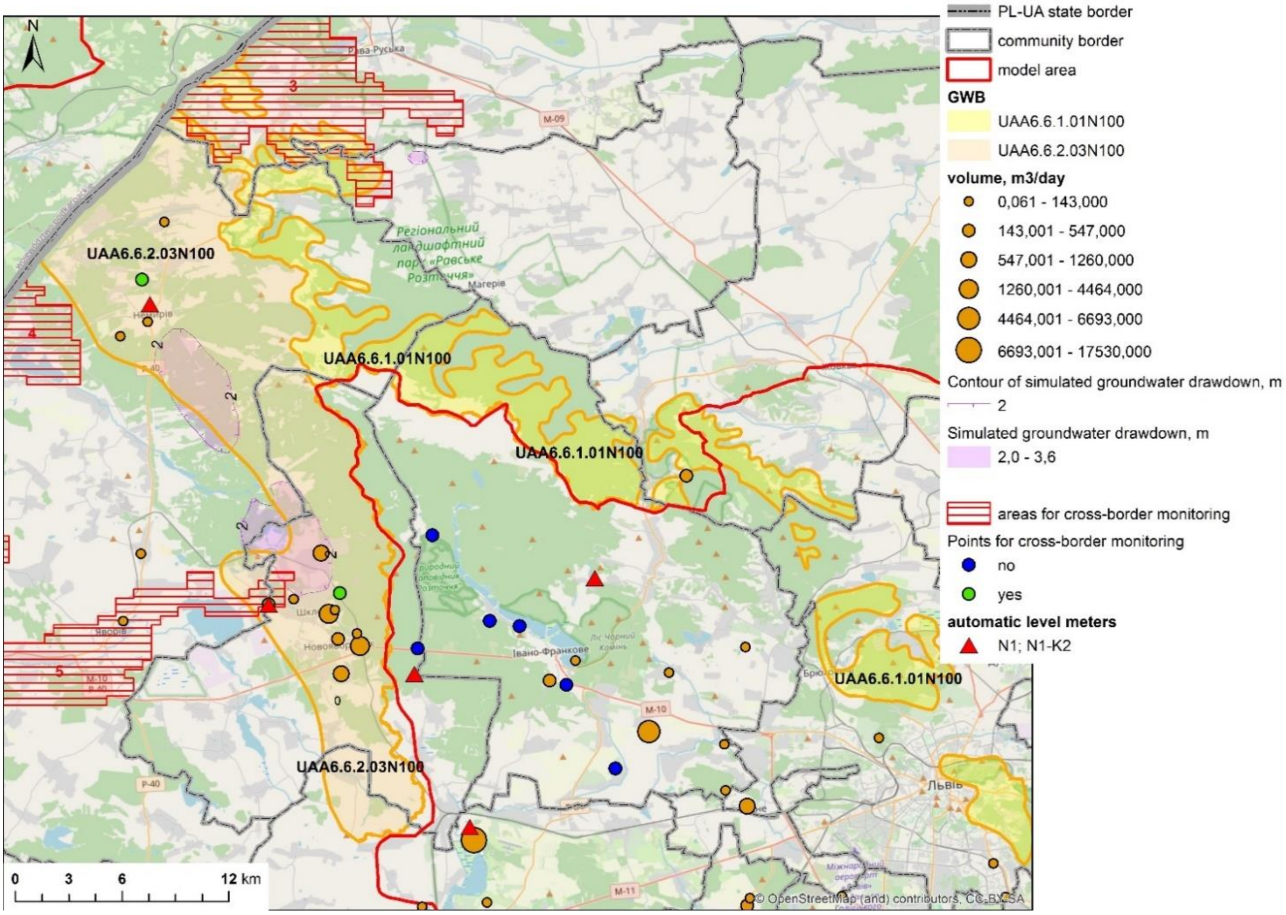


Figure 95. Status of monitoring of UAA6.6.1.01N100, UAA6.6.2.03N100 groundwater bodies in Miocene deposits

The UAA6.6.2.03N100 confined groundwater body in Miocene sediments is spatially located in the San River basin. It is actively exploited: 11 registered water intakes with a capacity of 4 to 3000 m3/day operate there. This has been reflected in simulation models, which revealed 2 fairly large locations which are highly sensitive to a decrease in groundwater level (by more than 2 m) (Figure 95). However, this groundwater body has 4 monitoring points, two of which are equipped with automatic groundwater level measurement devices and the points are located near areas of high sensitivity.

The UAA6.6.1.01K100 Upper Cretaceous aquifer (Figure 96) is widespread within the Western Bug River basin and the model area. It is important for the water supply of the region and is exploited by a large number of registered water intakes with different capacities (from 0.4 to 10,800 m^3/day), but without exceeding the permissible water withdrawal rates. Within the groundwater body, there is a small area of high sensitivity to a decrease in the groundwater level (by more than 2 m) near the Savchyn village in Sokalska TC.

There are enough monitoring points for the groundwater body, a total of 26 points. Of them 19 are in the model area; 4 wells are in areas No. 2 and No. 3, allocated for additional transboundary monitoring; 4 monitoring points are already equipped with automatic level measurement devices. Additional groundwater level monitoring is required in the "vulnerable to depletion" zone within Sokalska TC (Savchyn village), where a water intake with a capacity of 5,187 m3/day is located (Figure 93), and it is recommended to arrange an observation point in area No. 1, allocated for additional transboundary monitoring.

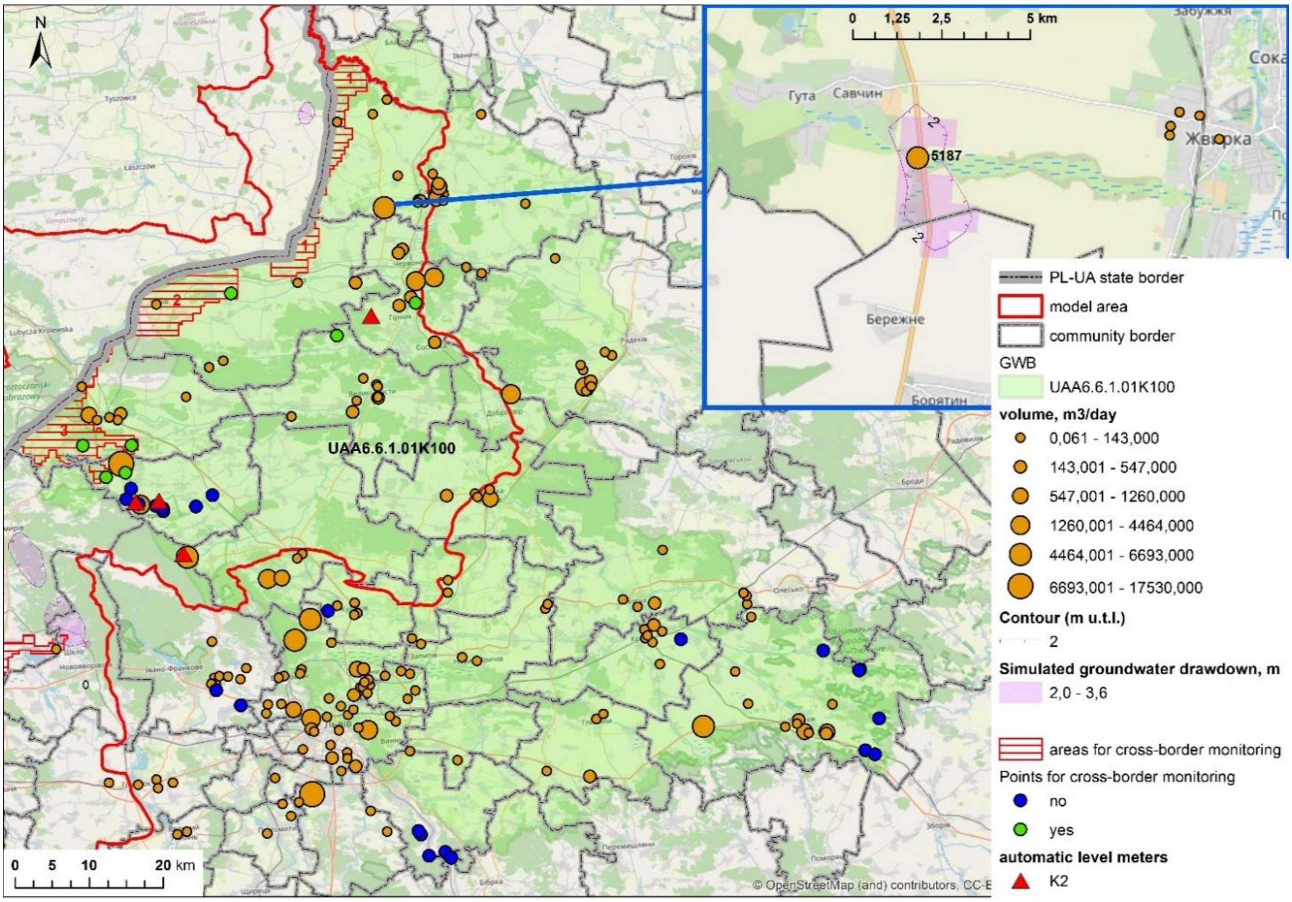


Figure 96. Status of monitoring of the UAA6.6.1.01K100 groundwater body in the Upper Cretaceous aquifer

The UAA6.6.2.03K100 confined Upper Cretaceous aquifer (Figure 97) is locally distributed within the San River basin and the model area. The groundwater body is not exploited by registered large water intakes. There are no monitoring points for the groundwater body. However, in the Miocene aquifer overlying the Upper Cretaceous aquifer, there are zones of high sensitivity to groundwater level decline. But if a threat of depletion of the Miocene aquifer can occur, it is necessary to provide for the possibility of using water from the Upper Cretaceous sediments. Therefore, it is recommended to equip the UAA6.6.2.03K100 groundwater body with 3 monitoring points, 2 of which should be located near the Voroblyachyn village (Yavorivska TC) and Novoyavorivsk town (Novoyavorivska TC).

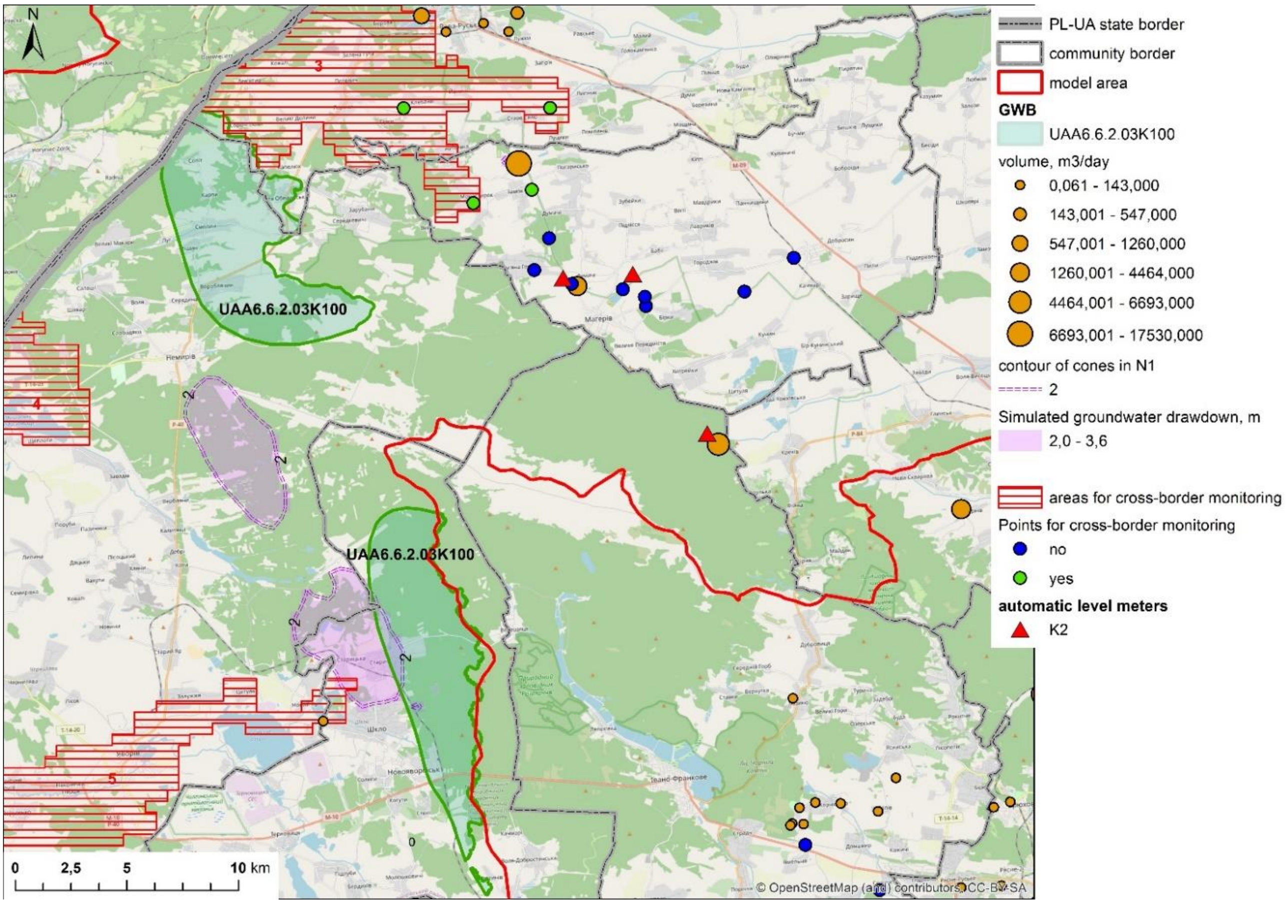


Figure 97. Status of monitoring of the UAA6.6.2.03K100 groundwater body in the Upper Cretaceous aquifer

Table 12. Recommendations for quantitative protection of transboundary groundwater in the Vistula River basin

No.	GWB code	Occurrence depth (m)	Risk of failure to achieve environmental objectives (quantitative)	Activity (according to the Resolution of the Cabinet of Ministers of Ukraine No. 336)	Technical description of measures to protect the quantitative state of groundwater	Territorial community (TC)	Authority/organization responsible for the implementation	Implementation period, years
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	UAA6.6.1.01Q100	0.75-1.5	No risk	Monitoring of GWB quantitative and qualitative status	Equip 2 monitoring wells with automatic level measurement devices	Velykomostivska TC, Krasnenska TC	SE Zakhidukrgeologiya, Lviv Geological Exploration Expedition,	2024-2030
2	UAA6.6.2.03Q100	0.75-1.5	No risk	Monitoring of GWB quantitative status within the transboundary monitoring network	Arrange 3 additional monitoring points within the designated transboundary areas and equip them with automatic level measurement devices	Nemyriv & Krakivets (Yavorivska TC), Nyzhankovychi (Dobromylska TC)	SE Zakhidukrgeologiya, Lviv Geological Exploration Expedition,	2024-2030
3	UAA6.6.2.03Q200	3.0-5.0	No risk	Monitoring of GWB quantitative and qualitative status	Arrange 3 monitoring points in areas marked with high sensitivity to groundwater level decline with automatic level measurement devices	Zaverkhy & Mostyska (Mostyska TC), Makuniv (Sudovovyshnyanska TC)	SE Zakhidukrgeologiya, Lviv Geological Exploration Expedition,	2024-2030
4	UAA6.6.1.01N100	2-25	No risk	Monitoring of GWB quantitative status within the transboundary monitoring network	Equip 3 monitoring points with automatic level measurement devices	Kovali (Rava-Ruska TC); Maidan (Zhovkivska TC); Lviv city (Lvivska TC)	SE Zakhidukrgeologiya, Lviv Geological Exploration Expedition,	2024-2030
5	UAA6.6.2.03N100	0.5-27.2	Intensive exploitation of groundwater (formation of depression cones, drainage of wetlands, karst development). **Risk of depletion**	Monitoring of GWB quantitative status within the transboundary monitoring network	Equip 2 monitoring points with automatic level measurement devices	Nemyriv (Yavorivska TC); Shklo (Novoyavorivska TC)	SE Zakhidukrgeologiya, Lviv Geological Exploration Expedition,	2024-2030

6	UAA6.6.1.01K100	from 1.5-8 to 15-22	Intensive exploitation of groundwater (formation of depression cones, drainage of wetlands, karst development). **Risk of depletion**	Monitoring of GWB quantitative status within the transboundary monitoring network	To equip 2 monitoring points with automatic level measurement devices	Savchyn & Uhryniv (Sokalska TC)	SE Zakhidukrgeologiya, Lviv Geological Exploration Expedition,	2024-2030
7	UAA6.6.2.03K100.	3-10	No risk	Monitoring of GWB quantitative and qualitative status	Equip 3 monitoring points with automatic level measurement devices	Sopit & Voroblyachyn (Yavorivska TC); Novoyavorivsk (Novoyavorivska TC)	SE Zakhidukrgeologiya, Lviv Geological Exploration Expedition,	2024-2030

Additional quantitative protection measures for PL-UA TAS

Measures to control groundwater abstractionh

Control and systematic assessment of the volume of groundwater abstraction are intended to prevent wastage of water and its resources. Activities related to the control and assessment of collection volumes in Poland and Ukraine are carried out within the legal order. In Poland, there are rules for ordinary (in Ukraine called individual) and special water use. In Poland and Ukraine, ordinary water use is used to meet the needs of one's own household and does not require direct recording and measurement with control devices. Although in Poland there is a limit on the amount of water abstraction as part of normal water use - the amount does not exceed the annual average of 5 m^3 per day, and in Ukraine there is no limit, this type of groundwater abstraction is a big problem in rural areas of both countries. Concentrating numerous individual intakes with a capacity of less than 5 m3 per day in situations of low aquifer resourcefulness may have a real impact on the quantitative status of groundwater and the development of regional lowering of the groundwater table, which was proven as part of model simulations performed in the EU-Waterres project (report " Transboundary impacts as a result of exploitation of groundwater resources in Polish-Ukrainian and Estonian-Latvian pilot areas»https://eu-waterres.eu/nextcloud/index.php/s/BrzJf829oymGZFe). Therefore, additional protective measures would include the introduction of the obligation to measure each amount of groundwater abstracted by systematic measurement with control devices of each intake drawing groundwater.

Measures for planning in water management

In addition to the obligatory Water Management Plan, it is recommended to prepare planning documentation specifying the conditions for using groundwater, which include:

- identification of the impact of changes in groundwater levels;
- specifying the conditions for using the waters of the water region, which, in relation to the abstraction of groundwater, include the introduction of restrictions on the use of water, including the abstraction of groundwater to achieve established environmental goals.

Measures to save water

These measures are aimed at reducing water consumption, using water-saving techniques for irrigating arable land and managing rainwater in agriculture. In addition, they include an analysis of the possibilities of rebuilding/reconstructing drainage systems.

7. Program for the quality protection of groundwater in the Polish-Ukrainian TAS

PL-UA TAS groundwater resources undergo qualitative degradation as a result of anthropogenic impacts. In the report of the EU-Waterres project entitled "Assessment of cross-border anthropogenic pressure on groundwater state", the causes of the deterioration of the quality of groundwater PL-UA TAS were identified and a quantitative assessment of the cumulative threats to the quality of groundwater was carried out. It was established that areas of intensive agriculture, mining areas, especially unreclaimed sulfur mining facilities, and settlement areas are areas of large-scale qualitative degradation of PL-UA TAS waters. The Ukrainian part of the TAS is subject to the greatest pressure from pollution hotspots, in particular the Dniester catchment area, the southern part of the Bug catchment area and the eastern part of the San catchment area. The highest risk values for UA TAS were obtained for communes characterized by high population density, a negligible degree of sewerage (over 100 people/km^2 do not use collective sewage systems), and numerous local pollution hotspots. These communes include: Volodymyr Volhynianskaya, Novovolynskaya, Kulykovskaya, Lvivskaya, Zymnovodovskaya, Sokilnycka, Obroshinskaya, Novojavorowska, Rozvadiwska, Sambirska, Drohobycka, Boryslavskaya and Truskavetskaya. On the Polish side of TAS, the highest risk to the quality of groundwater was recorded in the most urbanized communes - Chełm and Tomaszów Lubelski.

The threat to the quality of groundwater does not translate directly into the poor chemical condition of groundwater. This state depends on the type of pollution source, the properties of the polluting substances, the nature of the hydrogeochemical environment through filtration of pollutants and the conditions of introducing pollutants into the environment. With regard to components that migrate easily in the environment - chlorides, sulfates and nitrates - the extent of contamination is determined primarily by the migration time. The EU-Waterres project conducted a quantitative assessment of the migration time of contaminants to the first PL-UA TAS aquifer. Areas with high susceptibility to pollution include those where the migration time is less than 25 years. The results of this assessment indicate that PL-UA TAS is mostly an open system (without insulation with low-permeability formations) with high susceptibility to surface contamination. Therefore, a poor chemical status of groundwater can be expected here. The groundwater monitoring carried out so far does not allow for a detailed assessment of the degree of qualitative degradation of the usable resources of the PL-UA TAS groundwater levels and an objective assessment of the chemical status because the network of sampling points is small (about 30 points) and unevenly distributed. Therefore, on both sides of the border, the chemical condition of the GWB, according to official data, is good. However, if we refer to the official results of testing a larger group of points (over 200 points) that do not belong to the groundwater monitoring core network, the picture becomes objective (detailed information in chapter 3. Identification of areas at risk of groundwater pollution within the Polish-Ukrainian Cross-Border Aquifer System using the hydrogeochemical anomaly method). It can be mentioned here that in the vicinity of the Lviv agglomeration and the border post-sulfur mining area, the mineralization of shallow groundwater is 1,500-3,400 mg/l. This indicates that the chemical composition of groundwater in these areas has been significantly changed as a result of anthropopressure. Such drastic anomalies were not recorded on the Polish side, but this was due to the too low density of the monitoring network. However, on the Polish side of the border, clear increasing trends in the content of sulphates, chlorides, nitrates, magnesium and sodium have been recorded over the last two decades (see: 3. Identification of areas at risk of groundwater pollution within the Polish-Ukrainian Cross-Border Aquifer System using the hydrogeochemical anomaly method). A particularly important trend occurs in the case of point II/514/1, which indicates a significant deterioration of water quality as a result of anthropopressure.

Qualitative protection is understood as maintaining or achieving good chemical status of groundwater bodies by introducing a number of prohibitions or restrictions on the use of land or the use of specific substances. This fulfills the overriding principle of protecting groundwater against pollution (the principle of prevention). These types of regulations include in particular:

- prohibition of discharging sewage directly into groundwater or land;
- implementation of an action program aimed at reducing water pollution with nitrates from agricultural sources and preventing further pollution (based on the EU Directive on the protection of waters against pollution caused by nitrates from agricultural sources);
- implementation of the municipal wastewater treatment program (based on the EU Directive on municipal wastewater treatment);

- establishing protection zones for groundwater intakes, where orders, prohibitions and restrictions regarding land use and water use apply;
- establishing protection areas of the Main Groundwater Reservoirs.

Therefore, the protection of groundwater must be implemented using administrative tools through a number of different types of measures included in the Water Management Plan in the river basin area. The measures involve, in particular, the gradual reduction of groundwater pollution by reversing significant and persistent upward trends in pollution caused by human activity. Measures are divided into basic and supplementary ones aimed at improving or maintaining good water status in river basin areas. Core measures are aimed at meeting minimum requirements and include, among others: not introducing pollutants directly into groundwater, understood as introducing them in a way other than through percolation through the soil and subsoil, unless they threaten the achievement of environmental goals for the GWB, and measures to prevent the release of substances particularly harmful to the aquatic environment from technical installations in significant quantities, as well as to preventing or mitigating the effects of unforeseeable pollution.

The program of protective measures, an integral element of the Water Management Plan, was developed only for the Polish part of the TAS area. The most widely used protective measures aimed at reducing chemical pressure generally recommended in Water Management Plans include:

- development of proposals for the purposes of establishing protective areas of inland water reservoirs and regulations establishing these areas, along with substantive support related to their establishment;
- identification of the occurrence of new contaminants in groundwater in areas of intense urbanization, agricultural and industrial pressure,
- conducting training for those running agricultural activities in the application of measures from the Collection of recommendations of good agricultural practice for voluntary use,
- monitoring groundwater for contamination with halogenated compounds and compounds indicating industrial pressure, as well as developing an expert opinion aimed at determining the extent and source of pollution in post-industrial areas.

Mandatory qualitative protection measures for the Polish part of the TAS resulting from the Vistula Water Management Plan

The measures were selected and assigned to GWB individually and their implementation within the indicated GWBs is obligatory regardless of their current status or the risk of failure to achieve environmental goals (Table 13).

Table 13. Mandatory protective measures for the Polish part of TAS

GWB number	Name of the measure, implementation schedule	Description of measure	Type of pressure that the measure is aimed at	Unit responsible for implemetnation
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136	Support for the activities of administrative bodies in establishing protective areas of the Main Ground Water Reservoir (GZWP), until 2027.	Preparation of hydrogeological data necessary to develop an application for the establishment of the GZWP protection area No. 407 (Chełm-Zamość Reservoir within the Lublin Basin)	Chemical pressure	Polish Hydrogeological Survey
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136	Preparation of an application for the establishment of the GZWP protection area by 2027.	Preparation of an application for the establishment of the GZWP protection area no. 407	Chemical pressure	Regional Water Management Board

PLGW200067 PLGW200091 PLGW2000121 PLGW2000136	Ustanowienie obszaru ochronnego GZWP, do 2027	Issuance of a regulation establishing the protection area of the inland water reservoir, by way of a local law act for GZWP No. 407	Chemical pressure	Voivode
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Reduction of emissions and discharges of priority substances, continuous measure	Obligation to ensure that the limit values for pollutants in sewage discharged into water and land are not exceeded	Chemical pressure	An entity using water services that discharges sewage into water or land
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Construction or modernization of sewage treatment plants, continuous measure	Measures aimed at sealing sewage systems and septic tanks (using available techniques to effectively seal sewage systems and septic tanks)	Chemical pressure	Owner, municipalities
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Control of home sewage treatment plants, continuous measure	Records of household sewage treatment plants in order to control the frequency and method of disposal of municipal sewage sludge and to develop a plan for the development of the sewage network	Chemical pressure	Municipality
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Inspection of septic tanks, continuous measure	Records of septic tanks in order to control the frequency of their emptying and to develop a plan for the development of the sewage network	Chemical pressure	Municipality
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Monitoring of the chemical state of groundwater, continuous measure	Identification of significant and persistent upward trends and defining points of initiation of actions to reverse such trends (applies to the assessment of the state of GWB)	Chemical pressure	Polish Hydrogeological Survey
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Protection of the intermediate protection zone of the water intake, continuous measure	Imposing an obligation to liquidate inactive wells located in the intermediate protection zone of the water intake if these wells threaten the quality of the water intake	Chemical pressure	Land owner
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Environmental impact assessment, continuous measure	Obligation to conduct a cross-border environmental impact assessment for projects for which a significant cross-border impact has been identified	Chemical and quantitative pressure	The investor in the scope of submitting an application for a decision on environmental conditions, the authority competent to issue a decision on environmental conditions, the Chief Directorate for Environmental Protection
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Reduction of groundwater pollution, continuous measure	Obligation to connect the property to the existing sewage network or, if the construction of a sewage network is technically or economically unjustified, to equip the property with a septic tank for liquid waste or a home sewage treatment plant	Chemical pressure	Land owner
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Registration activities, continuous measure	Obligation to include groundwater reservoirs, water intake protection zones and inland water reservoirs protection areas in spatial planning acts	Chemical and quantitative pressure	Authorities competent in matters of spatial planning + authorities competent to issue decisions on development conditions and land development
PLGW200067 PLGW200091 PLGW2000121	Water permits, continuous measure	Obligation to obtain a water law assessment for investments and	Chemical and quantitative pressure	An entity planning to implement investments or activities that may

PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169		activities that may affect the ability to achieve environmental goals		affect the ability to achieve environmental goals
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Water permits, continuous measure	Obligation to obtain water permits	Chemical and quantitative pressure	Entity using water services
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Establishing protection zones for water intakes, continuous measure	Preparation of risk analyzes or hydrogeological documentation for water intakes covering the direct protection area and the indirect protection area	Chemical pressure	Groundwater intake owner
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Groundwater monitoring, continuous measure	Conducting monitoring of the GWB in terms of quantitative and chemical status, maintaining and developing the groundwater observation and research network	Chemical and quantitative pressure	Polish Hydrogeological Survey
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Establishing protection zones for water intakes, continuous measure	Compliance by obligated entities with the provisions arising from the local law on the establishment of protective zones for water intakes and areas of inland water reservoirs	Chemical pressure	Land owners, entities conducting agricultural and industrial activities
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Reclamation of hazardous objects, continuous measure	Reclamation of open pits in a way that limits the risk to the quality of groundwater	Chemical pressure	An entity conducting mining activities
PLGW200067 PLGW200091 PLGW2000121 PLGW2000136 PLGW2000154 PLGW2000168 PLGW2000169	Reduction of groundwater pollution, continuous measure	Prohibition of discharging sewage directly into groundwater	Chemical pressure	Entity using water

Mandatory quality protection measures for the Ukrainian part of TAS

Protection of groundwater from pollution consists of strict compliance with legislation and legal documents on the protection of groundwater; implementation of technical and technological measures aimed at reducing groundwater pollution, namely: reducing the amount of waste produced by industry, creating waste-free production, multiple-use of water in the technological cycle, construction of treatment facilities, as well as improvement of methods of cleaning and disposal of waste; strict compliance with the requirements for groundwater exploration, design, construction, and operation of groundwater intakes; introduction of water protection measures to protect groundwater.

In Ukraine, a system of legal acts regulates the use and protection of underground water resources. Groundwater protection is carried out by water legislation by enterprises, organizations and institutions whose activities affect the state of groundwater. These enterprises, organizations and institutions are obliged to carry out measures that ensure protection against pollution, clogging and depletion, as well as improvement of the state and regime of waters.

Contaminated groundwater is considered to be one whose composition and physical properties have deteriorated under the influence of human activity compared to the natural groundwater of the area, which is not affected by anthropogenic influence and has become less suitable for use. When groundwater is polluted, both an increase in the content of components found in natural groundwater (chlorides, sulfates, iron, etc.) and the appearance of elements and compounds not characteristic of them, associated with human activity can occur.

Analysis of the qualitative state of groundwater in the modelling area of the Polish-Ukrainian border was carried out by identifying hot spots, based on the concept of positive hydrogeochemical anomalies, that is, increases in the hydrogeochemical background. It is based on the assumption that each positive hydrogeochemical anomaly signals a transformation of the chemical composition caused by the influence of natural or anthropogenic factors, i.e. pollution. Based on certain prerequisites and expert knowledge, the influence of natural factors can be determined quite accurately. In this way, anthropogenically caused hydrogeochemical anomalies are singled out. Then these territories were classified as hot spots - zones of risk of groundwater pollution (see: 3. Identification of areas at risk of groundwater pollution within the Polish-Ukrainian Cross-Border Aquifer System using the hydrogeochemical anomaly method).

If we analyze the drinking water standards of the World Health Organization and most of the leading countries in the world, none of them have strict requirements for the minimum or optimal salt content in water. The norms of the national and European standards of total salinity coincide - up to 1000 mg/dm^3. The contents of the rest of the main macro-components are regulated by the State Sanitary Rules and Regulations (DSanPiN) regarding sanitary and chemical indicators of safety and quality of drinking water: Ca – 130, Mg – 80, SO_4 – 250, Cl – 250, Na+K – 200 mg/dm^3.

In this Chapter, the detected hydrogeochemical anomalies are analyzed for their belonging to groundwater bodies.

UAA6.6.1.01Q100, UAA6.6.2.03Q100 groundwater bodies in alluvial Quaternary sediments and UAA6.6.2.03Q200 groundwater body in fluvioglacial Quaternary deposits

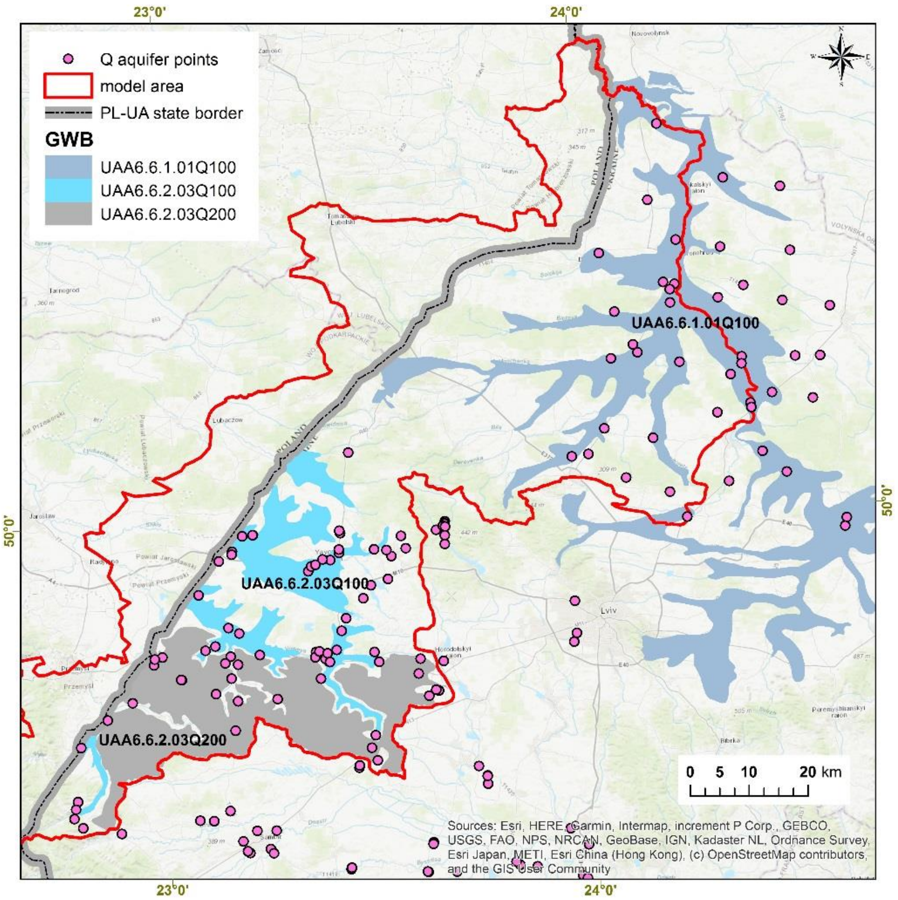
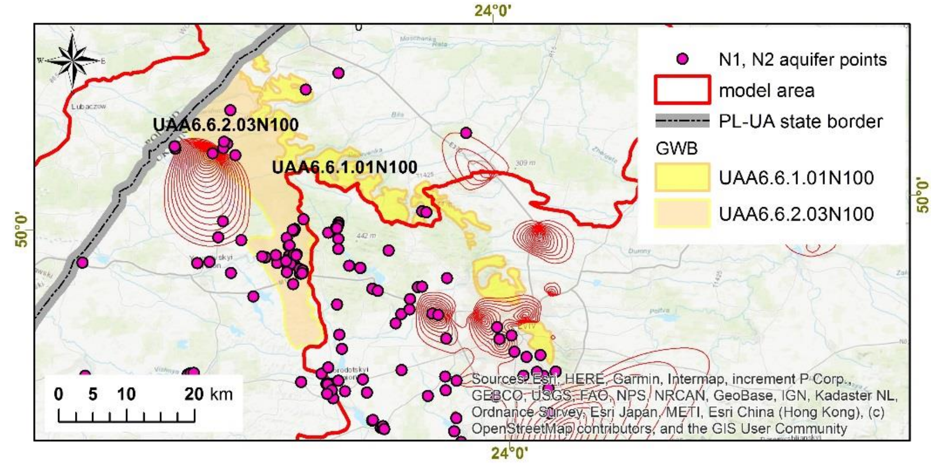


Figure 98. Analysis of the qualitative state of of Quaternary groundwater bodies

Unconfined groundwater bodies of alluvial and fluvioglacial Quaternary deposits UAA6.6.1.01Q100, UAA6.6.2.03Q100, UAA6.6.2.03Q200 do not have excesses in terms of the main hydrochemical macro-indicators (Figure 98).

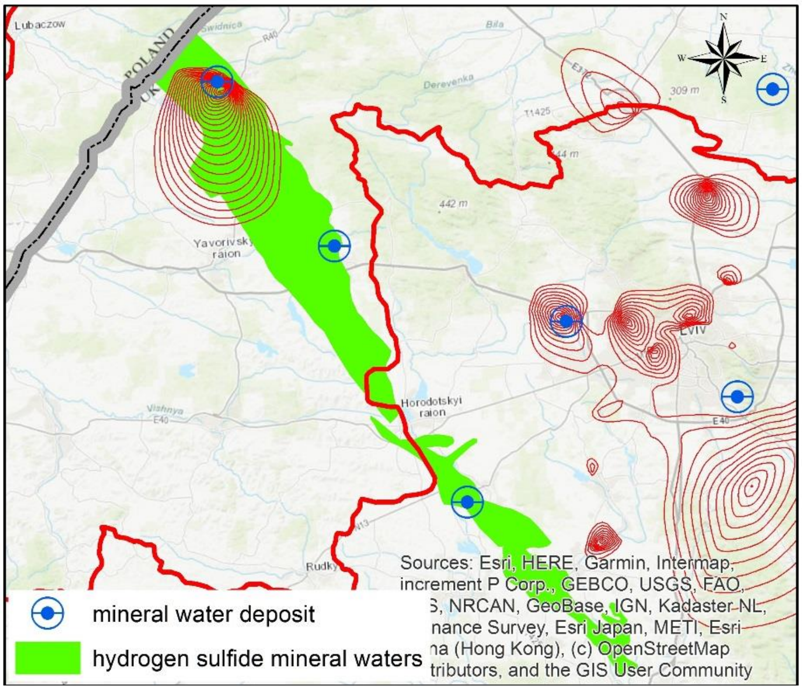
UAA6.6.1.01N100, UAA6.6.2.03N100 groundwater bodies in the Miocene aquifers



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 99. Analysis of the qualitative state of Miocen groundwater bodies (red isolines - TDS anomalies, > 1000 mg/dm³)

It can be seen from the figure that within the UAA6.6.2.03N100 groundwater body there is an anomaly in mineralization values. It is associated with the distribution of hydrogen sulfide-type mineral waters in this area. Figure 100 shows the distribution zone of hydrogen sulfide-type mineral waters.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, S, NRCAN, GeoBase, IGN, Kadaster NL, nance Survey, Esri Japan, METI, Esri na (Hong Kong), (c) OpenStreetMap tributors, and the GIS User Community

Figure 100. Distribution of mineral waters of the hydrogen sulfide type

Anomalies of elevated values of chlorides and calcium coincide in location with the anomaly of mineralization (Figure 101, Figure 102).

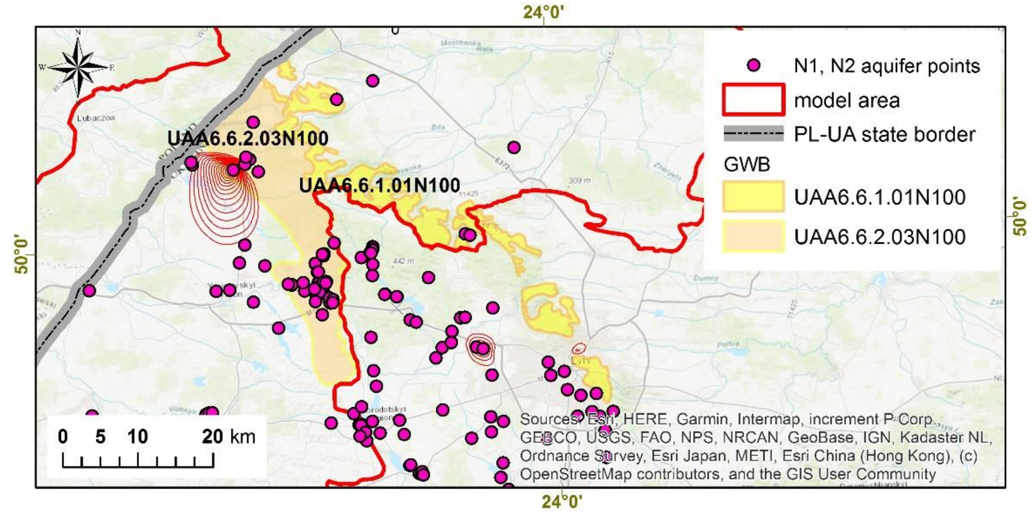


Figure 101. Analysis of the qualitative state of Miocen groundwater bodies (red isolines - Cl anomalies, > 250 mg/dm^3)

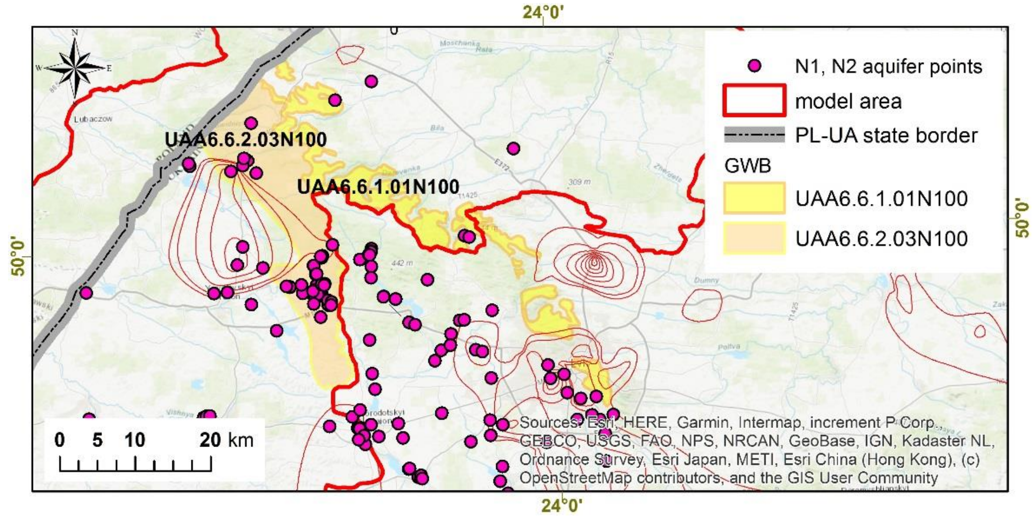
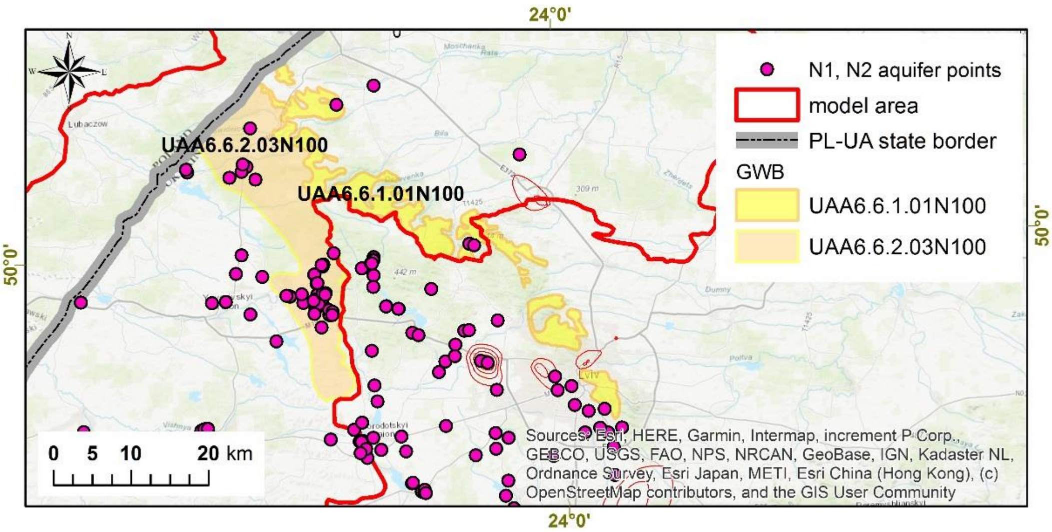


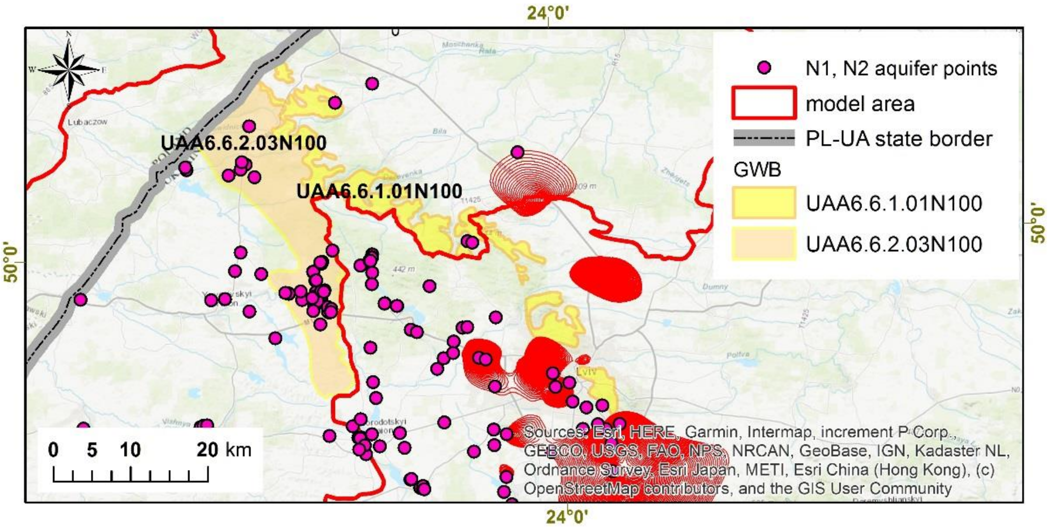
Figure 102. Analysis of the qualitative state of Miocen groundwater bodies (red isolines – Ca anomalies, > 130 mg/dm^3)

Within the Neogene massifs, there are no anomalies in the content of Magnesium, and minor anomalies of Sodium+Potassium and sulfates are outside the boundaries of the modeling area (Figure 103, Figure 104)



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 103. Analysis of the qualitative state of Miocen groundwater bodies (red isolines – Na+K anomalies, > 200 mg/dm^3)



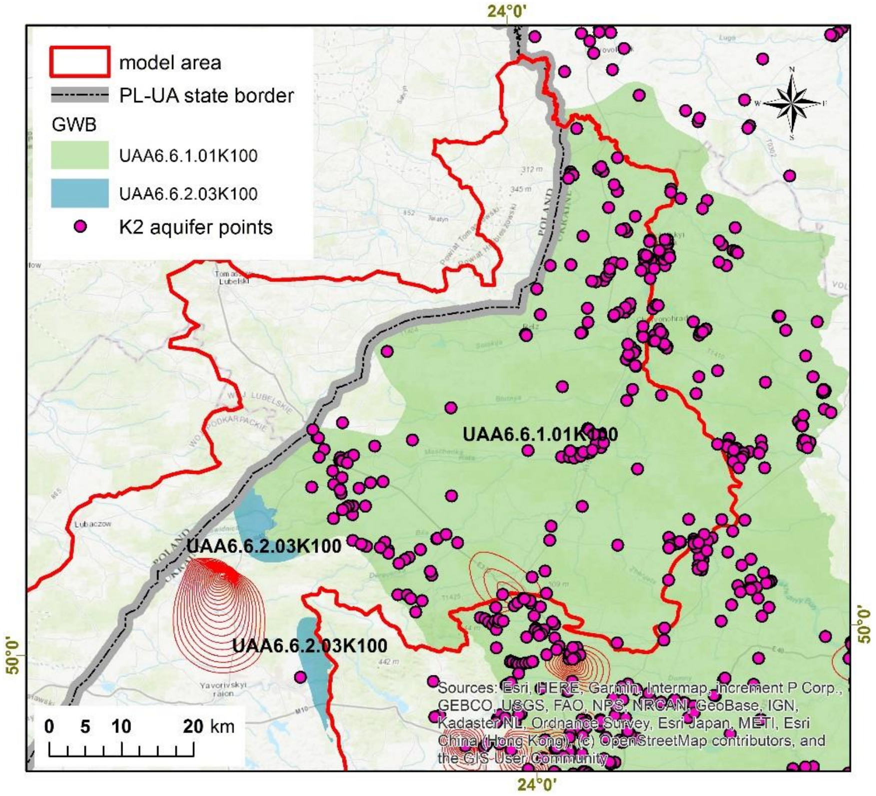
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 104. Analysis of the qualitative state of Miocen groundwater bodies (red isolines – SO_4 anomalies, > 250 mg/dm^3)

UAA6.6.1.01K100, UAA6.6.2.03K100 groundwater bodies in the Upper Cretaceous aquifer

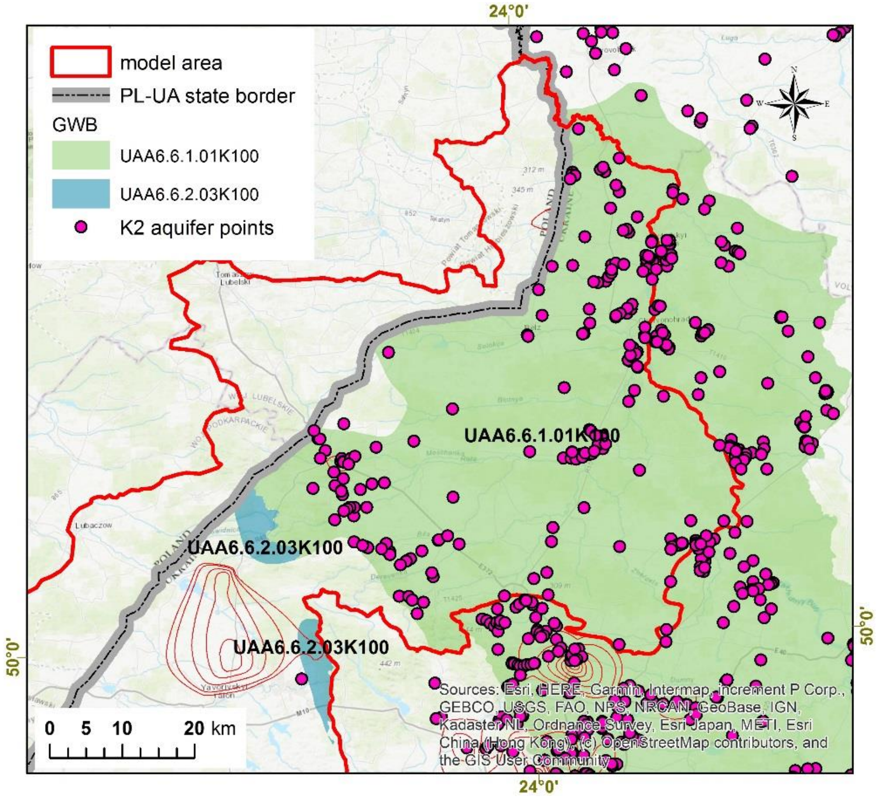
Increased mineralization is observed at the boundary of the modeling area in the massif UAA6.6.1.01K100. In the massif UAA6.6.2.03K100, no excesses of mineralization were detected (Figure 105).

Increased calcium content does not fall within the limits of the modeling area (Figure 106). Insignificant Na+K anomalies are spatially confined to elevated values of mineralization in the massif UAA6.6.1.01K100 (Figure 107). The anomaly of sulfate content is also connected with it (Figure 108).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 105. Analysis of the qualitative state of Cretaceous groundwater bodies (red isolines - TDS anomalies, > 1000 mg/dm³)



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 106. Analysis of the qualitative state of Cretaceous groundwater bodies (red isolines – Ca anomalies, > 130 mg/dm³)

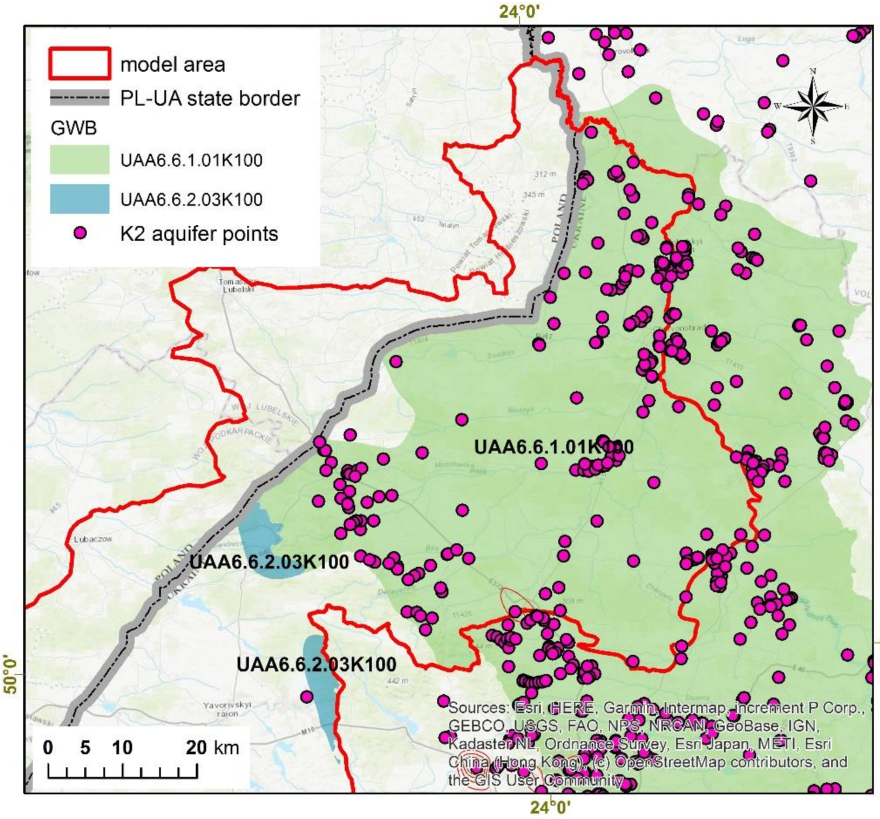


Figure 107. Analysis of the qualitative state of Cretaceous groundwater bodies (red isolines – Na+K anomalies, > 200 mg/dm³)

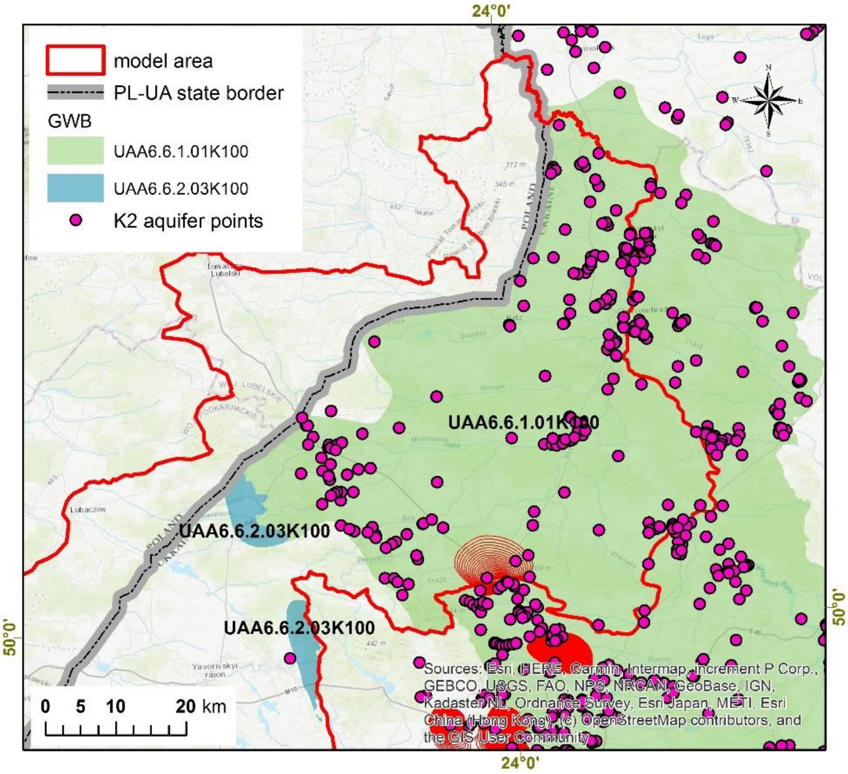


Figure 108. Analysis of the qualitative state of Cretaceous groundwater bodies (red isolines - SO_4 anomalies, > 250 mg/dm³)

Additional quality protection measures for PL-UA TAS

Based on the threat and risk assessment for groundwater carried out as part of the EU-Waterres project (Report entitled "Assessment of cross-border anthropogenic pressure on groundwater state in PL-UA and LV-

EE pilot areas"), additional protective measures were developed, which were grouped into four types and assigned to GWB, where there is a specific justification for their implementation (Table 14).

Table 14. Additional quality protection measures for PL-UA TAS

Type of measure	Bug catchment	San catchement	Dniestr catchement
Protection measures in agricultural areas	PLGW200091 PLGW2000121 UAA6.6.1.01Q100 UAA6.6.1.01K100	PLGW2000154 UAA6.6.2.03Q100 UAA6.6.2.03Q200	UAM5.2.0.01Q100 UAM5.2.0.01Q200 UAM5.2.0.01Q300
Protection measures in mining and industrial areas	UAA6.6.1.01Q100 UAA6.6.1.01K100	PLGW2000136 UAA6.6.2.03Q100	
Protection measures in urbanized areas	PLGW200091 PLGW2000121 UAA6.6.1.01Q100	UAA6.6.2.03Q200	UAM5.2.0.01Q100 UAM5.2.0.01Q200 UAM5.2.0.01Q300
Protection measures in areas of intensive exploitation of roads		PLGW2000136 UAA6.6.2.03Q100	UAM5.2.0.01Q100

Measures to protect groundwater in agricultural areas

These activities should cover in particular the following issues:

- rationalization of fertilization of agricultural land and the use of plant protection products;
- construction of appropriate sewage and waste disposal systems;
- construction of facilities and safeguards that eliminate or limit the negative impact of farming and enable rational use of organic fertilizers on agricultural land;
- rationalization of agricultural wastewater use systems;
- rational shaping of agricultural landscape elements, drainage systems and water management facilities.

The proper solution to the problem of wastewater disposal is the construction of a collective sewage system and a sewage treatment plant. Individual sewage treatment systems with seepage drainage and discharge of pre-treated sewage into drainage ditches are therefore not an appropriate solution from the point of view of groundwater protection. They cause contamination of groundwater with nitrates and sulphates and can only be used in the case of highly dispersed land use, where it will not pose a threat to existing intakes and specially protected groundwater reservoirs.

Proper waste management is also important in the protection of groundwater. First of all, it is necessary to point out the need for proper location of waste landfills, taking into account hydrogeological criteria, and their appropriate protection.

Reducing the negative impact of fertilization and plant protection products requires compliance with a number of recommendations in the field of good agricultural practice and proper shaping of all elements of the agricultural landscape.

Proper protection of wells is also important in the protection of groundwater in agricultural areas. The immediate surroundings of the well should be sealed with clay or concrete with a slope to the outside, and the well should be covered. It is unacceptable and reprehensible to use closed wells to fill them with all types of waste.

Measures to protect groundwater in mining and industrial areas

Water protection in mining should be implemented through rational development of mining drainage systems and the utilization and management of water pumped from mines. Proper waste management and disposal are also important. Proper management of water pumped from mines means using it not only to supply streams and reservoirs, but also to increase ground retention. Mining waste should be collected in a way that ensures the protection of usable groundwater (location of landfills and heaps taking into account hydrogeological criteria, application of technical protection).

The protection of groundwater in industry is primarily associated with the problem of proper disposal and management of waste. Industrial sewage should be properly treated before it is introduced into the receiving body. Landfills where hazardous waste has accumulated should be covered with an insulating layer to limit their impact on the environment.

Measures to protect groundwater in urbanized areas

The most important thing is the construction of collective sewage systems, which significantly reduces the contamination of groundwater with nitrates. Individual wastewater treatment systems should not be used on a large scale, especially in areas supplying water intakes and utility groundwater reservoirs. Even treated sewage discharged into the ground or drainage ditches is a source of nitrate contamination of groundwater. In the field of waste, groundwater protection is aimed at all activities limiting the amount of stored waste (selective collection). However, landfills will remain the main method of waste disposal for a long time. Due to the long-term threat they pose to groundwater, their location should be determined based on hydrogeological criteria. It is also important to use appropriate solutions to secure landfills.

Measures to protect groundwater in areas with intensively used roads

Protective measures should be differentiated, taking into account criteria such as:

- protection zones of intakes and main groundwater reservoirs;
- the importance of local utility groundwater reservoirs;
- conditions for isolation of usable groundwater levels.

In areas where it is necessary, measures such as:

- sealing the substrate;
- collecting rainfall runoff from roads and roadsides and discharging them outside the protection zone and/or effective cleaning;
- shielding the road and its immediate surroundings with screens.

In the case of other facilities posing a threat to groundwater, fuel stations accompanying communication routes should be indicated and should be properly secured (ensuring appropriate tightness standards of tanks and pipelines, monitoring systems).

PART II

WP5 Output 3 report

Program of protection of transboundary groundwater against pollution and depletion on the eastern border of EU

Estonian-Latvian pilot area

Contents

1. Latvian-Estonian pilot area overview

1.1. Conceptual model for the pilot area

1.1.1. Geological and hydrogeological setting of the pilot area

Transboundary aquifers between Estonia and Latvia were delineated based on the surface watersheds, and the boundaries were extended to cover the whole Estonian-Latvian TBA and include major towns and cities. Typically, the hydrological boundaries match with the hydrogeological boundaries of upper aquifers (Quaternary and Upper Devonian Pļaviņas-Ogre aquifer systems), while the deeper aquifer systems (Middle to Upper Devonian Aruküla-Amata) have much larger watersheds. In the delineation of Estonian-Latvian TBA, hydrological boundaries were applied rather than hydrogeological mainly because the area should not be too large to ensure a balance between monitoring costs and data analysis, and the delineated area still ensures meeting all management goals (e.g. includes groundwater-dependent ecosystems that rely on the upper aquifers).

The terrain of the territory is flat and mostly covered by plains and lowlands, while the highlands are distributed only in the eastern part of the area (Figure 1). The majority of the Estonian-Latvian TBA is covered by forests (63%), followed by agricultural lands (32%) and wetlands (3%). Human population density in the pilot area is small – in the settlements, it is ~11 inhabitants per km^2, while in rural areas ~3 inhabitants per km^2.

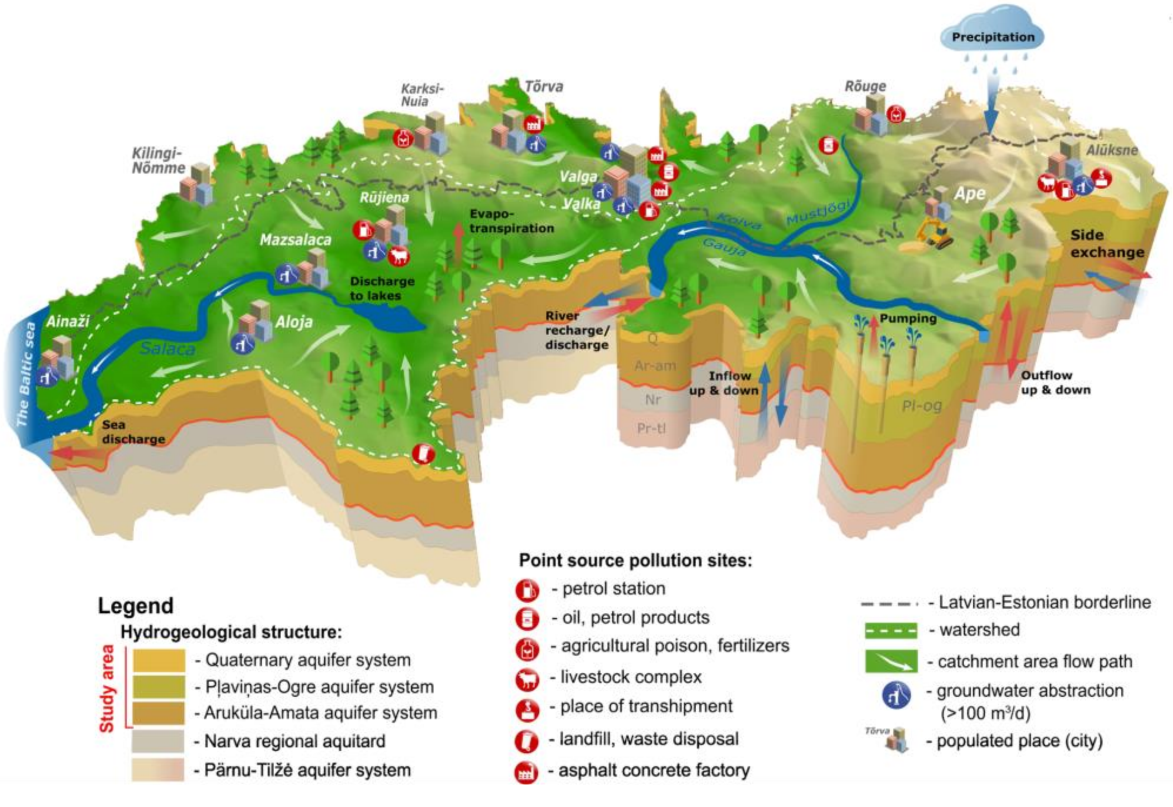


Figure 1. **Conceptual model of the Estonian-Latvian TBA**

Based on the aquifer hydrodynamic interconnection and water chemical composition, aquifers were grouped into aquifer systems: (1) Quaternary, (2) Upper Devonian Pļaviņas-Ogre, and (3) Middle to Upper Devonian Arükula-Amata (Figure 2). These three aquifer systems are forming the groundwater active exchange zone. The Quaternary aquifer is composed of sand and loam, while the dominant water-bearing material in bedrock aquifers is sandstone. Local aquitards are formed of clay and siltstone, while regional Narva aquitard, formed of marl and clay, separates the study area from deeper aquifers. Below lies the Middle Devonian Pärnu aquifer, which also contains fresh groundwater in the transboundary area but was not the subject of this study. The total thickness of groundwater active exchange zone in the study area is up to 135-352 meters, and aquifer systems mainly contain Ca-Mg-HCO_3 fresh groundwater with TDS less than 0.5 g/l and naturally highlighted Fe_{tot} content above drinking water standard.

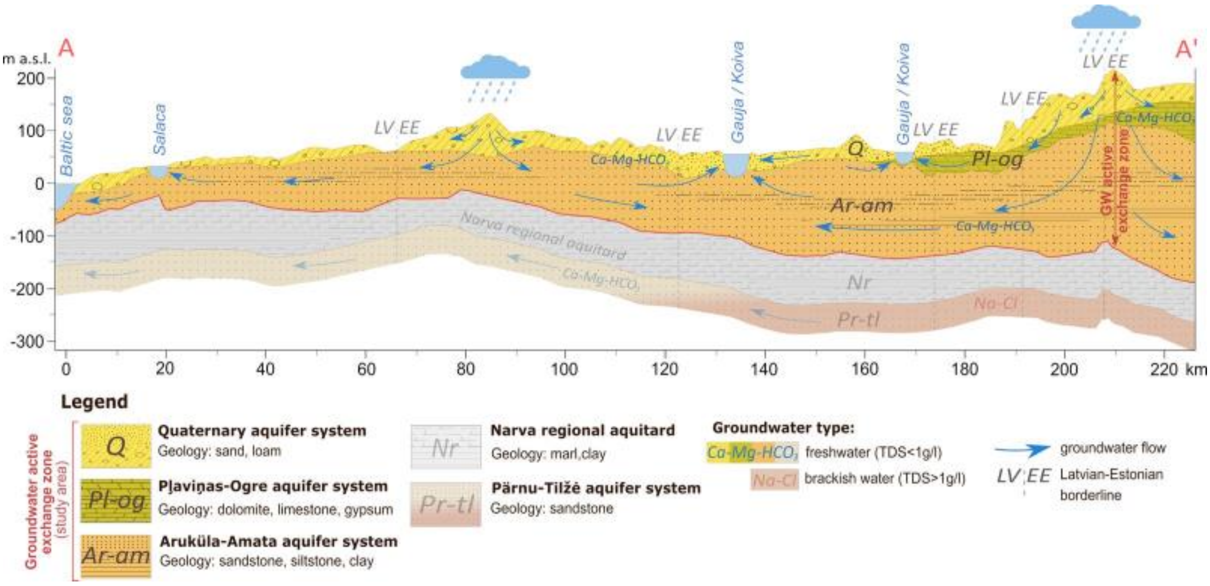


Figure 2. **Conceptual hydrogeological cross-section of the Latvian-Estonian TBA**

Significant transboundary groundwater flows have been identified in both Upper Devonian Pļaviņas-Ogre and Middle Devonian Aruküla-Amata aquifer systems. The most significant pressures on groundwater in the Estonian-Latvian TBA are caused by groundwater abstraction and polluted sites - the main pressure areas are located around the cities (the largest groundwater abstraction sites are located in the cities of Valka and Valga) (more detailed information available in the next chapter).

Using a regional-scale hydrodynamical hydrogeological model developed in the EU-WATERRES project (Hunt et al., 2023), natural groundwater resources were calculated for the Estonia-Latvian TBA (Table 1).

Table 1. **Natural groundwater resources (m^3/d) of the Estonian-Latvian TBA**

Aquifer system	**Quaternary (Q)**	**Upper-Devonian (Pļaviņas-Ogre)**	**Upper-Middle-Devonian (Aruküla-Amata)**
Natural GW resources (NR)*	1406000	431000	1510000
Current GW abstraction (GA)	595	1787	7671
Increased GW abstraction	874	2864	32096
Minimal available natural resources for groundwater abstraction (NR-GA)	1405405	429213	1502329

*Includes recharge and inflow from overlying aquifers

More detailed information about the method for the natural groundwater resources calculation of the Estonian-Latvian TBA is available in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state".

1.1.2. Assessment of transboundary anthropogenic pressures

1.1.2.1. Point-source pressure

Significant point-pressure sites in the Estonian-Latvian TBA were initially identified in the WP3 report "Integrated groundwater observation network between neighboring countries for 2 transboundary aquifers". In total, 17 point-pressure sites were identified in the Estonia-Latvian TBA, of which eight were located on the Latvian side and nine - on the Estonian side. In the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", the list was revised. As a result, it was supplemented with one polluted site in the territory of Latvia, in the city of Valka (Figure 3).

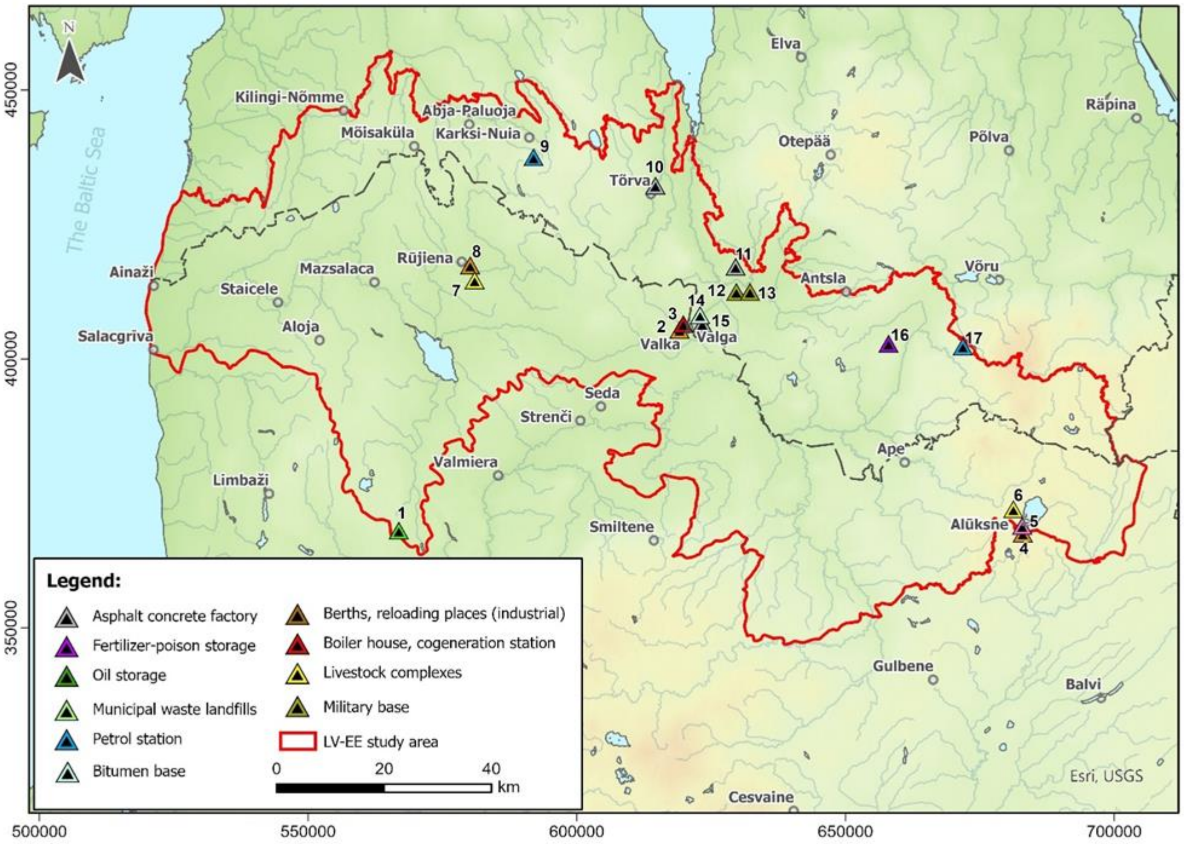


Figure 3. **Identified significant point-pressure sites in the Estonian- Latvian TBA**

Significant point-pressure sites in the Estonian-Latvian TBA are mainly located near large settlements - most of the sites are concentrated in the surroundings of the city of Alūksne (on the Latvian side), as well as in the territory of Valka and Valga cities. Alūksne city is further away from the Latvian-Estonian border, however, Valka and Valga are located directly on the border line of the two countries.

To assess the potential impact of the identified significant point-pressure sites on groundwater, in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", the path of pollution particle flows for a 30-year period was modelled for each site using MODPATH - particle-tracking, post-processing program developed to complement MODFLOW, a widely used groundwater flow model created by the U.S. Geological Survey (USGS). The purpose of MODPATH is to track the movement of particles, such as contaminants or water particles, in the groundwater system simulated by MODFLOW. A detailed description of the applied method can be found in Chapter 4.2 of the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state".

Figure 4 illustrates modeling results - the flow paths calculated based on the model, revealing that the maximum flow path length at specific locations over a 30-year period is 1.8 km. On average, the flow paths are approximately 0.7 km in length. These findings suggest that the potential movement speed of pollutants is relatively slow, resulting in shorter flow paths. This can be attributed to the small hydraulic gradient, as well as the relatively low groundwater conductivity and porosity of the aquifer.

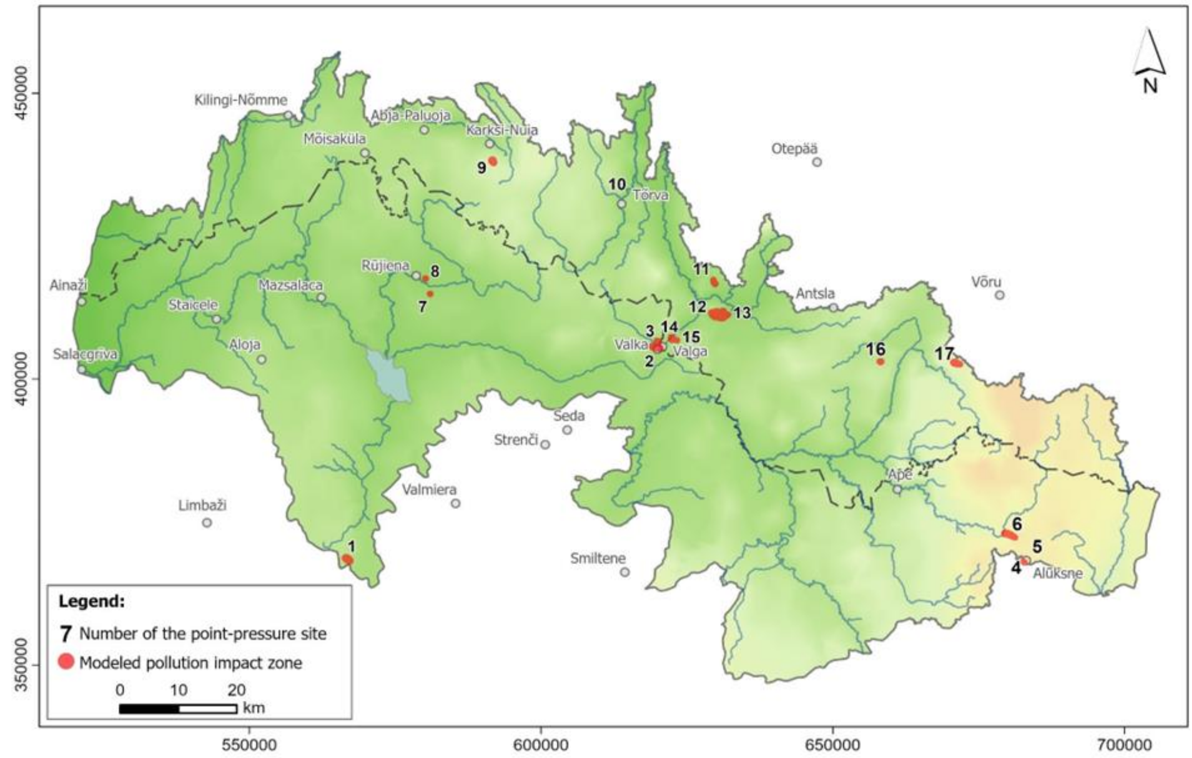


Figure 4. **Potential impact zones of significant point-pressure sites in the Estonian-Latvian TBA**

In general, it was concluded that potentially significant impacts are mostly caused by sites located in the territory of settlements and cities. In the Estonian-Latvian TBA, the largest pressure is concentrated in the cities of Valka/Valga, which are located right on the Estonian-Latvian borderline. There are four contaminated sites that may pose a potential threat to groundwater quality and the surrounding environment and model results show that in some sites, the potential contamination flow could cross the boundary in over a longer period. This confirms the previously expressed statements that the cities of Valka/Valga are places where, in the future, in the context of transboundary groundwater management, increased attention should be paid. More detailed modeling results as well as analysis of these results for each of the sites, can be found in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state".

1.1.2.2. Diffuse pressure

Identification and assessment of diffuse pressures were performed in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state". According to CORINE Land Cover data, the Estonian-Latvian TBA is mainly covered by natural territories (forests and natural grassland areas, wetlands, and water bodies), which in total form up 67% of the total area of the TBA and cannot show significant adverse effects on the quality of groundwater (Figure 5). On the contrary, 33% of the TBA is covered by urbanized and agricultural areas, which may be anthropogenically affected and can cause anthropogenic groundwater pollution. Of these, agricultural areas can be counted among the main causes of diffuse pollution and emission sources of nutrients (biogenic elements - phosphorus and nitrogen compounds), as well as other chemical elements (pesticides, heavy metals). It was assumed that in all intensively used agricultural lands, especially heavily fertilized arable lands and pastures, shallow groundwaters may be contaminated mainly by nitrates and, to a lesser extent, by pesticides.

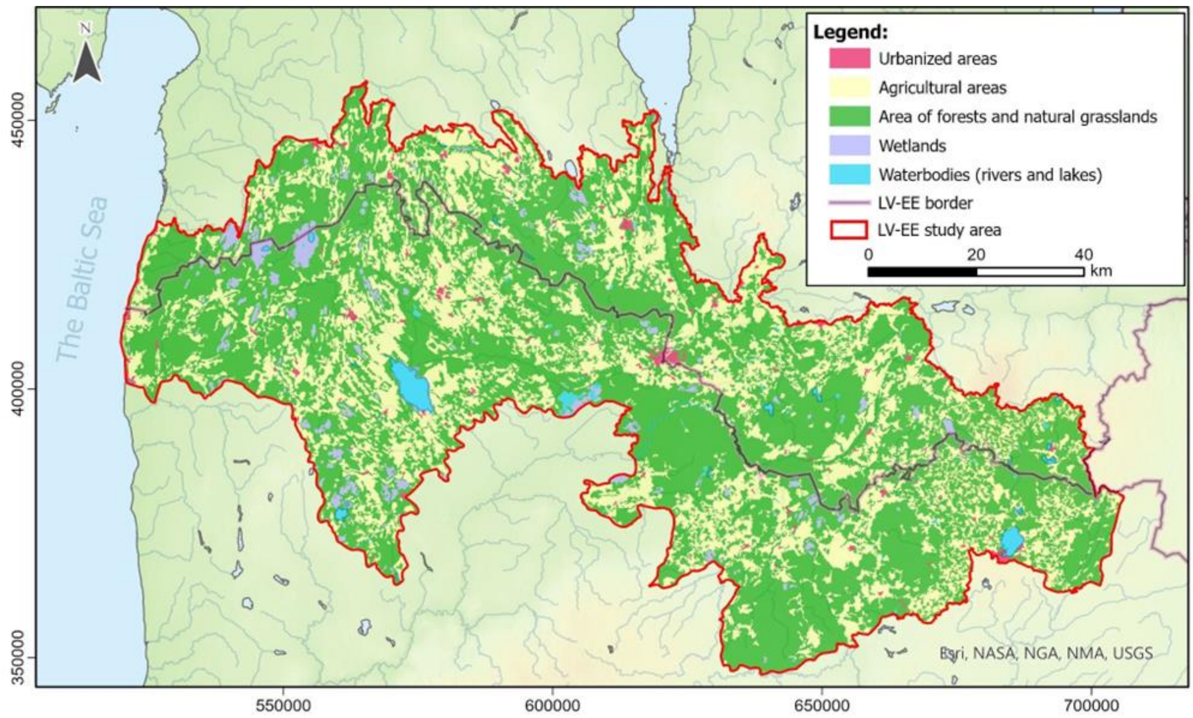


Figure 5. **Land use types in the Estonian-Latvian TBA, according to CORINE Land Cover (2018) data**

Based on the collected data, it was concluded that the Estonian-Latvian TBA is not significantly affected by diffuse agricultural pressure. It should be considered that the pressure of diffuse pollution in the examined area is uneven and depends on many factors and their mutual interaction. The most important factors are the vulnerability of shallow groundwaters to pollution and the type of land use. More detailed information can be found in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state".

In the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", a modified DRASTIC method was used for the impact of the diffuse pressure assessment and risk maps were developed for both Quaternary and main useful aquifer layers. According to the results, the impact of diffuse anthropogenic pressure on the main useful aquifer is insignificant because only 8.3% of the Estonia-Latvian TBA area is classified as a high or very high pollution risk zone, and those areas may have been affected by intensive agriculture or urbanized areas. However, it should be noted that the risk of pollution of the D_3*pl-og* aquifer system is greater than the pollution risk of the $D_{2\text{-}3}$*ar-am* aquifer system. At the same time, the Quaternary aquifer is even more exposed to pollution (20.6% of the Estonian-Latvian TBA is at high or very high pollution risk) and the impact of anthropogenic pressure.

More detailed results of the diffuse pressure assessment performed in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", as well as developed risk maps for both Quaternary and main useful aquifer, can be found in Chapter 2 of this report, as well as in full in the aforementioned report.

1.1.2.3. Groundwater abstraction pressures

To identify and estimate groundwater abstraction pressure, in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", locations of groundwater abstraction wells and quarries, as well as groundwater abstraction volumes and rates from these places were obtained from the Latvian Environment, Geology and Meteorology Center (2023), as well as Estonian Environmental Agency (2023) databases.

In the Estonian-Latvian TBA, two main aquifer systems are exploited: the Pļaviņas-Ogre and the Aruküla-Amata aquifer systems (abstraction from the Quaternary aquifer system is included in the aquifer system lying immediately below it since the abstraction from it is rather insignificant and in most cases - not officially accounted for).

The Pļaviņas-Ogre aquifer system is distributed only in the eastern part of the Estonian-Latvian TBA and is mainly exploited for decentralized water supply and individual water abstraction needs. From this aquifer system, groundwater is also pumped in large volumes in the dolomite quarry "Ape" to lower the groundwater levels for the purposes of dolomite mining. In the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", it was concluded that the largest number of groundwater intakes are located on the Latvian side, in the vicinity of the Alūksne city, where based on maximum abstraction volumes, an area with total water intake above 100 m^3/d were identified. The largest maximum groundwater abstraction and pumping can be observed in the dolomite quarry "Ape" - in this area, groundwater abstraction practically every year exceeds 500 m^3/d (Figure 6).

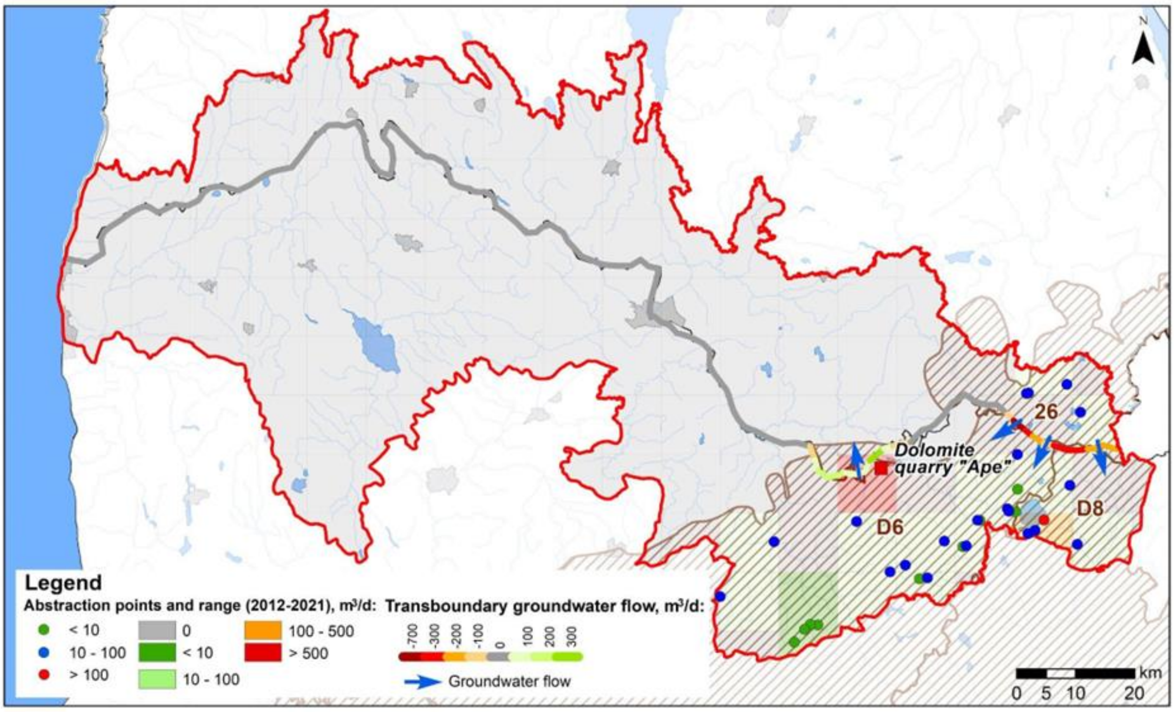


Figure 6. **Groundwater abstraction in Pļaviņas-Ogre aquifer system**

The Aruküla-Amata aquifer system is distributed throughout the whole Estonia-Latvian transboundary area, and in the eastern part of the transboundary area, it lies under the Pļaviņas-Ogre aquifer system. The Aruküla-Amata aquifer system is mainly exploited in areas where it lies immediately below the Quaternary sediments but is less exploited in the rest of the transboundary area; it is extensively exploited for both centralized and decentralized water supply, as well as in the individual sector. In the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", it was concluded that areas with intensive groundwater abstraction (greater than 500 m^3/d) are located near the largest cities of the Estonian-Latvian transboundary area (Figure 7). Near Tõrva city, the total amount of groundwater abstraction during the last 10-year period has fluctuated from 1.85 thousand m^3/d up to 3.11 thousand m^3/d, while in the vicinity of Valga and Valka cities, the total amount of groundwater abstraction has fluctuated from 2.19 thousand m^3/d up to 3.33 thousand m^3/d. Maximum groundwater abstraction from individual wells above 100 m^3/d can be observed in the vicinity of Abja-Paluoja city, Ape city and Rūjiena city.

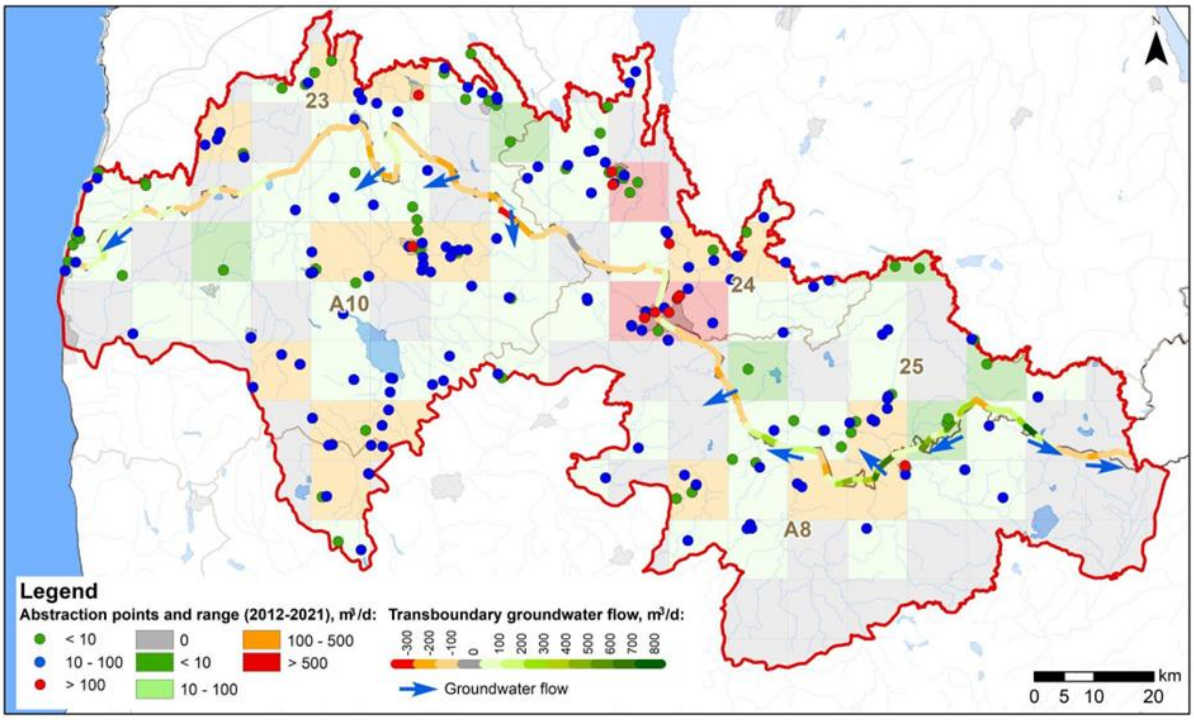


Figure 7. **Groundwater abstraction in Aruküla-Amata aquifer system**

For groundwater abstraction pressure assessment in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", a regional-scale hydrodynamical hydrogeological model was used, which was developed in the EU-WATERRES project and was created specially to assess the water level changes of the groundwater aquifers in the Estonian-Latvian transboundary area. The hydrogeological model was developed using open-source software MODFLOW-NWT and aggregated geological and hydrogeological data on the research area. More detailed information about the model (model structure, grid, boundary and other) is available in the WP5 report "Transboundary impacts as a result of exploitation of groundwater resources in Polish-Ukrainian and Estonian-Latvian pilot areas".

The conducted simulation of groundwater abstraction showed that the impact of current groundwater abstraction is insignificant and does not form large depression cones that could affect the hydrodynamic state of the aquifer system. Most of the drawdown in the transboundary area is mainly 0.0-0.2 m, and only in some local places reaches 1 m, which is mainly due to more intensive abstraction in individual groundwater abstraction wells. The largest depression cone is formed only in the territory of Latvia, in and near the area of the operating dolomite quarry "Ape". Accordingly, in the Quaternary and Pļaviņas-Ogre aquifer systems, the groundwater level is more than 2 m lower in the dolomite quarry "Ape" area (Figure 8).

Figure 8. **Simulated groundwater drawdown in the Estonian-Latvian TBA with current groundwater abstraction**

The calculated groundwater balance showed that the current volumes of groundwater abstraction do not significantly affect the hydrodynamic conditions in any of the identified aquifer systems and, accordingly, do not pose a risk to groundwater resources in the Estonian-Latvian TBA. Current volumes of groundwater abstraction make up 0.01% of the natural renewable groundwater resources. In balance terms, changes in the TBA's system under the influence of current groundwater exploitation for the analyzed variant have been presented in Table 2.

Table 2. **Water budget of the Estonia-Latvia TBA in the current exploitation model**

		Latvia, 10^5 m^3/d	**Latvia*, %**	**Estonia, 10^5 m^3/d**	**Estonia*, %**
Inflow	**Surface water infiltration**	62.64	0	42.21	0
	Rainwater infiltration	19.83	0	13.63	0
	Groundwater inflow from outside the model area	0.87	0	2.61	0
	Inflow from deeper aquifer	9.59	0	9.41	0
Outflow	**Discharge to streams (river)**	70.51	0	50.87	0
	Discharge to lakes	0	0	0.00	0
	Discharge to Baltic Sea	1.10	0	0.27	0
	Evapotranspiration	cannot be calculated with the model			
	Pumping amount from wells	0.05	-	0.03	-
	Groundwater outflow to outside the model area	1.24	0	1.97	0
	Outflow to deeper aquifer	10.94	0	5.42	0
	Amount going out to storage (Up)	8.98	0	8.08	0
Transboundary flow (inflow)		+0.93	0	+1.29	0
Transboundary flow (outflow)		-1.29	0	-0.93	0
Total Inflow		92.93	0	67.86	0

Total Outflow	92.77	0	66.61	0
Error, %	-0.00001	-	-0.00001	-

More detailed modeling results (including other groundwater abstraction scenarios) can be found in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state".

1.2. Hydrogeological model

The hydrogeological model developed for the Baltic Sea coastal region in North-East Europe covers approximately 45,000 km². The 3D groundwater flow model, created using MODFLOW-6, comprises eleven layers and around 200,000 cells per layer, representing transient conditions with yearly variations. Calibration results, based on water level and stream baseflow measurements, showed a reasonable fit, with RMSE values of 4.5 m for water levels and 0.6 m³/s for stream baseflows.

The water balance analysis revealed that the Quaternary aquifer primarily receives recharge from precipitation and inflow from the Upper-Devonian and Upper-Middle-Devonian aquifers. Groundwater discharge to streams is the largest component. The Upper-Devonian aquifer receives recharge from the overlying Quaternary aquifer, with the primary discharge being groundwater outflow to the Quaternary aquifer. The Upper-Middle-Devonian aquifer receives recharge from the Upper-Devonian aquifer, with the primary discharge being to streams and groundwater outflow to the Upper-Devonian aquifer.

The calibrated model allowed the quantification of transboundary groundwater flow across the Estonian-Latvian border for each aquifer system. Groundwater flow patterns were identified, showing bidirectional flows in the Quaternary aquifer system and varied patterns in the Upper-Devonian aquifer. The Upper-Middle-Devonian aquifer system represented the main transboundary flow, with flow from Latvia to Estonia exceeding the opposite direction.

Hydraulic conductivities were refined based on calibration results, with the Quaternary aquifer's conductivity values ranging from 0.2 m/d to 5 m/d, the Upper-Devonian aquifer from 0.3 m/d to 50 m/d, and the Upper-Middle-Devonian aquifer from 0.8 m/d to 6 m/d. Various boundary conditions, including no-flow boundaries, constant head boundaries, and general head boundaries, were implemented to simulate interactions with the wider Baltic Artesia Basin and surface water bodies. Groundwater withdrawal from pumping wells was simulated, accounting for anthropogenic influences on groundwater dynamics.

The water balance analysis highlighted the important role of groundwater in sustaining baseflow in surface water bodies. The active water exchange zone, extending up to the Narva confining unit, was identified as a more sensitive zone to pollution and climate change due to extensive water exchange and interactions with surface water bodies. More information about the model parameters, structure, and results can be found in the document WP5 output 1 - 'Transboundary impacts as a result of the exploitation of groundwater resources in Polish-Ukrainian and Estonian-Latvian pilot areas.

In conclusion, the hydrogeological model, through calibration and simulation, provides valuable insights into groundwater dynamics, cross-border flow, and water balance in the Baltic Sea coastal region. The refined hydraulic conductivities enhance the model's reliability, making it a valuable tool for groundwater management and environmental assessments.

The given model is not suitable for pollution flow modeling, considering the potential dissolution of substances at emission sources. It is a regional model, and conducting such an analysis would require the creation of local models for problematic areas. Detailed and specific studies on local groundwater dynamics in these regions would be needed to perform more accurate and detailed assessments.

1.3. Transboundary groundwater monitoring

According to the WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area", in the Estonian-Latvian TBA 22 monitoring points are located, of which 13 monitoring points (wells) are located in the territory of Estonia and 9 monitoring points (3 springs and 6 wells in 2 stations) in the territory of Latvia (Figure 9). Monitoring points characterize Pļaviņas-Ogre and Aruküla-Amata aquifer systems and provide mostly continuous quantity and/or quality monitoring. The exception is 4 monitoring points in the territory of Estonia, which are not currently active and have not been monitored in recent years.

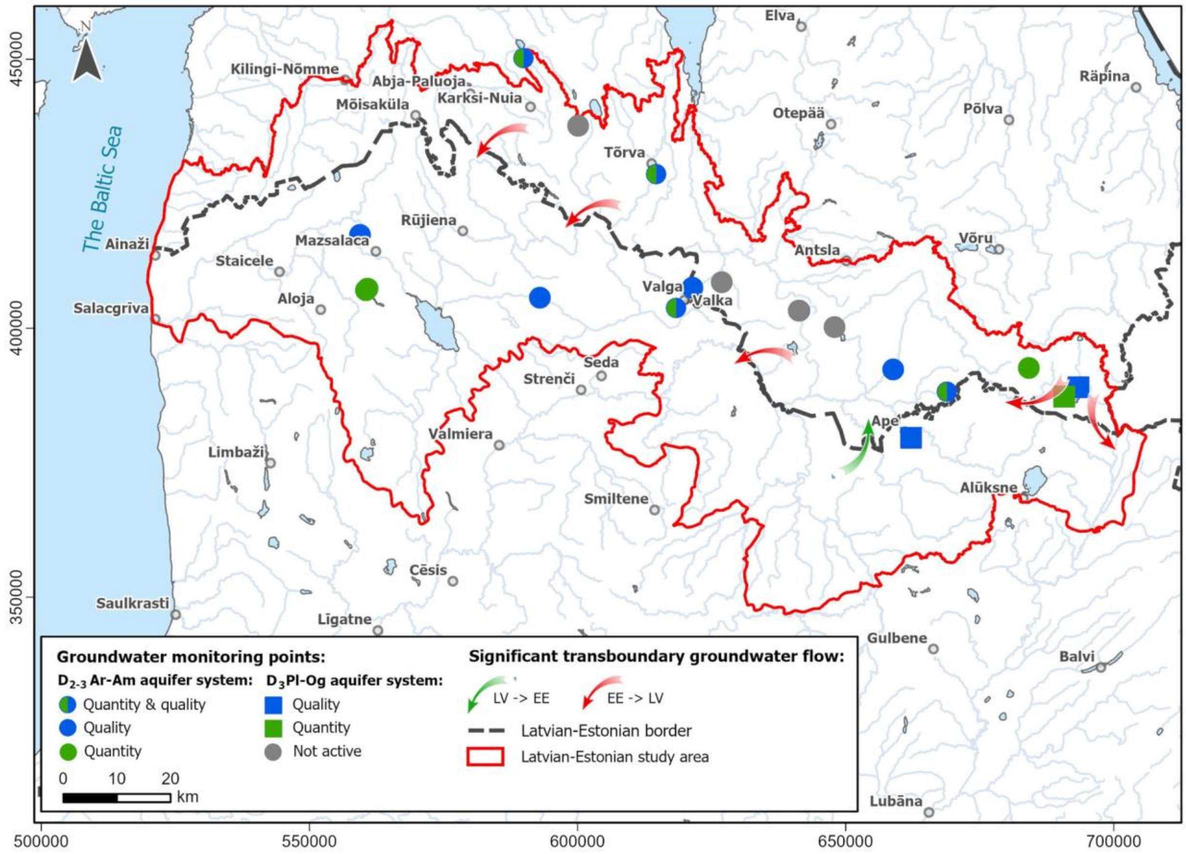


Figure 9. **Transboundary groundwater monitoring network in the Latvian-Estonian TBA**

The existing monitoring network coverage mainly allows assessing only the chemical status of transboundary groundwaters, as it is not possible to achieve the quantitative target set by the WFD - transboundary groundwaters should be provided with a sufficient number of monitoring points to assess the direction and flow rate of the groundwater through the Member State boundary. In order to achieve this goal, it would be necessary to set up a significant number of new monitoring points, which would not be financially adequate. However, in the context of the Estonian-Latvian TBA, the establishment of such a new and expanded monitoring network would not be adequate and rational, as no significant groundwater abstraction pressure was identified in the TBA, which could lead to changes in the regional hydrogeological regime, which was also confirmed by modeling groundwater abstraction scenarios (WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state"). Detailed information about the transboundary groundwater monitoring network is available in the WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area", but aspects of the transboundary groundwater monitoring program are available in the WP3 report "Program of cross border groundwater monitoring for Polish-Ukrainian and Estonian-Latvian transboundary areas".

In order to improve the coverage of the transboundary groundwater monitoring network in the Estonian-Latvian TBA, areas that may be prospective for future research and monitoring network expansion were identified in the WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area". The existence and intensity of transboundary flows between the two countries were the key factors in identifying these areas, as no significant anthropogenic pressures were identified in the TBA (with the exception of Valka-Valga cities, where more intense groundwater abstraction was identified). The conceptual model developed for the Estonian-Latvian transboundary area and the data analysis performed were used as the basis for the selection of these sites. As a result, seven prospective areas for the improvement of the transboundary groundwater monitoring network were identified in the Estonian-Latvian TBA, which have been given priority based on the flow intensity. It should also be mentioned that within the Interreg Estonian-Latvian project No.Est-Lat155 "*Joint actions for more efficient management of common groundwater resources* (WaterAct)" chemical analyses and watershed delineation of springs in the Estonian-Latvian TBA identified 8 potential springs that could also be included in the transboundary monitoring network in the future (Figure 10).

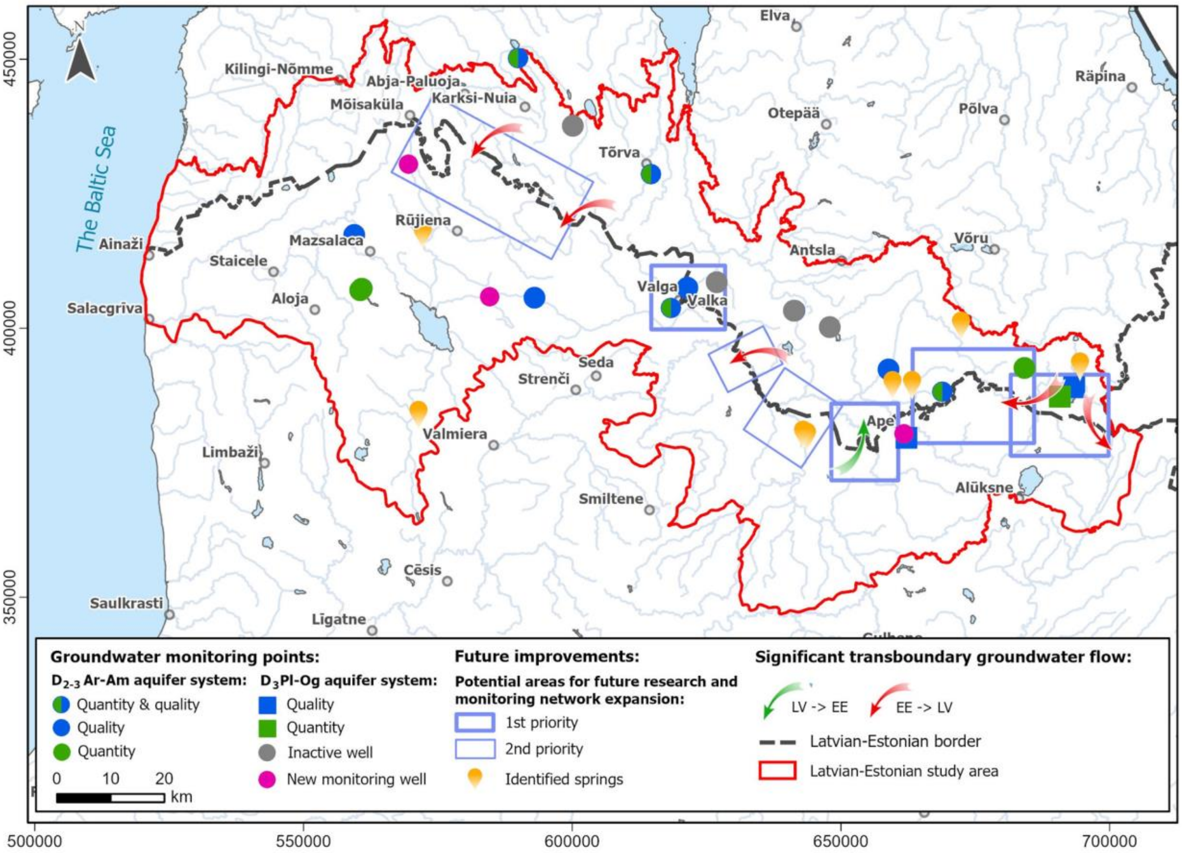


Figure 10. **Identified potential areas for future research and monitoring network expansion, the newly installed monitoring wells and identified springs for future transboundary monitoring network improvement**

It should be noted that since no significant anthropogenic pressure was identified in the Estonian-Latvian TBA, the installation of new monitoring wells and the integration of other monitoring points would be financially unjustified. But it also should be kept in mind that it is recommended to use the identified areas for further investigations - initially identified areas can and should be specified after new data have been obtained and a new knowledge base has been created. More information about potential transboundary groundwater monitoring network improvements can be found in the WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area".

2. Delineation of the areas in need of protection

2.1. Delineation of the areas vulnerable to pollution

Assessment of the vulnerability/sensitivity of groundwater or aquifers is a necessary tool in the planning and management of groundwater resources. Accordingly, in combination with risk maps, sensitivity maps can indicate particularly important threatened areas that require increased attention (propose additional measures) in the management of shared groundwater resources. In other words, the risk of pollution will depend on both the potential pollutants (point and diffuse pressures) and the vulnerability of aquifers. Low groundwater vulnerability can reduce the impact of high-level hazards. On the contrary - if anthropogenic activities do not take place in a cross-border area with a high degree of vulnerability, the risk may be negligible.

Vulnerability maps were created for the Estonian-Latvian TBA with two different methods: the DRASTIC method and the Macioszczyk method for vertical infiltration time calculation. While both methods evaluate the vulnerability, they differ in their approach and the parameters used. A vulnerability map for the Quaternary aquifer was created using the Macioszczyk method, while two vulnerability maps were created using the DRASTIC method for both Quaternary and pre-Quaternary aquifers. A more detailed description of the applied methods and their differences is available in Chapter 3 of the WP5 Report "Assessment of cross-border anthropogenic pressure on groundwater state".

The groundwater vulnerability maps generated using the DRASTIC and Macioszczyk methods are both classified into five classes according to their degree of vulnerability (Table 3).

Table 3. **Categorizations of the groundwater vulnerability**

GW Vulnerability class	**Percentage of the Di range** (for DRASTIC method)	**Vulnerability index (Di) values Quaternary/main useful aquifer** (for DRASTIC method)	**Time of pollution migration from the surface, years** (for Macioszczyk method)
Well protected	10-28.99	85.89/84.4	>100
Relatively well protected	29-46.99	105.69/108.9	50-100
Moderately protected	47-64.99	125.49/133.4	25-50
Weakly protected	65-82.99	145.29/157.9	5-25
Unprotected	83-100	164/181	<5

Figures 11-12 show the results of the groundwater vulnerability assessment obtained with the help of the DRASTIC method in Estonian-Latvian TBA, which are further used for the assessment of anthropogenic pressure. The groundwater vulnerability map created using the Macioszczyk method can be found WP5 Report "Assessment of cross-border anthropogenic pressure on groundwater state".

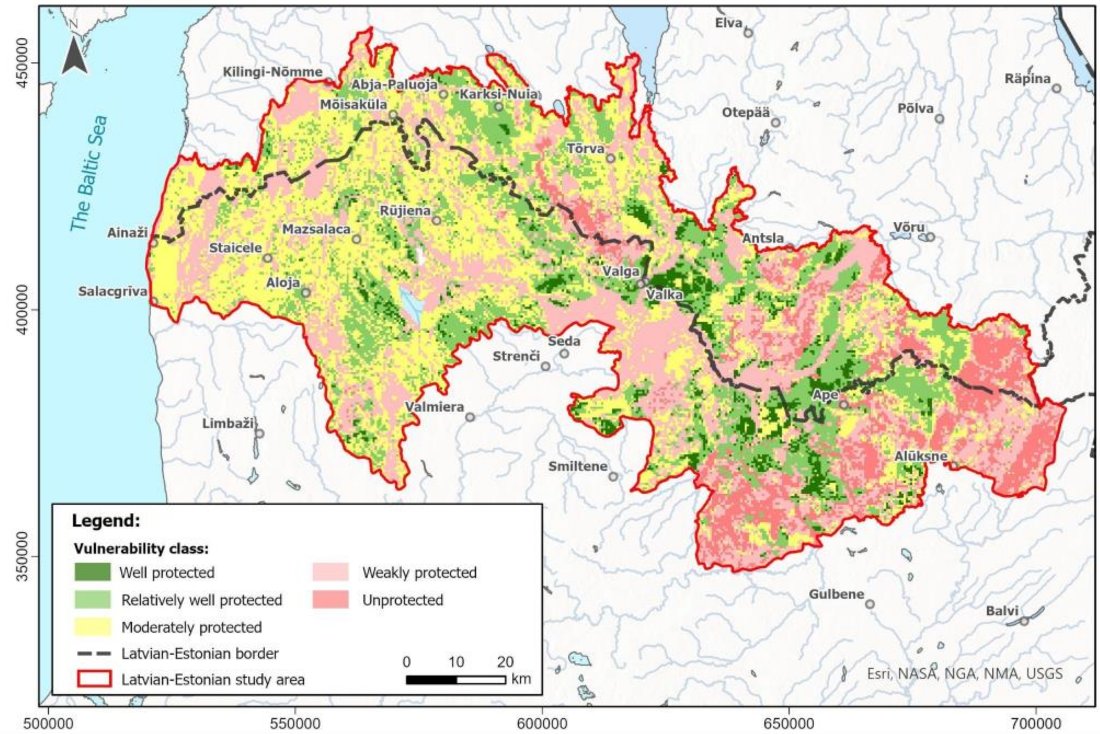


Figure 11. **Groundwater vulnerability map of the Quaternary aquifer in the Estonian-Latvian TBA**

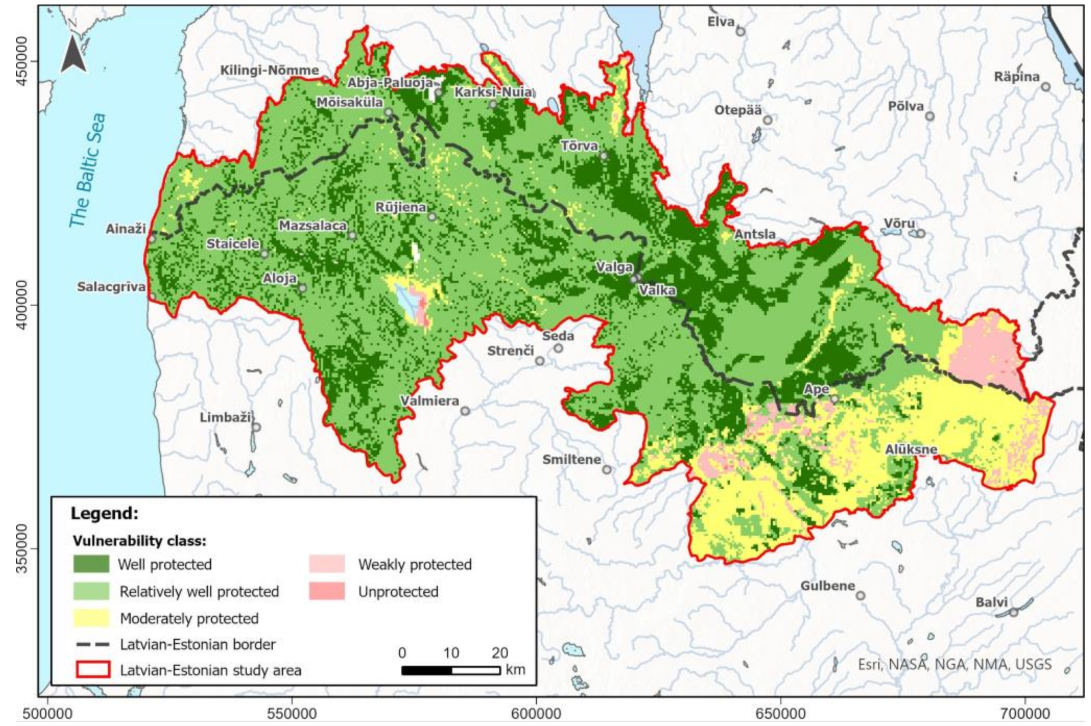


Figure 12. **Groundwater vulnerability map of the main useful aquifer in the Estonian-Latvian TBA**

The Quaternary aquifer is less protected from pollution and may be more exposed to anthropogenic influences. Weakly protected and unprotected areas make up 41.2% of the TBA and mainly coincide with areas covered with sand, as well as peatlands. It is the high groundwater level that is the reason for the lowest protection of these Quaternary aquifers, and such areas are mainly identified in the eastern part of the TBA. In these areas, the groundwater table is close to the ground surface and is not covered by thick layers of impermeable sediments. In the rest of the TBA, the protection of Quaternary aquifers is better and varies from moderately protected to protected areas. In a wider area, mainly in the western part of the TBA, where the surface is covered with moraine and a low groundwater level is observed, it is moderately protected (making up 33.1% of the TBA). On the other hand, in regions characterized by clay and moraine in the upper layer and in which lower groundwater levels are observed, the vulnerability of the Quaternary increases to protected.

It should be noted that the most useful (first bedrock) aquifer is better protected from pollution and can be exposed to anthropogenic pressure to a lesser extent because, in most of the study area, the first bedrock aquifer is covered by a Quaternary sedimentary cover with a significant thickness and/or the presence of clay layers. Protected and relatively protected areas account for about 82.1% of the TBA, and these areas mostly overlap with the outcrop of the Aruküla-Amata sandstone aquifers below the Quaternary sediments. In the eastern part of the TBA, or in the area of the Gauja-Koiva river basins, the Quaternary sediment cover is thinner or/and it is mostly formed of sand, and the Pļaviņas-Ogre aquifer lying below the Quaternary aquifer is less protected and its vulnerability to pollution increases - varying mainly from moderately protected areas to weakly protected areas, which in total occupy 17.7% of the TBA. It should be noted that unprotected areas can only be identified in a small part of the TBA, and they make up only 0.1% of the total area of the TBA.

A risk map was developed to assess the impact of current diffuse pressure on transboundary groundwater resources, as the risk of pollution depends on both the potential diffuse pollutants and the vulnerability of aquifers and groundwater. For example, a high degree of groundwater vulnerability can increase the risk due to diffuse pollution in the same area. In contrast, if there is no anthropogenic activity in a vulnerable region, the risk may still be low. A modified version of the DRASTIC method was used for the impact of the diffuse pressure assessment, and risk maps were created for both Quaternary and main useful aquifer layers.

Five classes were assigned to the risk maps, which identify how much the TBA is at risk (Table 4). In general, the first two classes can be considered as "no pressure", the next class as "potentially under pressure", and the last two classes - "with significant pressure".

Table 4. **Categorizations of the groundwater risk**

Riska classes	Percentage of the Di range	Di values Quaternary aquifer	Di values main useful aquifer
Very low risk	10-28.99	100.4	107.0
Low risk	29-46.99	129.2	137.4
Medium risk	47-64.99	158.0	167.8
High risk	65-82.99	186.8	198.3
Very high risk	83-100	214.0	227.0

Figures 13-14 show the results of the groundwater risk assessment on the Estonian-Latvian TBA.

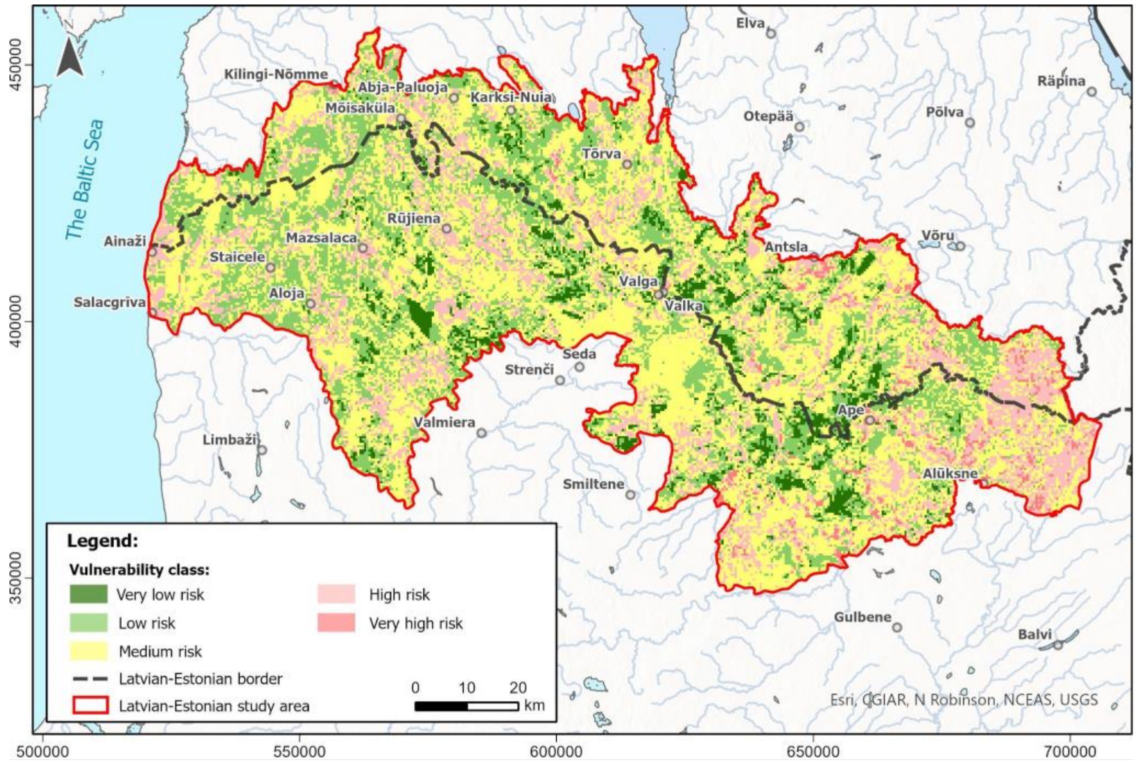


Figure 13. **Diffuse pressure analysis of the Quaternary aquifer using the DRASTIC-L method**

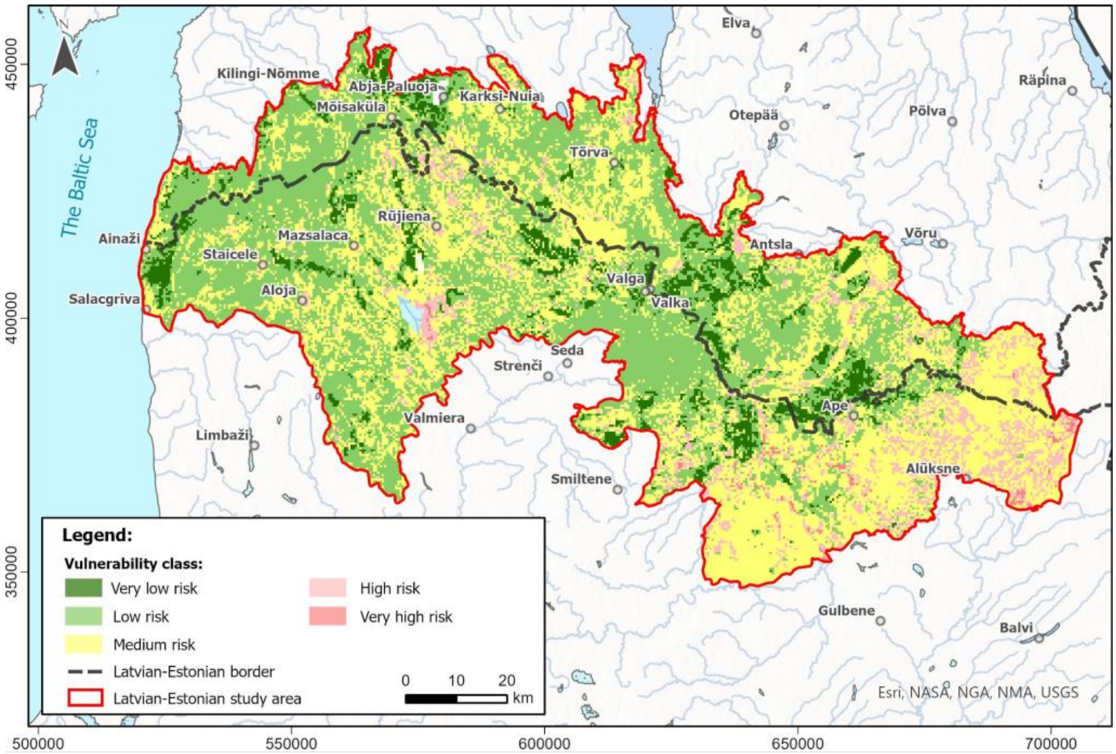


Figure 14. **Diffuse pressure analysis of the main useful aquifer using the DRASTIC-L method**

The maps show that the distribution of anthropogenic pressures has a significant impact on risk assessment: diffuse pressure zones described in Chapter 2.2. *Diffuse source pollution* remains at a high level in areas with the greatest risk of pollution. However, a low degree of vulnerability, or good groundwater protection, often mitigates the risks posed by the pressures.

The western part of the TBA is a clear example of a region where the high hazard of anthropogenic (diffuse) pressure is balanced by the low vulnerability of the sediments of the Aruküla-Amata aquifer, resulting in a significant reduction in the degree of risk in the aforementioned aquifer. On the other hand, it was concluded that Quaternary sediments and Pļaviņas-Ogre aquifers are mainly more exposed to risk due to greater vulnerability of these aquifers. At the same time, the results of the assessment and development of the risk map show that large, very sensitive areas of Quaternary aquifers (in the central part of the TBA) and the areas of Pļaviņas-Ogre aquifers (Gauja-Koiva river basin, on the Estonian side) are mainly not part of the area of significant risks, because currently in this area there are no significant threats from anthropogenic pressures.

The statistic of the distribution of risk classes on the map is presented in Table 5.

Table 5. **Distribution of risk classes within the Latvian-Estonian study area**

Risk clases	**Percent of the area, %** (Quaternary aquifer)	**Percent of the area, %** (main useful aquifer)
Very low risk	5.6	7.2
Low risk	26.4	43.2
Medium risk	47.4	41.3
High risk	18.7	7.9
Very high risk	1.9	0.4

In order to distinguish transboundary areas that may be more exposed to pollution and that require increased attention in future management of shared groundwater resources, the following data were collected:

1. areas with **vulnerability** classes - "Unprotected" un "Weakly protected" (indicate areas that may be threatened in the future due to an increase in anthropogenic pressure);
2. areas with **pollution risk** classes - "Very high risk" and "High risk" (indicate areas currently under anthropogenic pressure)
3. the direction of **groundwater flow** with the largest groundwater overflow between national borders (indicates the potential transboundary impact of the existing pressure and the increase of the anthropogenic pressure);
4. Point **pollution sites**, identified as significant during the development of the 3rd cycle RBMPs (mainly indicates contamination of Quaternary aquifers, contamination of deeper aquifers is excluded).
5. significant **groundwater abstraction** in the TBA.

As a result, maps classified into 4 classes were created for the Quaternary aquifer and the main useful aquifer (see Figures 15 and 16). Areas where the distribution of regions with high pollution risk and with high vulnerability exceeds the 50% limit, as well as significant transboundary groundwater overflows were identified, were considered the most important in the management of transboundary aquifers, or distributed GWBs. At the same time, priority was also given to those areas where the most intense groundwater abstraction was identified, and a possible increase in it could be expected in the future, or/and areas where several point sources of pollution near the TBA have been identified.

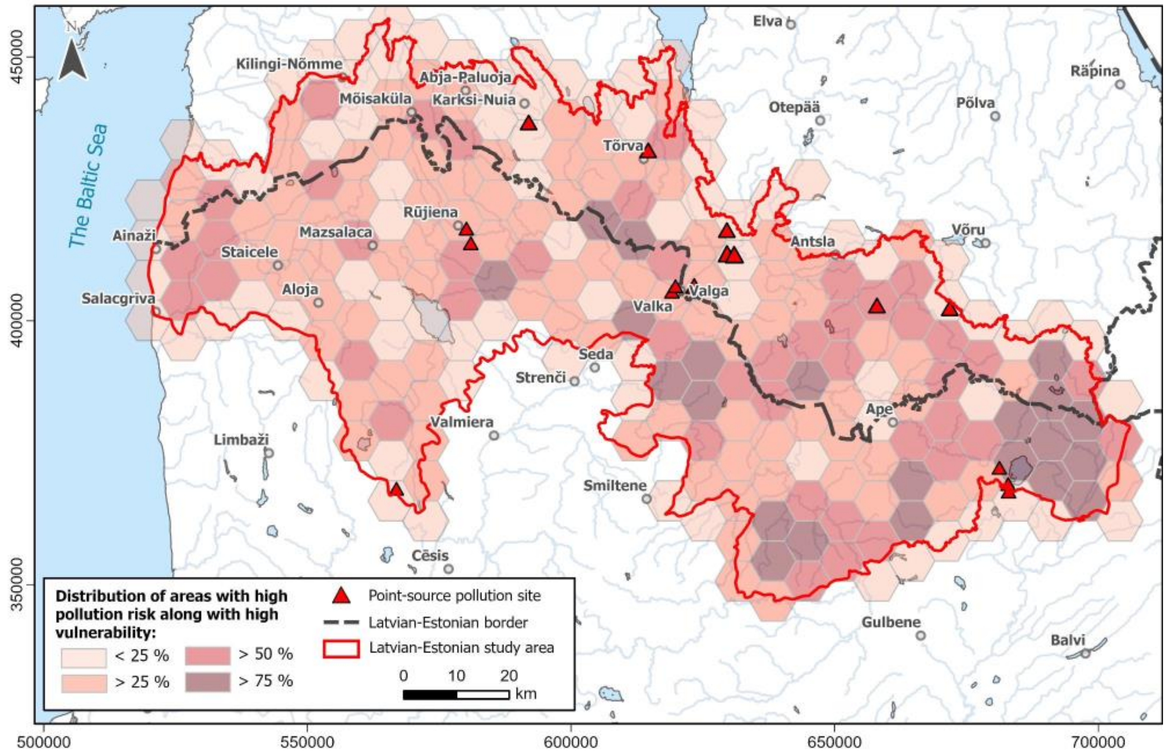


Figure 15. **Distribution of areas with high pollution risk along with high vulnerability for Quaternary aquifer system**

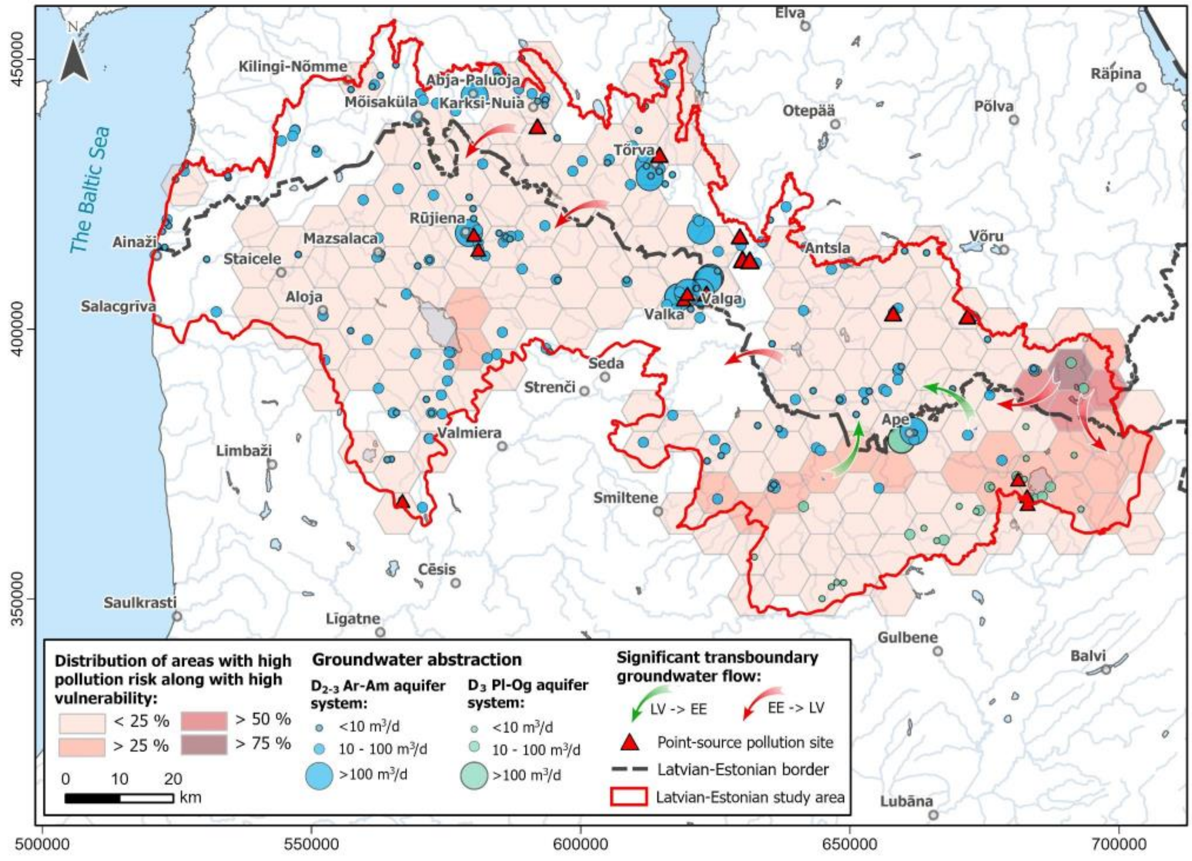


Figure 16. **Distribution of areas with high pollution risk along with high vulnerability for main useful aquifers**

Table 6 summarizes the identified areas as well as the priorities assigned to them. Visually, the places are shown in Figure 17.

Table 6. **Identified transboundary areas that need to pay increased attention to in the case of increased anthropogenic pressure**

No.	Criteria for area selection	Idenitfied areas				
		A	B	C	D	E
1.	Significant transboundary flow between national borders has been identified (respectively, higher pollution overflow is possible)	X	X		X	X
2.	Selected GW vulnerability + pollution risk classes make up > 50%	X			X	
3.	Intensive groundwater abstraction has been identified for the area, as well as potential for increased groundwater abstraction in the future		X	X		
4.	Several point pollution sites have been identified in the area			X		

Notes: A – Alūksne-Haanja highlands area, **B –** Ape area, **C –** Valka-Valga area, **D –** Gauja-Mustjõgi area, **E –** Northern part of study area

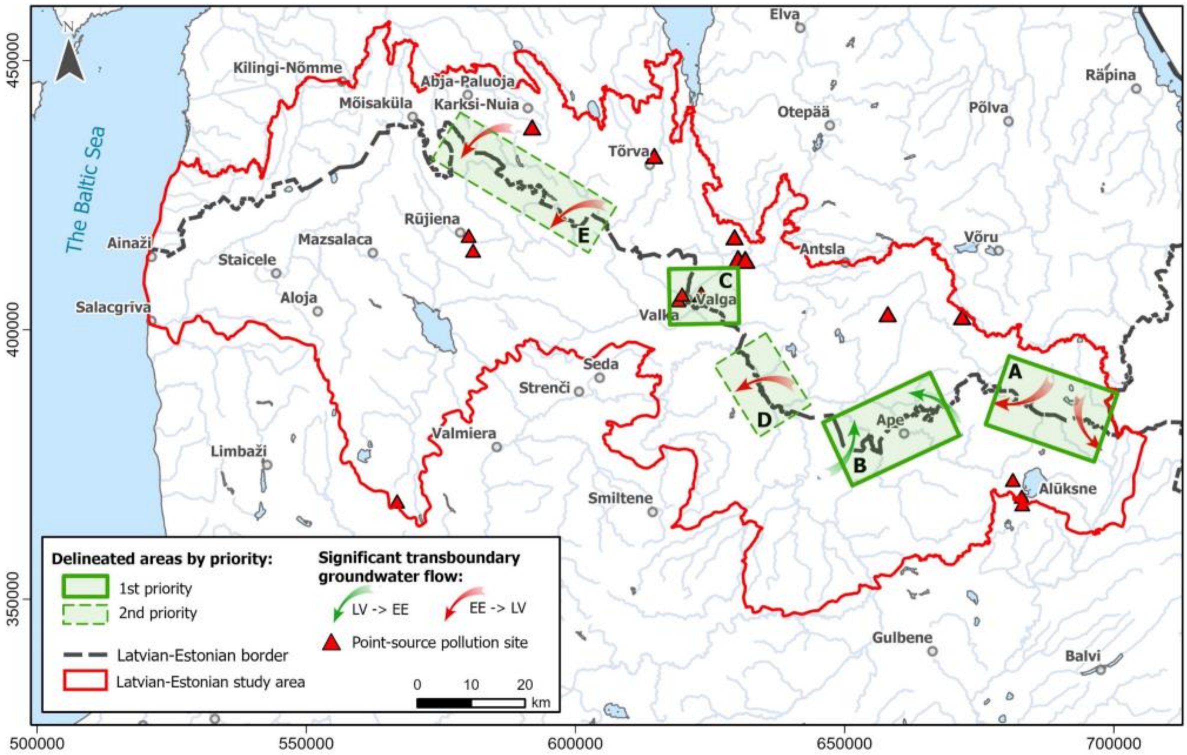


Figure 17. **Delineated areas vulnerable to pollution on Latvian-Estonian border area: A - Alūksne and Haanja highland; B - surrounding of Ape quarry; C - Valka-Valga area; D- Gauja-Mustjõgi area; E - Sakala highland.**

2.1.1. Alūksne- Haanja highlands area

The Alūksne-Haanja highland is located in the eastern part of the Latvian-Estonian study area and has been determined as a groundwater recharge area. According to the assessment, there is a high risk of pollution in this area - both the Quaternary and bedrock aquifers are weakly protected, and the modeling results also indicate a significant transboundary groundwater flow in the direction from Estonia to Latvia (both Quaternary and bedrock aquifers).

The territory is mainly dominated by forest areas, followed by agricultural areas. The population density in the border area is low, mainly individual households.

No significant point-pressure sites have been identified. Since the groundwater in this area is naturally weakly protected, a high risk of contamination, which could possibly arise from agriculture, is assessed here. Water extraction is not significant - a couple of water abstraction wells (in the Plavinas-Ogre aquifer system) have an extraction volume of up to 50 m3/d (Figure 18).

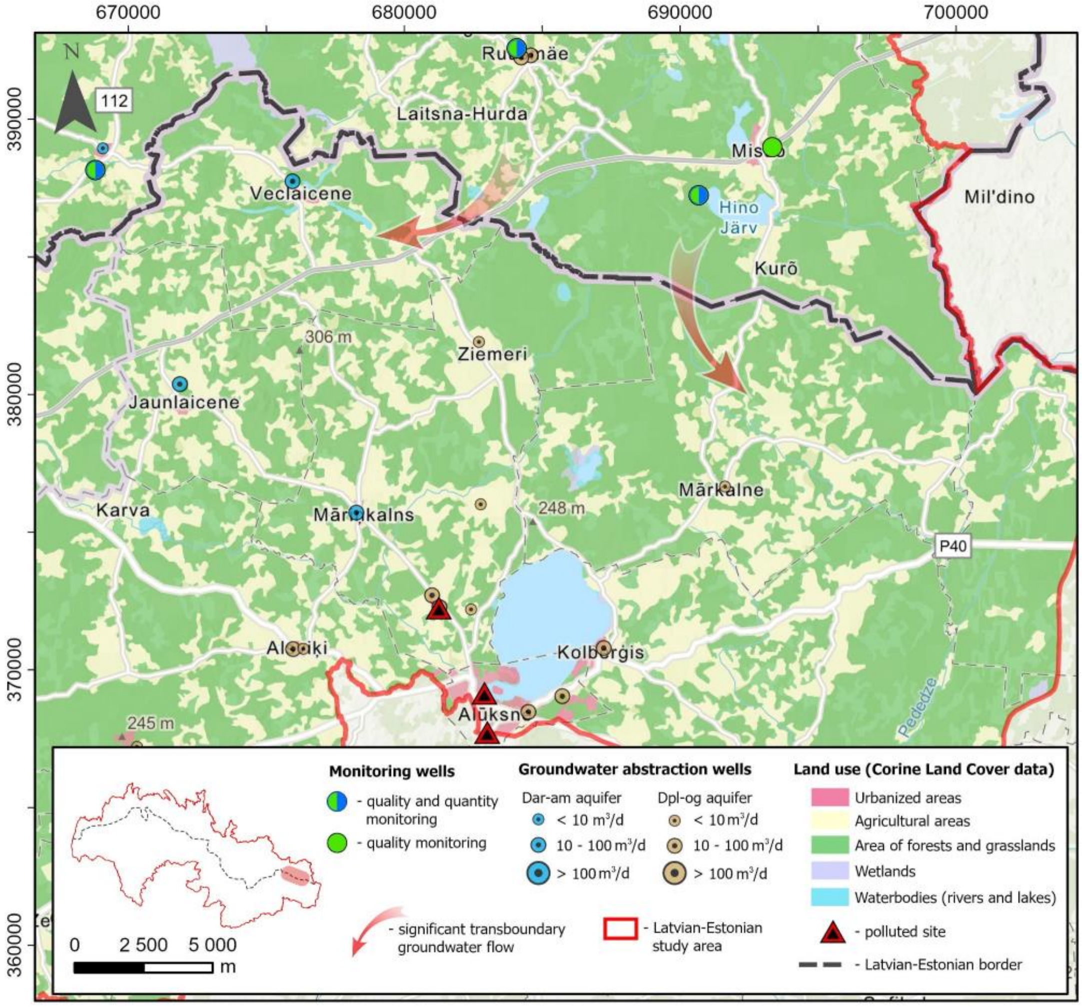


Figure 18. **Alūksne-Haanja highland area**

In order to improve transboundary monitoring, this territory was marked as a prospective area (priority 1) for improving cross-border monitoring (WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area"). There is no monitoring point on the Latvian side. Taking into account the above-mentioned circumstances, to improve transboundary monitoring, consider the possibility of installing groundwater monitoring points on the Latvian side as well.

In the current situation, the threat of transboundary pollution has not been noted, however, there is a groundwater recharge area, as well as the hydrogeological conditions of the territory, are favorable for the transfer of potential pollution. Due to the reasons listed above, it is necessary to pay more attention in the event that the anthropogenic pressure increases on the Estonian side.

2.1.2. Ape area

In this territory, a significant transboundary groundwater overflow from Latvia to Estonia has been assessed, as well as intensive groundwater abstraction is carried out on the Latvian side. As a result, this territory needs to be given increased attention in the transboundary context (Figure 19).

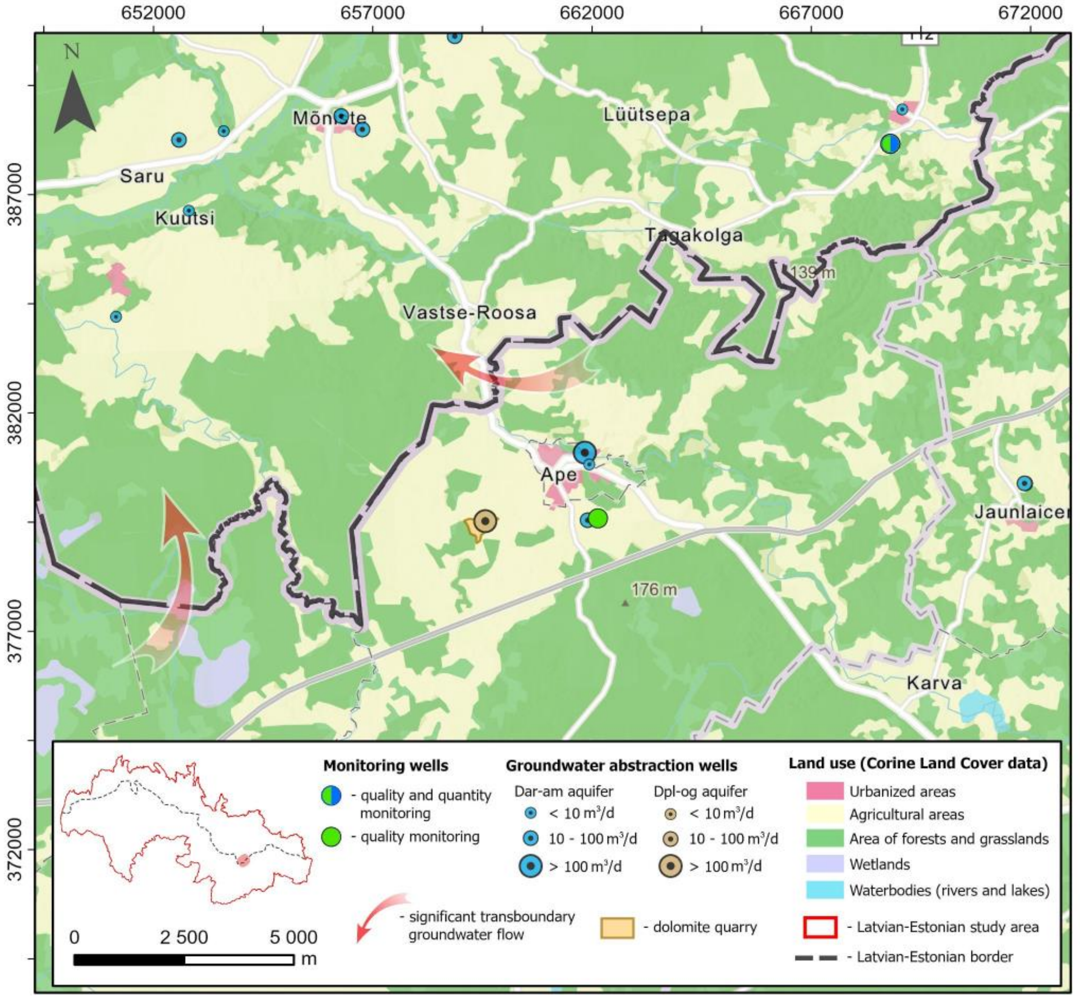


Figure 19. **Surrounding of Ape quarry**

The types of land use on the Latvian and Estonian sides are different - in Estonia, the border is dominated by forests, and the territory is basically uninhabited, while on the Latvian side, the anthropogenic pressure is greater - the city of Apes is located on the border, there are widespread agricultural lands, and dolomite quarry is located about 2 km from the border.

No significant point-pressure sites have been identified in the area. Although agricultural land is spread over the territory of Latvia, the risk of diffuse pollution in this place is not high because the groundwater is relatively well protected against pollution from the surface. The water abstraction situation in this area is different - on the Latvian side of the border, there is the Ape city. For the city's water supply, groundwater is extracted from one well, and the total abstraction rate does not exceed 100 m^3/d. The largest water abstraction in this area is from the open-pit dolomite quarry, which is located approximately 2 km from the Latvian-Estonian border. Extraction is not uniform (depending on the quarry working regime), so for example, in 2019, water lowering was not carried out at all, while in 2020, the volume of water pumping was 2069 m^3/d. Also, groundwater level lowering is performed in the quarry. Modeled simulations (with different water abstraction scenarios) indicate that dolomite quarries have a local impact and do not pose a threat to transboundary groundwater resources.

This area was previously identified as a prospective area (1st priority) for the improvement of transboundary monitoring (WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area"). On the Latvian side, there is one monitoring spring of the national monitoring network (for qualitative monitoring). Also, in 2023, a new observation station "Ape" has been installed on the Latvian side, where it is planned to monitor both the shallow Quaternary groundwater and the Ar-Am aquifer system. There are currently no monitoring points in this area on the Estonian side. As groundwater overflows in the direction from Latvia to Estonia, in the future, it is recommended to consider the possibility of installing groundwater monitoring points on the Estonian side to improve transboundary monitoring.

In the current situation, the threat of transboundary pollution has not been identified, however, a significant transboundary groundwater overflow from Latvia to Estonia has been noted here. Similarly, the Latvian side has a greater anthropogenic pressure, so in the future, it is necessary to pay increased attention to the further development of the territory and the potential impact on groundwater.

2.1.3 Valka-Valga area

In the Latvian-Estonian transboundary area, the greatest anthropogenic pressure is in the Valka-Valga border towns and this is also the place where the most intensive groundwater abstraction has been identified. Also, several point-source polluted sites have been registered here (Figure 20).

Compared to the rest of the border area, this region is the most densely populated and the city's built-up area dominates here. In the territory of the cities of Valka and Valga there are four point-polluted sites: Petrol station and former heating house/cogeneration station in Valka, as well as Asphalt concrete factory and Bitumen base in Valga.

Outside urban areas, mostly agricultural land is spread. The risk of diffuse pollution is not high because groundwater is well protected according to the vulnerability maps. The largest groundwater abstraction in Latvian territory is the groundwater well field "Valka", which ensures the centralized water supply of the city of Valka.

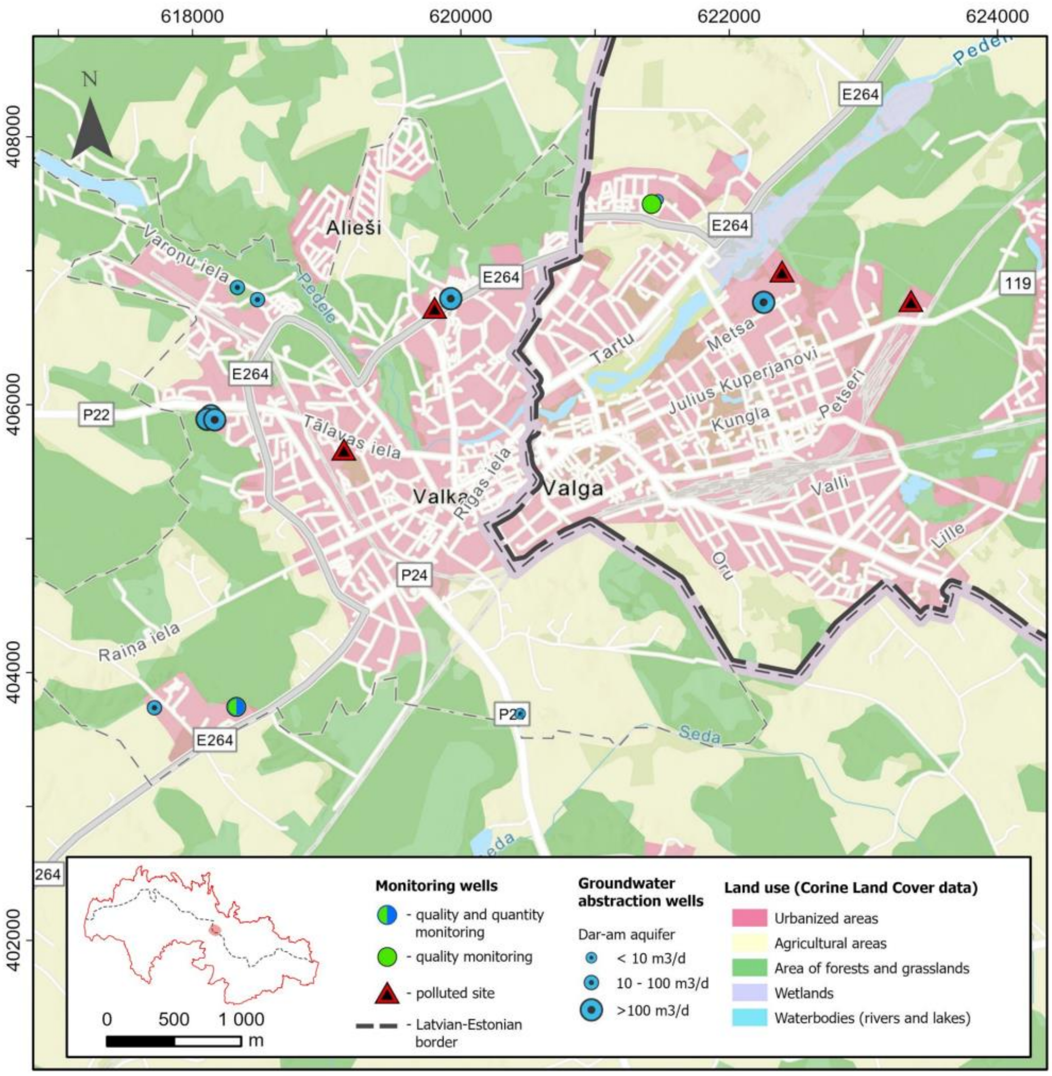


Figure 20. **Anthropogenic pressure in the urban area of Valka-Valka cities**

In Estonian territory, the largest abstraction sites are also in the city of Valga, which is a part of the central water supply. In both cities, the largest amount of groundwater is extracted from the Aruküla-Amata aquifer system, and total groundwater abstraction in this area reaches up to 2.4-2.7 thousand m^3/d. Since the anthropogenic pressure is the highest here, this area has also been selected as a prospective area (priority 1) for improving transborder monitoring, if necessary (WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area"). In the current situation, Valka has one monitoring point on both the Latvian and Estonian sides. Both quality and water levels are measured on the Latvian side, while water quality is monitored at the monitoring point in Estonia.

This area has the highest anthropogenic pressure on the entire Latvian-Estonian border. Although there is a monitoring station on both sides of the country and in the current situation, transboundary pollution has not been identified, it is still necessary to follow the development of the cities of Valka-Valka and the potential impact on groundwater in the future for the management of transboundary groundwater.

2.1.4. Gauja-Mustjõgi area

This area was chosen for precautionary reasons (2nd priority) - because a significant transboundary flow across national borders was assessed here. Accordingly, a higher pollution transfer is also possible. In addition, more than 50% of the territory has a high risk of potential pollution in the Quaternary aquifer. The territory is also important from the point of view of surface waters in the cross-border context - the rivers Gauja/Koiva (Latvia) and Mustjogi (a tributary of Gauja/Koiva from Estonia) converge here.

This transboundary territory is sparsely populated. Forest areas dominate on both the Latvian and Estonian sides. About 3.5 km from the border, on the Estonian side, is the Koikküla and Tsirgumäe villages (Figure 21).

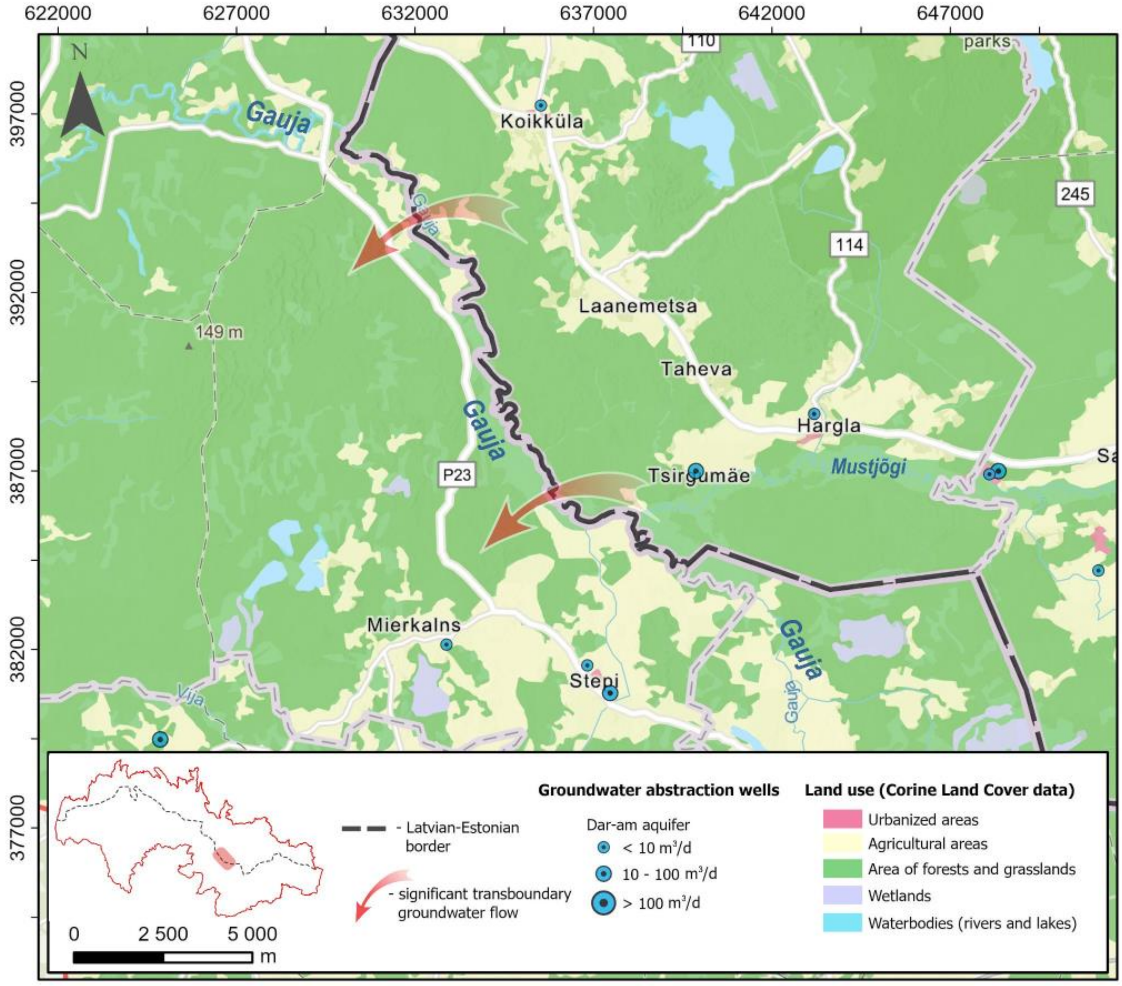


Figure 21. **Gauja-Mustjõgi area**

No significant point pressure has been identified here. Although a significant diffuse pressure has not been noted in the area, due to the specific geological conditions, a high risk of potential contamination of the shallow Quaternary groundwater is assessed here. Bedrock aquifers are well protected, so the risk of contamination is low. There is also no intensive groundwater abstraction. In the village of Koikküla, one water abstraction site is registered, where the extraction volume is less than 10 m^3/d. Accordingly, water abstraction in this area does not significantly affect the groundwater flow pattern and resources in general.

No monitoring station has been installed in this area, as there is minimal anthropogenic pressure on both sides. For the improvement of Latvian-Estonian transboundary monitoring, this territory was marked as a prospective territory with the 2nd priority (WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area"). If agriculture or other economic activity will develop here in the future, it is recommended to evaluate the installation of monitoring stations for the observation of groundwater.

In the current situation, the threat of transboundary pollution has not been detected, however, a significant transboundary groundwater overflow from Estonia to Latvia has been noted here, and the fact that the Gauja/Koiva is a common transboundary river basin that must be managed by both countries in the future should, also be taken into account. Considering the above mentioned, in the future, it is necessary to pay more attention to the future development of the territory and the potential impact on groundwater.

2.1.5. Northern part of study area

The territory is located in the northern part of the Latvian-Estonian transboundary area and belongs to the Salacas/Salatsi river basin. This area was chosen for precautionary reasons (2nd priority) - because a significant transboundary flow across national borders was assessed here. Accordingly, a higher pollution transfer is also possible. Groundwater flow is directed in the direction from Estonia to Latvia (Figure 22).

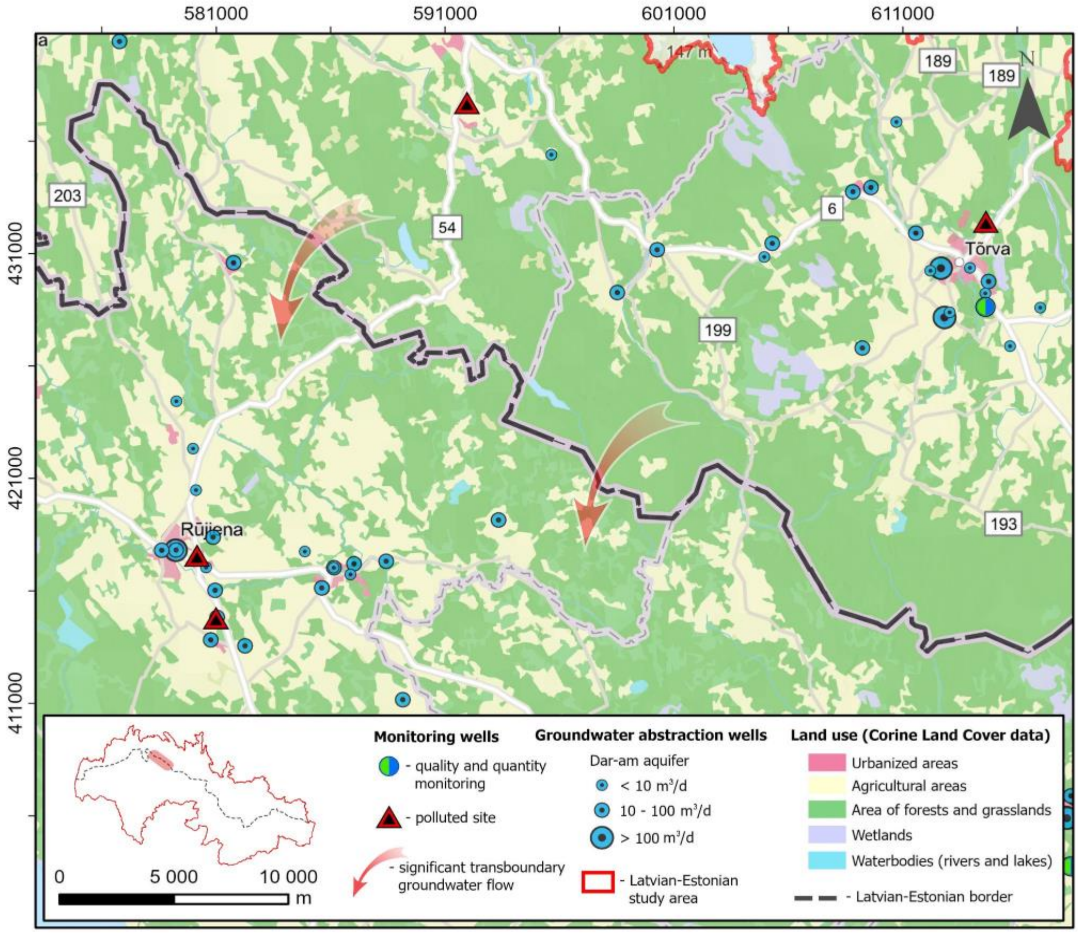


Figure 22. **Northern part of study area**

Agricultural lands are more common in the north-western part of the territory, while the rest of the territory is dominated by forest areas. This transboundary territory is sparsely populated. In the northern part there are a couple of small villages and individual households.

No significant point-pressure sites have been identified in the area. In the northern part, more than 50% of the area is assessed to have a high risk of diffuse pollution (to shallow Quaternary groundwater) due to agriculture. For bedrock aquifers, the diffuse pollution risk is low. Intensive water abstraction has also not been identified - some water abstraction sites have been registered, with extraction up to 100 m3/d, mainly for the water supply of residential houses in villages.

No monitoring station has been installed in this area, as there is minimal anthropogenic pressure on both sides. For the improvement of Latvian-Estonian transboundary monitoring, this territory was marked as a prospective territory with the 2nd priority (WP3 report "Integrated groundwater observation network in Latvian-Estonian transboundary area"). If agriculture or other economic activity will develop here in the future, it is recommended to evaluate the installation of monitoring stations for the observation of groundwater.

In the current situation, the threat of transboundary pollution has not been detected, however, a significant transboundary groundwater overflow from Estonia to Latvia has been noted here, and the fact that the Gauja/Koiva is a common transboundary river basin that must be managed by both countries in the future should, also be taken into account. Considering the above-mentioned, in the future, it is necessary to pay more attention to the future development of the territory and the potential impact on groundwater.

2.2. Delineation of the areas exposed to depletion or deficit of transboundary groundwater

For the assessment of Estonian-Latvian TBA groundwater resources, a 3D hydrogeological model was developed, which made it possible to assess the overall balance of groundwater resources and identify the places with the most intensive overflow of groundwater between national borders. The model results highlighted the significance of the Quaternary, Upper-Devonian and Upper-Middle-Devonian aquifer systems in the TBA, with varying groundwater flow rates and directions across the Estonian–Latvian border area (Figure 23). The majority of transboundary groundwater flow occurs in the Eastern part of the TBA, in the Gauja/Koiva river basin area.

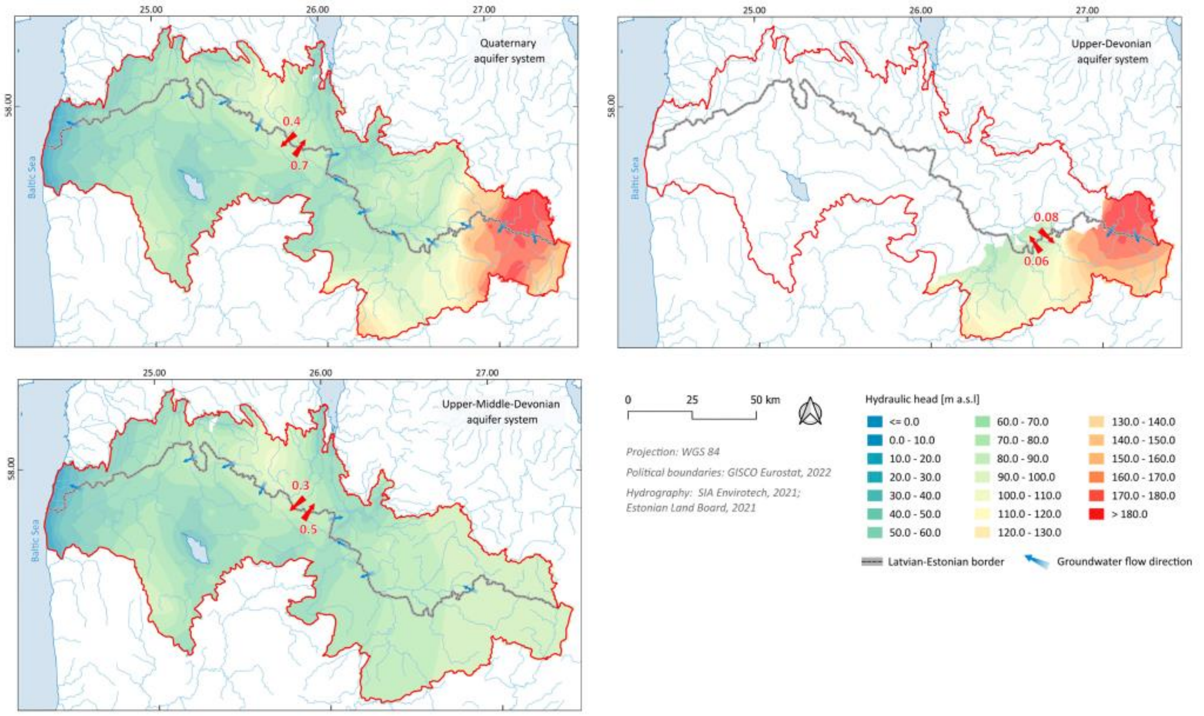


Figure 23. **Groundwater budget between aquifers in the Quaternary, Upper-Devonian and Upper-Middle-Devonian aquifer systems (×10^5 m^3/d) in Estonian-Latvian TBA (Hunt et al., 2023)**

The total groundwater balance of the transboundary area is 39*10^5 m^3/d, of which the Quaternary aquifer water exchange is 26*10^5 m^3/d, the Upper-Devonian aquifer water exchange 1*10^5 m^3/d and the Upper-Middle-Devonian aquifer water exchange 12*10^5 m^3/d. Aquifers are recharged by precipitation and discharged through river runoff or groundwater flow to the sea. The regional water flow of all aquifers in the study area is from east to west. The direction of local groundwater flow is determined by highlands to river valleys.

The results of the model calculations confirmed that the natural resources of groundwater are significantly greater than current water abstraction. Hence, the current abstractions in the territory practically do not affect the transboundary groundwater overflow. With increased volumes of groundwater abstraction up to approved resources (including groundwater abstraction in quarries) in the Estonian-Latvian TBA, however, small changes can be observed, which are mainly identified only in the Upper-Devonian aquifer system near the quarries and are local in nature. More detailed information was performed in the WP5 report "Transboundary impacts as a result of exploitation of groundwater resources in Polish-Ukrainian and Estonian-Latvian pilot areas".

2.3. Catchment simulation for delineated Valga/Valka area

The Valga/Valka region, designated as a cross-border area with the highest water consumption and prioritized as a Priority 1 area, played a central role in our study. In this context, we conducted calculations for the catchment areas of groundwater wells that consume more than 100 m^3/d. The region encompasses a total of ten boreholes: four in the western part of the Valka water abstraction point, four in the northeastern outskirts of the Valga water abstraction point, and two belonging to industrial facilities.

On the Latvian side, Valka's water abstraction wells have a maximum allowable water extraction of 1060 m^3/d, while a well located to the south of the city has a maximum allowed consumption of 600 m^3/d. On the Estonian side, the maximum allowed consumption for Valga's water abstraction wells are 3200 m^3/d, and for a well in the northeastern part of the city, it is 480 m^3/d, designated for industrial use.

To calculate the catchment areas for these water abstraction points, we employed a dynamic hydrogeological model developed previously during the given research. Using backward particle tracking, the model projected the flow paths of water particles for the next 30 years.

The largest catchment area, spanning 2 km^2, emerged for Valga's water abstraction wells (Figure 24). This area predominantly consists of forests, grasslands, and fields, with a few scattered residences. Additionally, it is traversed by the Jõhvi-Tartu-Valga highway. The second-largest catchment area, covering 0.6 km^2, is projected for Valka's water abstraction wells over the next three decades at maximum consumption levels. This area includes both forested and residential zones. No polluted sites fall within the catchment area of the water abstraction points.

Smaller catchment areas are associated with two privately-owned boreholes. One, situated on the Latvian side, covers 0.4 km^2 and includes a polluted site – a boiler house and cogeneration station – amidst forest and grassland. The catchment area for the privately-owned borehole on the Estonian side, covering 0.2 km^2, encompasses a residential area with no polluted sites.

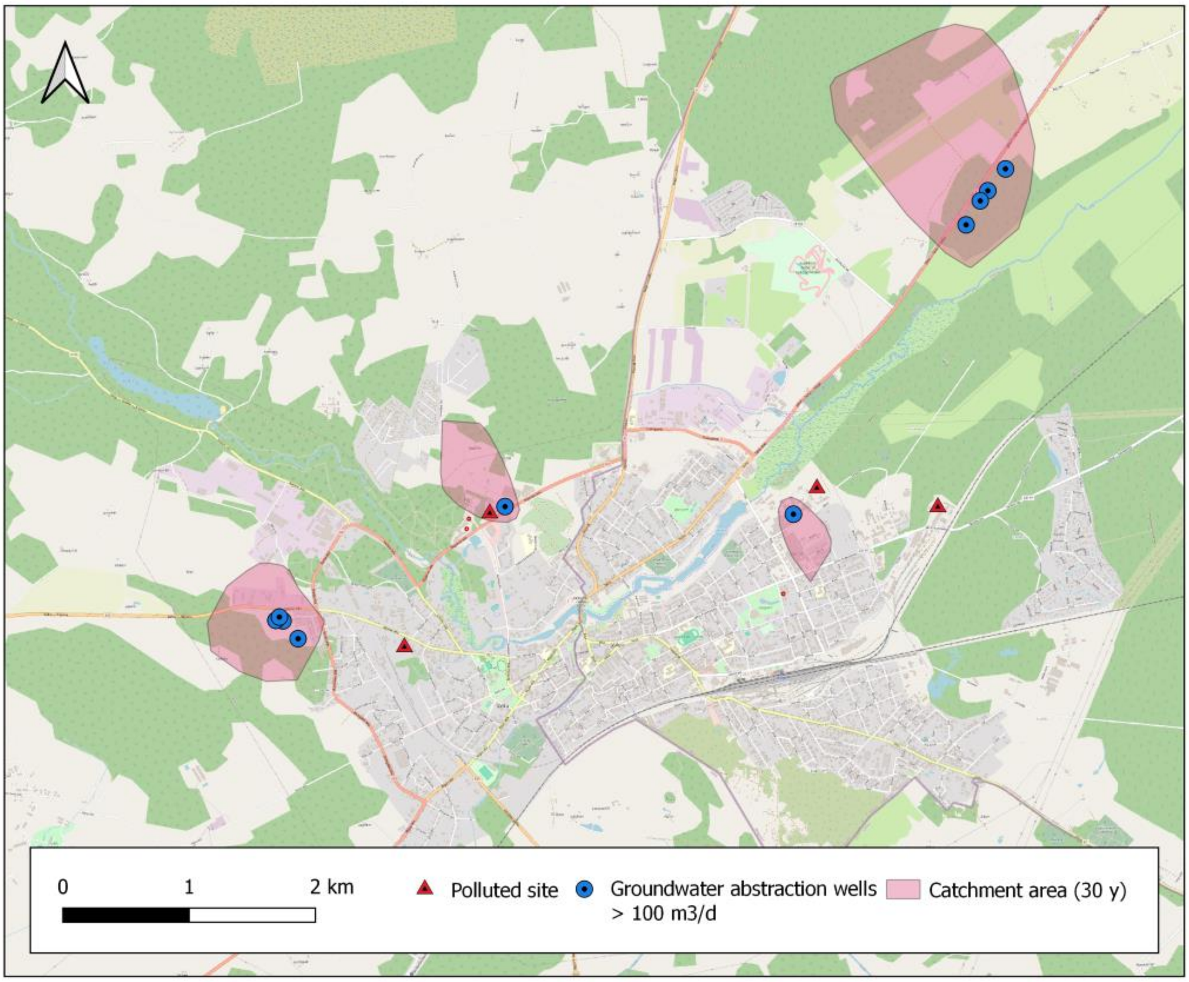


Figure 24. **Catchment areas in Valga/Valka area**

3. Analysis of spatial distribution and trends of changes in concentrations of chemical components of groundwater

In the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", identification and assessment of the diffuse pressures on groundwater was performed. According to CORINE Land Cover data, 33% of the Estonian-Latvian TBA is covered by urbanized and agricultural areas. Agriculture, especially highly fertilized lands, is a key factor in diffuse pollution, contributing nutrients like phosphorus and nitrogen compounds, as well as other substances like pesticides and heavy metals. It was assumed that intensively used agricultural lands might have nitrate contamination, mainly from fertilizers.

Given that agriculture is the main pressure on the EE-LV TBA, nitrate concentrations in all wells are examined. Subsequently, a trend analysis is conducted in monitoring wells to reveal patterns over time. The objective is to correlate nitrate data points with vulnerability maps and pollution risk maps presented in the WP5 report "Assessment of cross-border anthropogenic pressure on groundwater state", providing insights into their interrelationships. By overlaying these maps, spatial correlations between vulnerable groundwater areas and zones with heightened nitrate contamination can be revealed. As nitrates are a reliable indicator of potential pollution sources, they are often used to validate the precision of vulnerability assessment (Gupta et al., 2023; Goodarzi et al., 2022).

The focus is on nitrates as they are a crucial measure for assessing groundwater pollution, especially where agriculture is a significant human activity. High nitrate levels in groundwater often signal contamination from farming practices. Nutrients from fields can seep into groundwater, posing a potential threat to water quality, so monitoring and analysis are essential. The importance of nitrate concentration monitoring is highlighted by its inclusion in the national quality assessment monitoring of Estonia and Latvia, ensuring a strong database for analysis. Nitrogen pollution is a shared concern in the Nordic and Baltic countries (Kitterød et al., 2022), emphasizing the need for thorough research and monitoring.

3.1. Trends in nitrate levels

For nitrate concentration trend analysis, monitoring data from both Estonian and Latvian monitoring networks were used. Monitoring data is available (data density varies in different wells) from 1973 in Latvia (Latvian hydrogeological database "Wells", 2023) and from 1995 in Estonia (Environmental Monitoring Information System, 2023).

In Latvia, the nitrate concentration in monitoring wells shows variable trends (Figure 25). In some wells (22652 and 9600), a trend of decreasing levels can be seen. In monitoring spring 24554 and wells 9601 and 9637 temporarily higher levels of nitrate are observed, indicating short-term fluctuations or specific events influencing nitrate concentrations. Wells 24561 and spring 24563 demonstrate variable trends, with nitrate levels showing fluctuations — rising at times and then returning to lower levels. However, it is important to note that all nitrate levels observed in the Latvian monitoring wells, including those with varying trends, remain below the permitted drinking water level of 50 mg/l. This indicates that, despite fluctuations, the nitrate concentrations in the monitored wells do not pose a risk to drinking water quality.

Similar to Latvia, all nitrate levels in Estonian wells remain below the established threshold of 50 mg/l (Figure 26), ensuring that the groundwater in the monitored areas meets the drinking water standards. Temporary fluctuations in nitrate concentrations are evident, similar to the observations in Latvia. These fluctuations may be influenced by short-term environmental factors or specific events affecting nitrate levels. Notably, some wells in Estonia show changes to lower values in recent years. This shift is attributed to the use of more precise measurement methods since 2018, which has enabled the identification of lower nitrate levels.

Additionally, it can be observed that the deeper Dar-am aquifer in the EE-LV TBA has very low nitrate levels, while higher nitrate concentrations are found in the shallow Quaternary aquifer (monitoring well nr 22652).

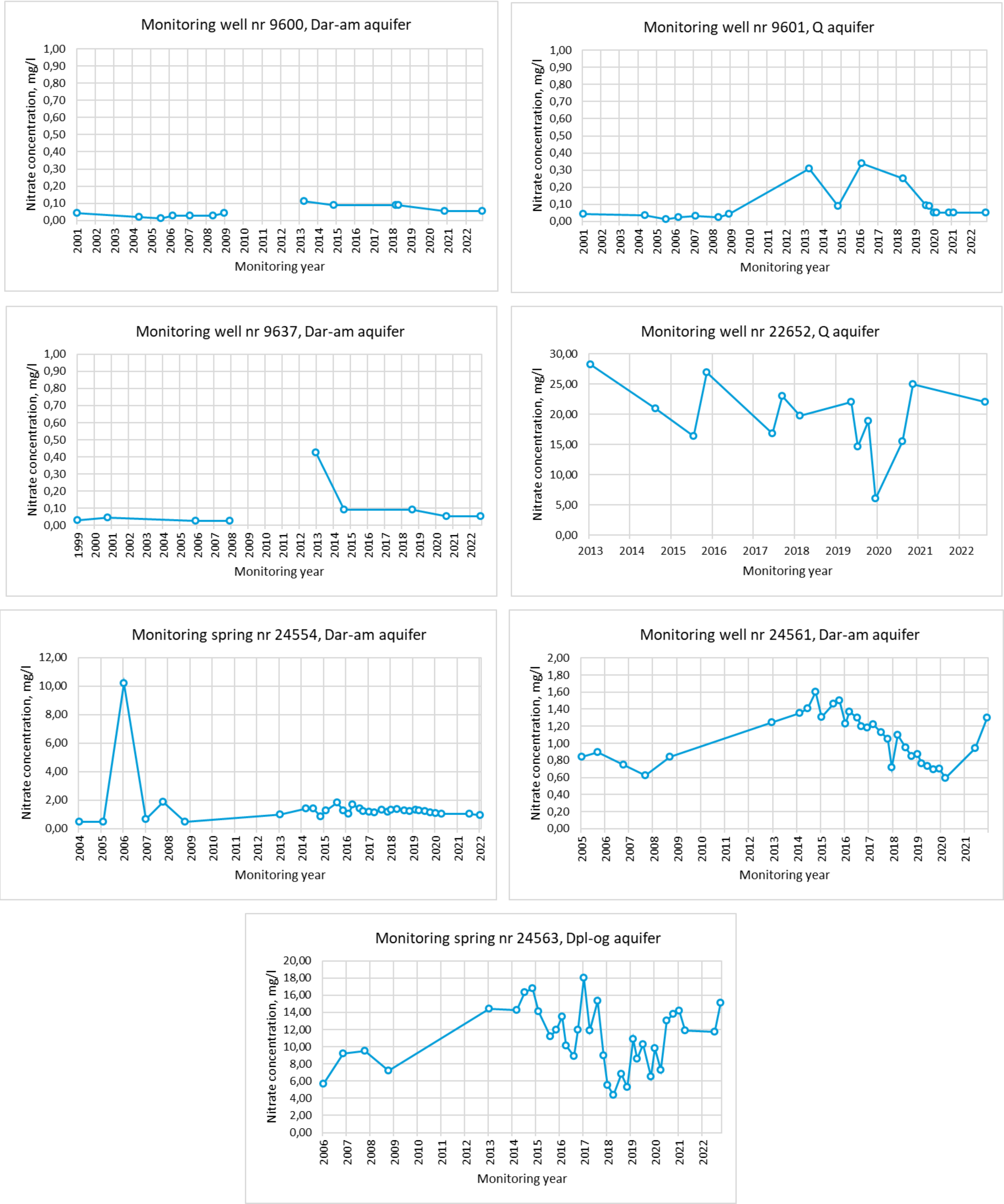


Figure 25. **Nitrate concentration trends in monitoring wells and springs in Latvia.**

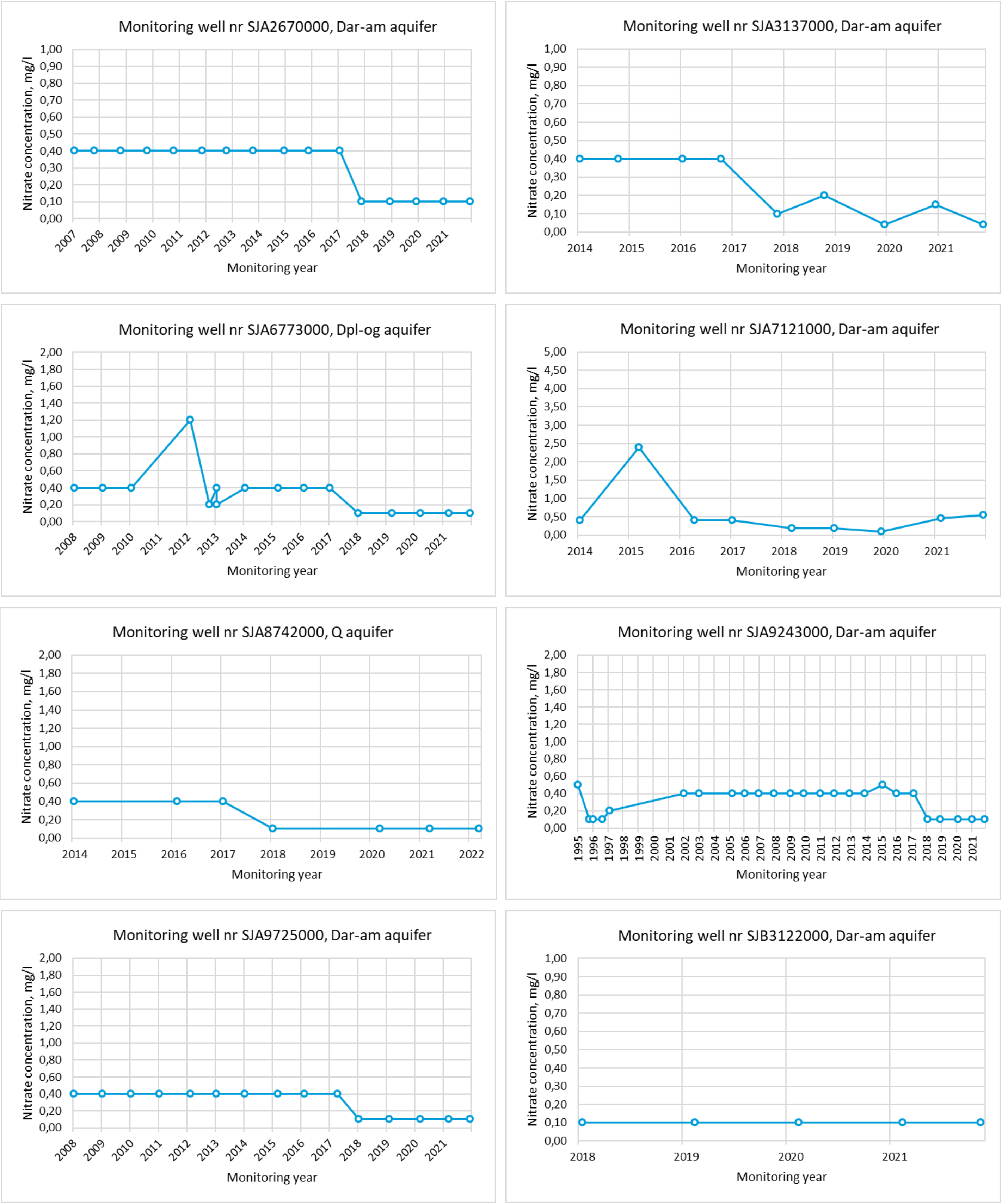


Figure 26. **Nitrate concentration trends in the monitoring wells in Estonia.**

3.2. Nitrate concentrations and vulnerability maps

For the analysis of the extent of correlation between the nitrate concentrations and pollution risk and vulnerability maps, chemical data from all of the wells in national databases (Latvian hydrogeological database "Wells", 2023; Estonian Nature Information System, 2023) on the Estonian-Latvian TBA was used (Figure 27).

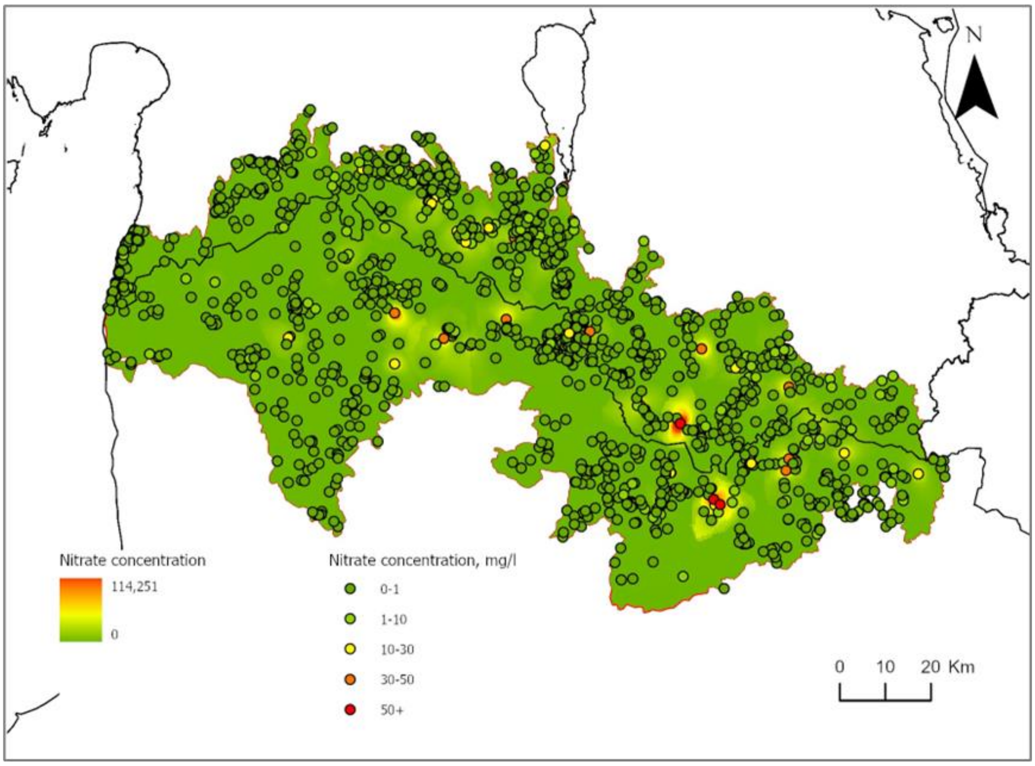


Figure 27. **Nitrate concentrations in the Estonian-Latvian TBA.**

Results from the correlation analysis of nitrate levels and pollution risk maps (Figures 28-29) reveal that, overall, there is a statistically significant correlation ($p < 0.05$) between the vulnerability index and nitrate concentration. This suggests that areas with higher vulnerability, as indicated by the vulnerability index, tend to exhibit elevated nitrate concentrations.

Despite the general correlation, there are areas where the vulnerability index indicates a higher level of vulnerability, yet no nitrate pollution is present. It's important to note that Estonia and Latvia typically maintain a background level of zero nitrates in groundwater. Any detectable nitrate concentration is considered an anthropogenic input, highlighting the sensitivity of nitrate concentration as a pollution indicator in this context.

The extensive monitoring of nitrate concentration in Estonia and Latvia contributes to a large database of observations. This abundance of data enhances the precision of analysis, however, it also contributes to the existence of areas where the vulnerability index suggests higher vulnerability, but no nitrate pollution is detected.

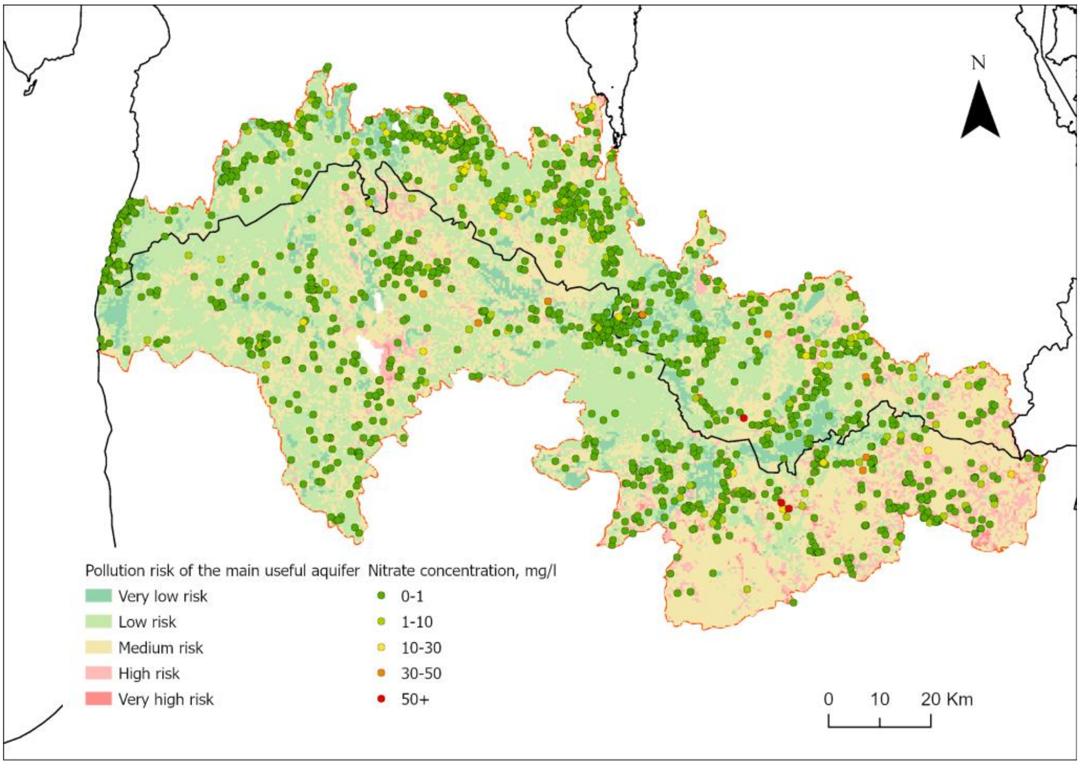


Figure 28. **Pollution risk of the main useful aquifer and the nitrate levels in the EE-LV TBA.**

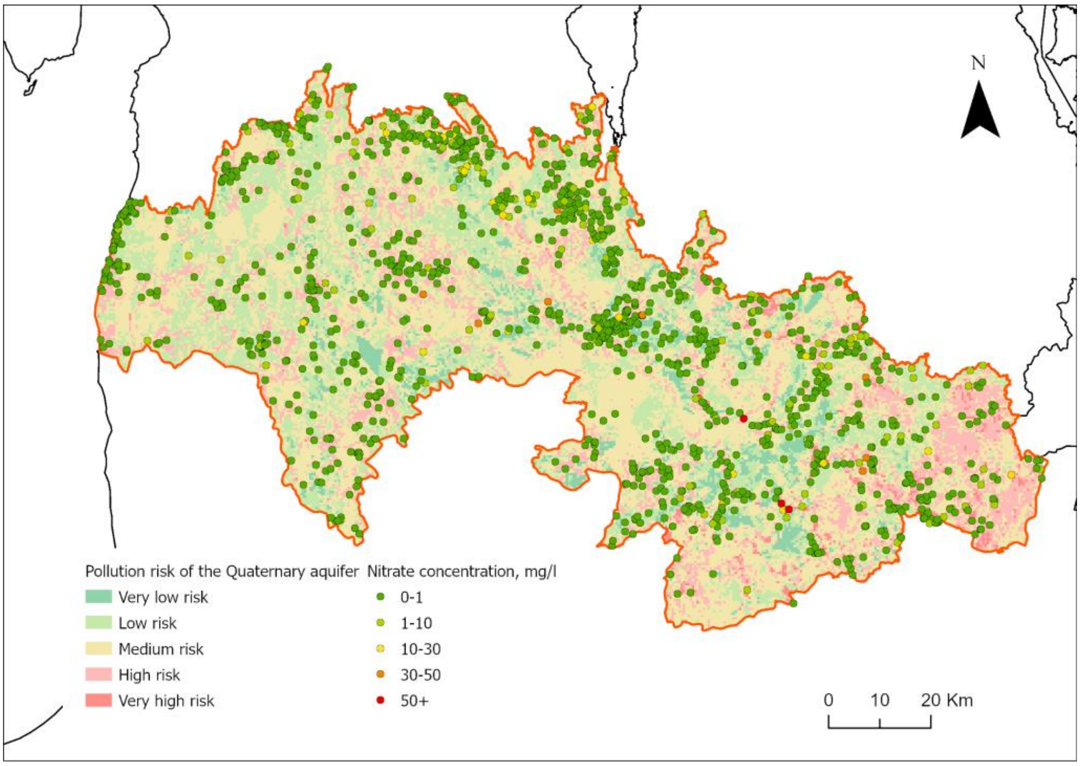


Figure 29. **Pollution risk of the Quaternary aquifer and the nitrate levels in the EE-LV TBA.**

Additionally, the correlation analysis between nitrate concentration and natural vulnerability maps (Figures 30-31) does not demonstrate a significant correlation ($p > 0.05$). This emphasizes the crucial role of integrating the land use parameter into vulnerability analysis for obtaining more accurate results regarding the actual risk of pollution.

The absence of a statistically significant correlation between nitrate concentration and vulnerability maps emphasizes the limits of relying solely on natural vulnerability as an indicator of pollution risk. By incorporating the land use parameter into vulnerability assessments, a more comprehensive understanding of the potential pathways of pollution can be achieved.

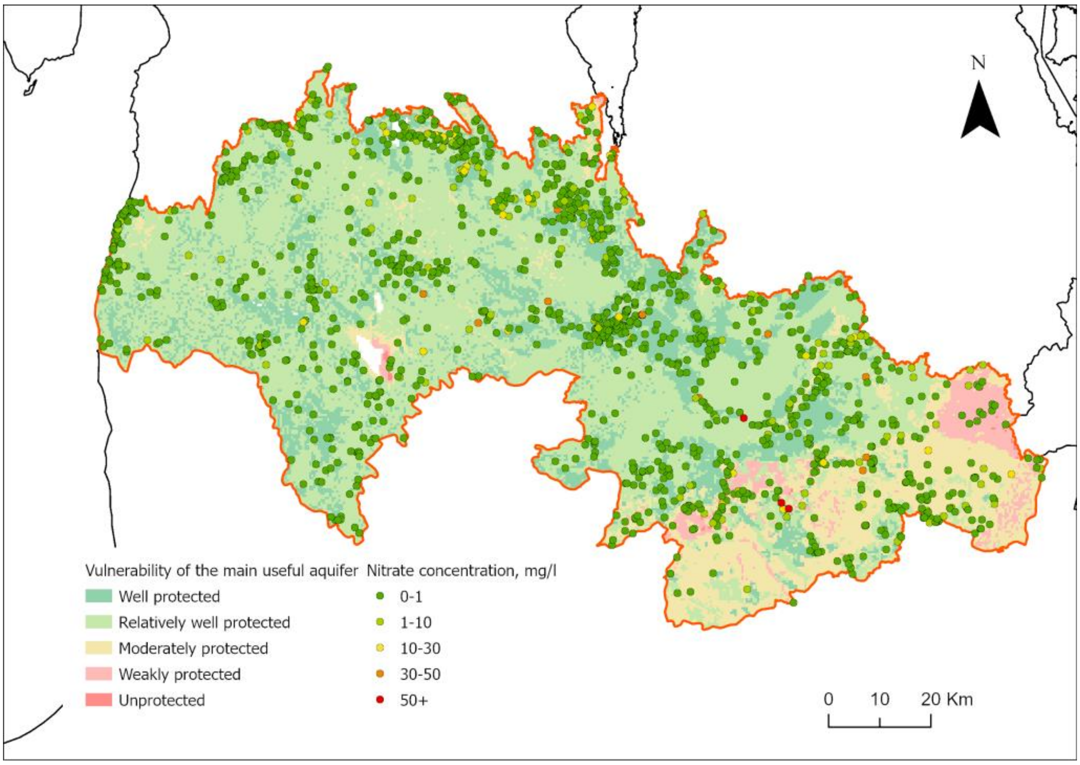


Figure 30. **Vulnerability of the main useful aquifer and the nitrate levels in the EE-LV TBA.**

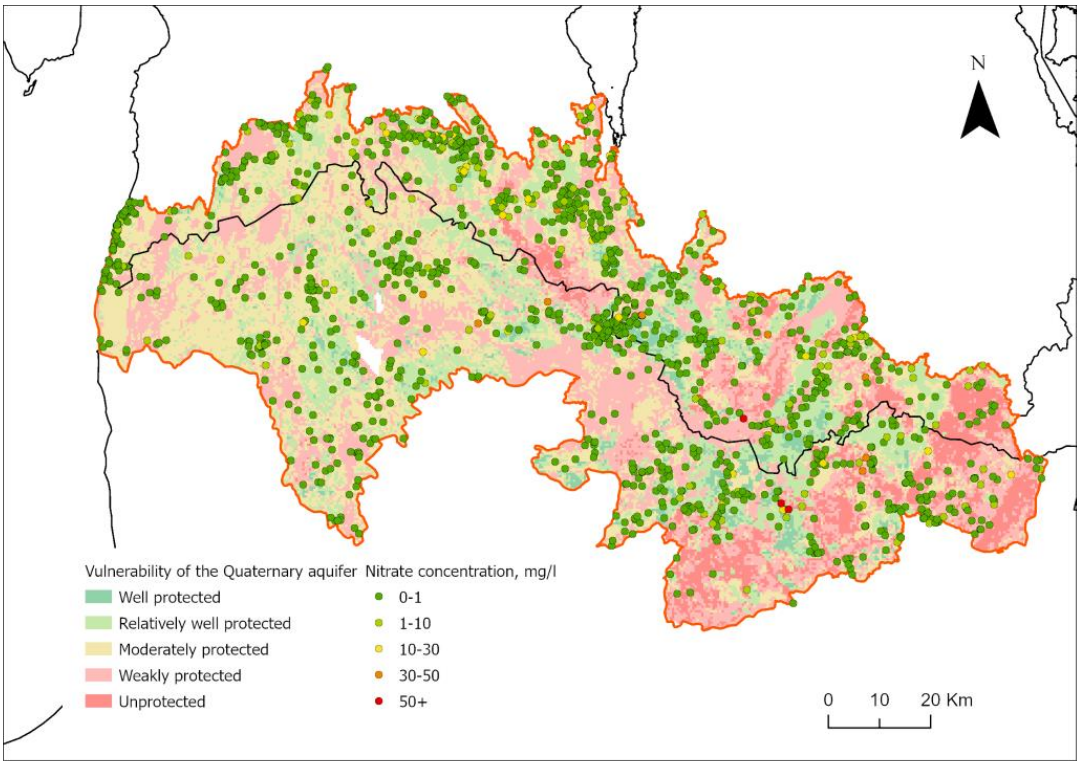


Figure 31. **Vulnerability of the Quaternary aquifer and the nitrate levels in the EE-LV TBA.**

4. Developing program of protection of transboundary groundwater for the Latvian border area

4.1. Program of measures and the proposed approaches

The EU Water Framework Directive (further as WFD or Directive) mandates the establishment of a "programme of measures" to achieve the environmental objectives set for each water body, as per Article 4. These measures, integral to the River Basin Management Plan, are detailed in Article 11. This programme introduces a comprehensive framework for regulating activities in the River Basin District. It encompasses strategies for controlling pollutants, preventing water pollution, and optimizing water use and reuse.

The formulation of this programme leverages data from river basin surveys to pinpoint necessary actions. Member States have the flexibility to tailor individual measures for each river basin district or implement broader legislative or regulatory approaches applicable to all basins, including segments of international basins within their borders. The Directive categorizes measures into two groups: "basic measures," which are mandatory, and "supplementary measures," which are optional but can be adopted as needed.

Some of the approaches to be considered when preparing programmes of measures under the WFD are summarized below:

- **Combined approach.** The Directive introduces a novel "combined approach" to manage polluting discharges, blending two historically distinct pollution control philosophies. The first, the emission limit value approach, sets maximum permissible pollution levels based on industry and effluent composition, often disregarding the environmental impact. The second, the water quality objective approach, concentrates on preserving a minimum water quality to ensure uninterrupted use, taking into account both point and diffuse pollution sources. The EU Water Framework Directive, particularly Article 10, now mandates this combined approach. It incorporates regulations from various directives and integrates emission limit values with quality objectives. When conflicts arise, the stricter of the two standards is used. The combined approach establishes a clear connection between regulatory activities and the attainment of environmental goals. Most countries have regulatory mechanisms to reduce pollution from industrial processes, and many have adopted best practice systems for activities like agriculture. However, the direct link between these controls and achieving an environmentally sustainable level of biological abundance was previously unestablished.
- **Pollution control.** Establishing controls on diffuse sources of pollutants presents a greater challenge, yet it's crucial given that many main list pollutants and priority substances can enter water bodies through these means. The programme of measures under the Directive must tackle this issue. Approaches to managing diffuse pollution vary by country. Countries may employ different regulatory methods, including prohibitions on certain substances, to control diffuse pollution.
- **Waste management.** Waste disposal methods, including incineration and landfill, can significantly affect water quality. The European Union has specific legislative frameworks addressing these aspects, notably through directives that provide guidelines for managing both domestic and hazardous wastes. Recognizing the potential for pollutants listed in the EU Water Framework Directive to be present in solid wastes and their possible infiltration into surface and

groundwater is crucial. Compliance with the Waste Sector Directives is thus an integral component of the overall programme of measures.

- **Cost recovery.** The Directive introduces a key advancement in water management - the establishment of a cost recovery system. This system is designed to ensure that water pricing policies not only encourage efficient water use but also contribute to the environmental objectives of the Directive. It aims to adequately recover the costs of water services from the principal user groups, including industry, agriculture, and households. Central to this approach is the application of the "polluter pays principle".
- **Sustainable water use.** Directive calls for the implementation of measures to promote efficient and sustainable water use, a crucial step in protecting environmental objectives. While considered a "basic" measure, its specifics are quite broad. Potential implementations could be introducing charging regimes that encourage Member States to adopt water pricing policies that incentivize efficient water usage. Another approach could be the voluntary adoption of water re-use policies. Various countries have explored their groundwater resources, leading to the establishment of licensing schemes for water abstraction. These schemes often set limits on withdrawal amounts and impose financial and legal penalties for exceeding these limits. A critical aspect of this measure is assessing sustainability in relation to resource availability and understanding the impacts of over-use or unsustainable abstraction on water bodies.
- **Drinking water.** An emphasis is put on drinking water for over 50 people or with an abstraction rate exceeding 10 cubic meters per day. The goal is to prevent water quality deterioration, reducing treatment needs and ensuring compliance with the Drinking Water Directive standards. While specific protective measures aren't detailed, the Directive suggests the possibility of establishing "safeguard zones." Most EU countries and others globally already have well-documented drinking water sources, often protected through legislation and various types of protective zones, especially for groundwater. The Directive requires Member States to identify, catalog, and assess each drinking water source for necessary protection. This includes assessing human activity in catchment areas and water usage analysis. One protective measure is establishing zones for both groundwater and surface waters, the latter being less common. The establishment of protection zones faces challenges, particularly industry resistance due to the costs of pollution prevention measures. Land-use planning legislation can also play a role in preventing hazardous developments in these zones.
- **Water abstraction.** The Directive includes mechanisms for protecting water resources, often involving a charge or water tax. Artificial recharge activities are also regulated under this Directive. As these are typically large-scale operations conducted by water authorities and subject to licensing, they are not expected to significantly impact the Directive's requirements. The legislation's goal is to preserve water flow characteristics, which are influenced by the physical state of the water course, ensuring adequate water flow is maintained.
- **Floods and droughts.** Within the context of river basin management, the potential for flooding is a crucial consideration for any river basin plan. The Directive aims to mitigate the impacts of floods and droughts as part of ensuring good quality water, reducing groundwater pollution, and safeguarding territorial and marine waters. The influence of these extreme weather events on water quality and status is significant and must be addressed in the measures implemented to mitigate such issues.

4.1.1. Basic measures

Basic measures include the implementation of set of directives that are already in force. These are set out in Annnex VI and include the following:

- Bathing Water 76/160/EEC
- Birds Directive 79/409/EEC
- Drinking Water 98/83/EC
- Major Accidents (Seveso) 96/82/EC
- Environmental Impact Assessment 85/337/EEC

- Sewage Sludge 86/278/EEC
- Urban Waste-water Treatment 91/271/EEC
- Plant Protection Products Directive 91/414/EEC
- Nitrates 91/676/EEC Habitats 92/43/EEC
- Integrated Pollution Prevention Control 96/61/EC

Specifically, the Bathing Water Directive targets designated swimming areas, aligning with the WFDs identification of individual water bodies. The Birds Directive, Habitats Directive, Drinking Water Directive, and Nitrates Directive also play a significant role in addressing Protected Areas as outlined in this Directive. The implementation of these requirements is expected to have a minimal impact on Member States, given that these directives should already be transposed and in the process of implementation. However, there is a need to ascertain their specific application within river basin districts. This involves an administrative effort to integrate and articulate their roles within the River Basin Management Plans.

Some basic measures are all set in Article 11 of the WFD and include a set of minimum requirements like: Promote efficient and sustainable water use; Safeguard water quality to reduce drinking water purification needs; Control water abstraction and impoundment, including maintaining a register and requiring prior authorisation, with periodic reviews and updates; Regulate artificial recharge or augmentation of groundwater bodies; Require prior regulation or authorisation for point source discharges liable to cause pollution; Implement measures for diffuse sources liable to cause pollution; Prohibit direct discharges of pollutants into groundwater and more.

4.1.2. Supplementary measures

In addition to the above basic measures, the Directive permits the adoption of supplementary measures as a part of the programme. Possible measures are outlined in Annex VI and summarized below:

- Administrative instruments
- Economic or fiscal instruments
- Negotiated environmental agreements
- Emission controls
- Code of good practice
- Re-recation and restoration of wetlands
- Abstraction controlts
- Demand management measures
- Efficiency and reuse measures
- Construction projects
- Desalination plants
- Rehabilitation projects
- Artificial recharge of aquifers
- Educational projects
- Research, development and demonstration projects
- Other relevant measures.

Several supplementary measures are integral to the basic measures outlined in the Directive. For instance, most basic measures will inherently involve legislative and administrative instruments as part of their legal framework. While basic measures address certain emission controls, abstraction controls, and codes of good practice, there may be additional, country-specific measures that are relevant. Article 11(4) explicitly recommends the adoption of such unique measures where suitable. Furthermore, supplementary measures allow for the introduction of control aspects that extend beyond the typical scope of Community legislation, providing a broader range of management tools.

4.2. Measures for groundwater protection

The EU Water Framework Directive adopts an integrated approach to water management, emphasizing the importance of groundwater as part of the hydrological cycle. Groundwater, distinct from surface water due to its invisibility, potential for unnoticed pollution, limited self-purification, and difficulty in decontamination, significantly impacts surface water ecology and is vital for drinking water and irrigation. Recognizing these challenges, the Directive, in its preamble, underscores the need for early and long-term protective measures for groundwater due to its slow renewal rate. Directive mandates dedicated measures to prevent and control groundwater pollution and achieve good groundwater chemical and quantitative status by 2027 at the latest. The measures adopted at the Community level must be integrated into the Member States' programmes of measures under Article 11, ensuring a comprehensive and coordinated approach to groundwater protection across the EU.

4.2.1. Quantitative measures

The EU Water Framework Directive establishes a robust control system for managing water quantity. Article 11 mandates "basic" measures, including promoting efficient and sustainable water use and implementing controls over groundwater abstraction, which require prior authorization. This involves setting up a register for both groundwater and surface water abstractors. Exemptions may apply for abstractions that do not significantly impact groundwater status. In cases of groundwater augmentation or artificial recharge, a similar authorization system is required, with safeguards to ensure these activities do not adversely affect the source water's status. Key issues to address in implementing these provisions include the concept of responsible ownership of groundwater. Traditionally, in many countries, water rights are linked to land ownership. Landowners either own the water beneath their land or have rights to abstract and use it.

The Directive also addresses the re-injection of water used for geothermal purposes, which must be subject to an authorization scheme. The same applies to the re-injection of water from mining, mineral exploration, oil and gas extraction, or resulting from construction or civil engineering works. Many Member States already have permit systems for groundwater abstraction and maintain strict controls over artificial recharge to prevent contamination. Therefore, these new requirements are expected to integrate smoothly with existing regulatory frameworks.

4.2.2. Qualitative measures

Article 11 of the EU Water Framework Directive mandates "basic" measures, including a system to regulate point source discharges that could cause pollution. This involves either prohibiting such discharges into water bodies or authorizing them with specific controls like emission limits. This regulation is applicable to both surface and groundwater, particularly in scenarios where discharges do not directly enter groundwater but instead percolate through unsaturated zones or land surfaces.

Control of diffuse pollution sources is also essential, requiring prior regulation methods such as prohibitions or the adoption of general binding rules. These measures, although broad, are crucial for activities that could lead to groundwater pollution through ground percolation. Many European countries are aligning with the Groundwater Directive to protect water quality, with existing systems for authorizing direct discharges.

4.3. Recommended measures for groundwater protection in transboundary aquifers between Estonia and Latvia

A program of measures is already established for Latvia in 2021 (with an extension in 2023) for 2022-2027 planning period for all four river basin management units including Gauja river basin that is also a transboundary river basin with Estonia (LVGMC, 2023). Gauja river basin management plan covers both surface waters and groundwater in the Latvian side of Estonian-Latvian transboundary area. The established program of basic measures tackle the requirements by WFD Article 11 and link each of relevant measures of other directives according to Annex V to a national legislation acts that ensures the enforcement of specific measures. The specific program of measures in the Gauja river basin are focused both on surface waters and groundwater and are listed in Supplementary material “8.A.a” of the Gauja river basin management plan (LVGMC, 2023).

Program of measures are grouped in general courses of actions to achieve objectives of which groundwater and, subsequently, also transboundary groundwater is tackled in the following courses of actions:

- “To ensure the supply of quality drinking water in accordance with the requirements of laws and regulations, increasing the quality of life of inhabitants and ensuring sustainable use of natural resources”. The required measures include:
    - To obtain a permit for the use of water resources, if the abstraction of groundwater or surface water >10 m3/day is planned, or >50 people will be served, or mineral and thermal waters are being extracted and used in economic activity, or if the abstraction of water may cause significant impact on the environment. This is nationally regulated by Minister Cabinet No.736. "Regulations regarding the permit for the use of water resources".
    - To comply with the conditions included in the permit for the use of water resources issued by the RVP regarding the maintenance of protective zones of water abstraction sites, groundwater monitoring, water abstraction well openings, water level measurement, installation of sampling points, maintenance and provision of pump rooms against flooding, and protective measures for the protection of fish, etc. at surface water abstraction sites. Regulated by Minister Cabinet No. 736 "Regulations regarding the permit for the use of water resources".
    - Carry out appropriate treatment of drinking water from substances harmful to human health without impairing the quality of water intended for human consumption. Minister Cabinet No. 547 "Mandatory harmlessness and quality requirements for drinking water, procedures for monitoring and control".
    - To comply with the specified protection zones around drinking water intake points in order to ensure the preservation and renewal of water resources, as well as to reduce the negative impact of pollution on the quality of water resources throughout the entire period of operation of the water reservoir (not less than 25 years). Regulated by Protection Zone Law.
    - Water Merchants to Coordinate with Health inspection regional branches of drinking water monitoring and disinfection examination programmes, as well as radius of protection zones. Minister Cabinet No. 547 "Mandatory harmlessness and quality requirements for drinking water, procedures for monitoring and control".
    - To carry out regular monitoring of drinking water (regular and audit monitoring), if more than 50 people are supplied with drinking water or the amount of water exceeds 10 m^3/dnn, and to control its conformity with the quality requirements for drinking water. Minister Cabinet No. 547 "Mandatory harmlessness and quality requirements for drinking water, procedures for monitoring and control".
    - Control of the safety requirements for drinking water from the point of intake to the consumer. Regulated by Minister Cabinet No. 547 "Mandatory harmlessness and quality requirements for drinking water, procedures for monitoring and control".

  - To inform inhabitants about the harmlessness and quality of drinking water and to provide advice on the measures to be taken in ensuring and improving quality. Regulated by Minister Cabinet No. 547 "Mandatory harmlessness and quality requirements for drinking water, procedures for monitoring and control".
  - The determination and co-ordination of protection zones with the LEGMC and the Health Inspectorate, as well as informing the local government regarding the determination of the protection zone in its territory shall be ensured by the owner or user of the water intake point. Regulated by Minister Cabinet No.43 "Methodology for determining protective zones around water intake points".
  - Obtain a groundwater resources passport. Regulated by Minister Cabinet No.696 "Procedures for issuing licences for the use of subsoil and permits for the extraction of frequently occurring mineral resources, as well as procedures for leasing land of a public person for the use of subsoil".
  - Calculate the allowable groundwater abstraction stocks and accept them. Regulated by Minister Cabinet No.570 "Procedures for the extraction of mineral resources".
  - Monitoring of the quantity and quality of groundwater in accordance with the requirements laid down in the groundwater deposit passport shall be ensured and the results of the monitoring shall be submitted annually to LEGMC. Regulated by Minister Cabinet No.92 "Requirements for monitoring of surface water, groundwater and protected areas and development of monitoring programmes".
  - The water user must report once a year on the amount of water consumed electronically by filling in the National Statistical Report form. Regulated by Minister Cabinet No. 271 "Regulations regarding forms for official statistics on environmental protection and report on polluting activity".
  - Preparation of an annual groundwater stock balance on the quantitative and qualitative status of groundwater resources in groundwater deposits. Regulated by Law on Subterranean Depths.
- “To ensure wastewater treatment in accordance with the requirements of laws and regulations, reducing the pollution load entering waters”. This course of action includes the following measures tackling groundwater:
  - Prior to the commencement of operation of new wastewater treatment system and for the continuation of existing activities, to obtain a permit for polluting activity from the RVP, to comply with the requirements specified therein, as well as to use the best available techniques. Regulated by Minister Cabinet No. No.34 "On the emission of pollutants into water".
  - Do not discharge wastewater directly into groundwater, except for Minister Cabinet No 34 in the cases referred to in paragraph 23. Regulated by Minister Cabinet No. No.34 "On the emission of pollutants into water".
- “To ensure the performance of an environmental impact assessment in accordance with the requirements of laws and regulations” course is covered by the following measures:
  - To carry out an initial environmental impact assessment for activities that affect Natura 2000 sites, protection zones, groundwater or surface water bodies, protected areas, human health, etc. Regulated by Law On Environmental Impact Assessment.
  - To provide true information in the submission regarding the impact of the intended activity on specially protected nature territories, species and biotopes, impact on water bodies and watercourses, etc. the information required in Paragraph 6 of Minister Cabinet Regulation No. 30. Regulated by Law On Environmental Impact Assessment Minister Cabinet No.30 “Procedures by which the State Environmental Service issues technical regulations for the intended activity".
- “To ensure the reduction or prevention of nitrate pollution caused as a result of agricultural activity in accordance with the requirements of laws and regulations” is achieved by the following measures:
  - Comply with the requirements for the spreading of fertilisers (do not disperse on frozen, wet, snowy soil, floodplains, flood-prone areas, protection zones, slopes IETT >10°, 100 m from the coastline of a body of water/watercourse, spreading and embedding is not permitted; farmyard manure and digestion residues after spreading are

    incorporated within 24 hours, liquid manure and slurry within 12 hours; in autumn, liquid manure and digestion residues should be used only in conjunction with post-harvest residues of plants when incorporated into the soil by shelling or plowing. Regulated by Minister Cabinet No.1056 "Requirements for integrated cultivation, storage and labelling of agricultural products and control procedure" and by Minister Cabinet No. 834 "Requirements for the protection of water, soil and air from pollution caused by agricultural activities".
    - When designing new animal housing, the project provides for the construction of manure storage facilities. Regulated by Minister Cabinet No. 829 "Special Requirements for the Performance of Polluting Activities in Animal Housing".
- “To ensure the protection of surface water and groundwater against pollution/damage caused by plant protection products in accordance with the requirements of laws and regulations” measures:
    - To comply with the prohibition laid down in the Protection Zone Law for the use of fertilisers and chemical plant protection products in the protection zones of the strict regime around surface water bodies. Regulated by Protection Zone Law.
- “To ensure the preservation of biodiversity by protecting and managing natural habitats, wild flora and fauna in accordance with the requirements of laws and regulations” measures include:
    - It is prohibited to change the level of waters by operation, promote erosion, mining of mineral resources, forestry activities, motorized vehicles, chemicals, recreational facilities, bathing areas, land transformation, fish farming). Regulated by Minister Cabinet No. 264 "General protection of specially protected nature territories and conditions of use”.
    - It is prohibited to carry out in protected nature territories without a relevant permit or prior written coordination with the administration of the protected territory activities that cause a change in the level of groundwater, groundwater and surface water, to carry out archaeological research work and to issue a permit (licence) for the use of subterranean depths. Regulated by Minister Cabinet No. 264 "General protection of specially protected nature territories and terms of use”.
- “To ensure the prevention and control of pollution and the risk of major accidents related to hazardous substances in accordance with the requirements of laws and regulations” measures:
    - The operator of the polluting activity must submit an application for an RVP permit, comply with the measures specified in the permit and the recommended guidelines (best available technologies, activity less harmful to the environment and humans, measures for the prevention of the risk of accidents, etc.). Regulated by Minister Cabinet No. 1082 "Procedures by which Polluting Activities of Category A, B and C shall be Declared and Permits for the Performance of Category A and B Polluting Activities shall be Issued".
    - To obtain a permit for the use of water resources if it is planned to acquire or is already abstracting groundwater or surface water. Regulated by Minister Cabinet No. 1082 "Procedures by which Polluting Activities of Category A, B and C shall be Declared and Permits for the Performance of Category A and B Polluting Activities shall be Issued" and Minister Cabinet No. 736 "Regulations Regarding the Permit for the Use of Water Resources".
    - Local governments to identify and evaluate polluted and potentially polluted sites in the relevant administrative territory. Regulated by Law On Pollution.
    - The operator, when performing a polluting activity, shall take measures in order to prevent the occurrence of pollution or to reduce its emission, as well as to perform monitoring of the polluting activity. Regulated by Law On Pollution.
    - Provide for risk reduction measures and restrictions in spatial plans in places that may affect waters, protected areas, protection zones, etc. Regulated by Minister Cabinet No. 131 "Procedures for industrial accident risk assessment and risk assessment reduction measures”.
- “To ensure water protection in accordance with the requirements of laws and regulations, increasing the quality of life of inhabitants and ensuring sustainable use of natural resources” measures:

- To manage the waste of the landfill or landfill site in such a way as to prevent contamination of surface water and groundwater in compliance with the conditions included in the RVP permit, as well as to prevent the causes and consequences of environmental pollution in the vicinity of the landfill or landfill site, if environmental pollution has been detected at this site. Regulated by Minister Cabinet No. 1032 "Regulations for the Construction of Landfill Sites, Management, Closure and Recultivation of Landfill Sites and Waste Dumps".
- Preservation or disposal of water wells when no longer in use. Regulated by Minister Cabinet No.696 "Procedures for issuing licences for the use of subsoil and permits for the extraction of frequently occurring mineral resources, as well as procedures for leasing land of a public person for the use of subsoil".

Supplementary measures regarding groundwater in Gauja river basin area include the following specific measures to achieve a good water condition in all groundwater bodies and to ensure that the existing condition does not deteriorate the status:

- New data on the biogenic element (nitrogen) produced by agriculture and phosphorus compounds) distribution, circulation in soil and groundwater, how also for the processes affecting them (e.g. nitrification, denitrification, ammonification, sorption, etc.).
- Establishment of natural background levels and threshold values for transboundary aquifer system.
- Screening monitoring for emerging pollutants.
- Installation of new wells and inclusion of new springs in transboundary groundwater monitoring network.
- Updating of established transboundary hydrodynamic model.
- Assessment of hydrological (including groundwater) drought risk and impact evaluation on dependent ecosystems.
- Assessment of groundwater recharge rates for groundwater vulnerability assessment needs.
- Delineation of groundwater catchment for drinking water intake areas to implement new Drinking Water directive.

References

Environmental Monitoring Information System (2021) Estonian Environment Agency https://kese.envir.ee/kese/welcome.action

Estonian Nature Information System (2021) Estonian Environment Agency https://veka.keskkonnainfo.ee/veka.aspx?page=vekavek

Goodarzi, M.R., Niknam, A.R.R., Jamali, V. (2022) Pourghasemi, H.R. Aquifer Vulnerability Identification Using DRASTIC-LU Model Modification by Fuzzy Analytic Hierarchy Process. Model. Earth Syst. Environ, 8, 5365–5380) https://doi.org/10.1007/s40808-022-01408-4

Gupta, T., Kumari, R. (2023) Assessment of Groundwater Nitrate Vulnerability Using DRASTIC and Modified DRASTIC in Upper Catchment of Sabarmati Basin. Environ. Earth Sci, 82, 216. https://doi.org/10.1007/s12665-023-10880-9

Hunt, M., Marandi, A., Retike, I. (2023) Water Balance Calculation for a Transboundary Aquifer System between Estonia and Latvia. Water 15 (19) https://doi.org/10.3390/w15193327

Kitterød, N.O.; Kværner, J.; Aagaard, P., Arustiene, J., Bikše, J., Dagestad, A., Gundersen, P., Hansen, B., Hjartarson, Á., Karro, E., Klavins, M., Marandi, A., Radienė, R., Retike, I., Rossi, P., Thorling, L. (2022) Hydrogeology and Groundwater Quality in the Nordic and Baltic Countries. Hydrol. Res. 53, 958–982. https://doi.org/10.2166/nh.2022.018

Latvian hydrogeological database "Wells" (2021) Latvian Environment, Geology and Meteorology Centre.https://www.meteo.lv/pazemes-udens-datu-meklesana/?nid=475 .

Chave, P. 2001. The EU Water Framework Directive - An Introduction. IWA Publishing, ISBN 9781900222129.

LVGMC 2023. GAUJAS UPJU BASEINU APGABALA APSAIMNIEKOŠANAS PLĀNS UN PLŪDU RISKA PĀRVALDĪBAS PLĀNS 2022. - 2027. GADAM. [Gauja river basin management plan and flood risk management plant for 2022-2027]. Report. Latvian Environment, Geology and Meteorology Centre. Available: https://videscentrs.lvgmc.lv/files/Udens/Udens_apsaimniekosana_plani_2021_2027_update/Gaujas_UBA/Gaujas%20UBA%20plans%202022-2027.pdf

PART III

The elaboration of solutions for coordinated use and integrated protection of transboundary groundwater

Developing a catalog of activities for the coordinated use and integrated protection of transboundary groundwater reservoirs

Output 3. Report „Program of protection of transboundary groundwater against pollution and depletion on the eastern border of UE”

Developing a catalog of activities for the coordinated use and integrated protection of transboundary groundwater reservoirs.

(NGU/NVE-delivery by December 2023)

1. Present status and knowledge gaps for sustainable groundwater governance in Norway

The WFD was transposed into the Norwegian regulation by a framework for water management in 2007, usually referred to as 'Vannforskriften' or the Water Regulation (KLD, 2006). At present Norway has delineated 16 RBDs, which are administered by nine Competent Authorities (Fig. 1). Eleven of the 16 RBDs are international RBD shared with Sweden, Finland, and Russa.

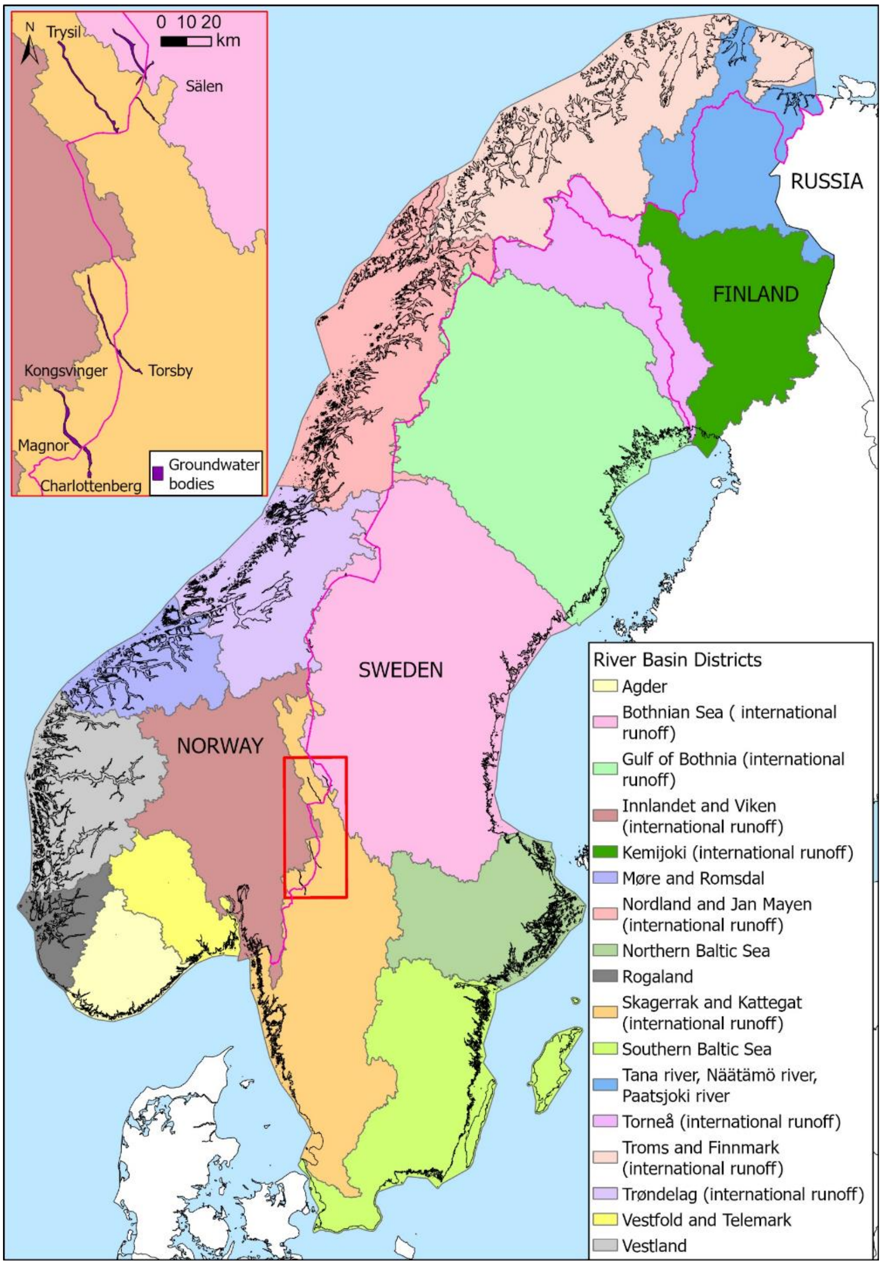


Figure 1. Map over river basin districts (RBD) in Norway (Obtained from Flem et al., 2022)

The historical implementation of the WFD in Norway is well described by e.g., Halleraker et al. (2013). A recent paper by Flem et al. (2022), written as part of the EU-WATERRES project, examines the implementation practices of the Water Framework Directive (WFD) in Norway, with a particular focus on International River Basin Districts (IRBDs) and transborder groundwater cooperation. The paper analyses the current situation, considering both national and transborder geological conditions and geographical parameters. It aims to provide an assessment of the significance of groundwater resources for human needs, ecological balance, and economic factors. Furthermore, the paper delves into the implications of differences in existing legal frameworks between Norway and Sweden for transborder groundwater management and cooperation. The analysis clearly shows the missing delineation of groundwater bodies and thus of cooperation between the countries. This is also evident in Vann-Nett, a database that includes maps illustrating the location of groundwater bodies and their quantitative and chemical statuses (https://vann-nett.no/portal/). The mismatch between the Norwegian and Swedish delineation of groundwater bodies are in Vann-Nett readily discernible (Fig. 2).

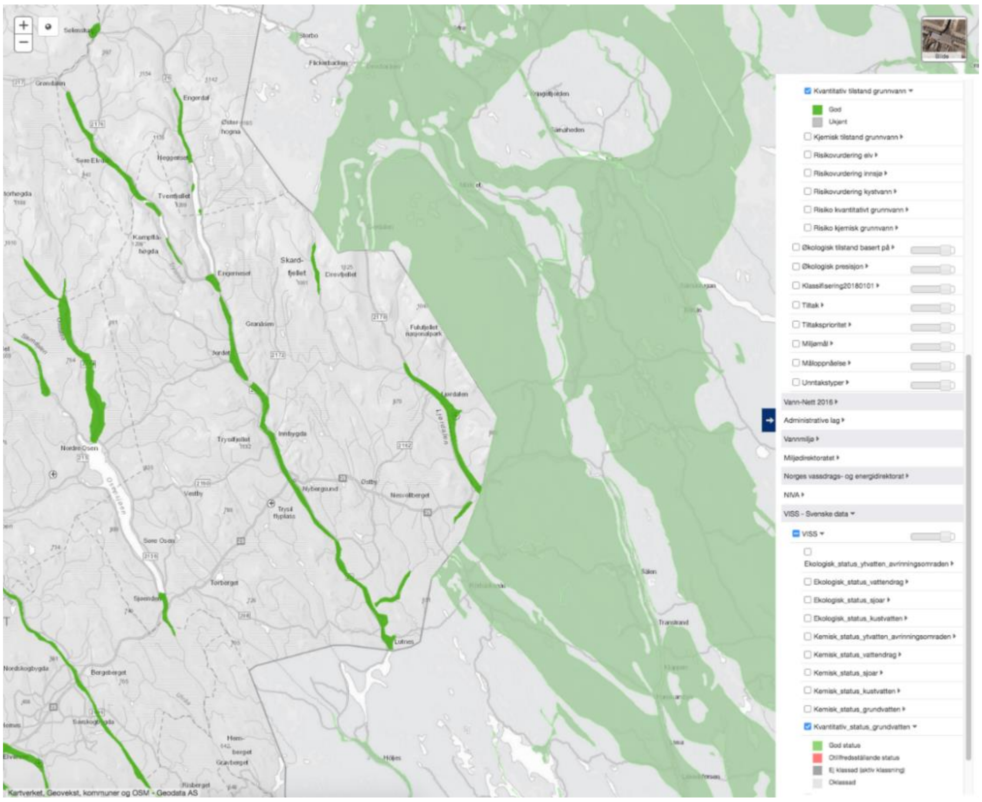


Figure 2 Screen shot from Vann-Nett showing an example on a total mismatch between the Norwegian and Swedish delineation of groundwater bodies.

Flem et al. (2022) additionally gives a review of national legislation, the implementation of the WFD, and transnational agreements and treaties to evaluate the overall effectiveness of water management systems. Their study explores the national legislation and features of water cooperation within river basins and river basin districts. The evaluation of the extent of transnational cooperation on Transboundary Aquifers (TBAs) relies primarily on the reporting of WFD requirements to the European Environmental Agency and the European Union database, known as WISE (https://water.europa.eu/) and the reporting of the SDG indicator 6.5.2, which concerns transboundary water cooperation, to the United Nations Economic Commission for Europe (UNECE) (https://unece.org/national-country-reports-sdg-indicator-652). Their main conclusion, which is in line with other authors such as e.g., Nielsen et al. (2013), Jager et al. (2016), and Solli (2020), is that the Norwegian national water management systems are fragmented and over-complex. On the national level there are several ministries with a responsibility for groundwater. The Ministry of Climate and Environment (KLD), as the coordinating ministry for The Norwegian Water Regulation (KLD, 2006), heads a ministry group which is responsible for the implementation of the WFD in Norway. The other ministries in this group are the Ministry of Petroleum and Energy (OED), the Ministry of Trade, Industry and Fisheries (NFD), the Ministry of Health and Care Services (HOD), the Ministry of Agriculture and Food (LMD), the Ministry of Transport (SD), the Ministry of Finance (FIN), and the Ministry of Local Government and Regional Development (KMD). The underlaying directorates of these ministries coordinate the WFD-work and are responsible for subgroups created for specific implementation tasks. In addition, there is a national reference group where all stakeholders can partake. On the RBD level committees are created as forums in addition to one on a lower level of subdivisions of the RBDs. The upside of this overly complex water management approach is that it ensures thorough implementation of the Water Framework Directive (WFD) across all levels.

The second paper written within the EU-WATERRES project by Flem et al. (2023), addressing groundwater management and monitoring in Norway, highlights that ISO 5667–11:2009 on groundwater sampling must be adopted to obtain uniform field performance and harmonised data nationally and transnationally. The national database hosting hydrological data, Vann-nett, should have the capability to accommodate metadata associated with chemical groundwater data. The data itself holds diminished value if crucial metadata, such as pumping procedures, are not made accessible.

1.1 Quantitative status

Quantitative status for all 1401 delineated Norwegian groundwater bodies has been evaluated as good based on monitoring stations operated by the Norwegian Water Resources and Energy Directorate (NVE) and the Geological Survey of Norway (NGU). This monitoring network, The National Soils- and Groundwater Network (LGN) (Gundersen et al. 2019; Seither et al. 2016; Gundersen et al. 2022), consists of 80 stations in areas without anthropogenic pressures and influence from surface water. In addition, data from groundwater bodies where there are concessions for extraction have been used.

The delineated groundwater bodies in Norway cover only a small percentage, 1.55% of the total land area of the country, and only quaternary deposits. Many of these are located where there are no pressures and mainly in aquifers seen as a possible source for drinking water. Most of the country where there are pressures have no delineated groundwater bodies, as the example shown in figure 3. This implies that there might be groundwater abstraction or encroachments into aquifers causing a status worse than good where there are no existing groundwater bodies covering these areas.

The methodology used was an interpolation to all groundwater bodies based on the data from the existing LGN stations and the overall monitoring of the natural groundwater level. The exception was for the few where concessions for abstraction is given, there are no monitoring of the effect of abstraction.

Over the last ten years a huge number of energy wells have been drilled due to the oil furnace ban put into action in 2020 (KLD 2018). The consequences of this extensive usage of groundwater as a source of thermal energy has not been considered. In general, there are no groundwater bodies covering these areas, with a few exceptions. Most of the wells are drilled into aquifers in bedrock in which no delineation of water bodies exists. In addition, more groundwater is used than before for industrial purposes such as aquaculture.

Due to the lack of delineation of groundwater bodies where there are pressures, one may presume that the picture for the quantitative status might change with a delineation covering the whole of Norway. A proposal for a new delineation is under construction based on the Scottish methodology both for groundwater in bedrock and sediments. Characterisation and classification will be done based on this methodology and on the available digital pressure data.

Radar data from the NGU and Norwegian Space Agency project InSAR gives an implication about the effect on the quantitative status from energy wells. There are cases in Oslo where the subsidence due to drilling of energy wells have caused severe damages (Brodahl & Cogorno 2023).

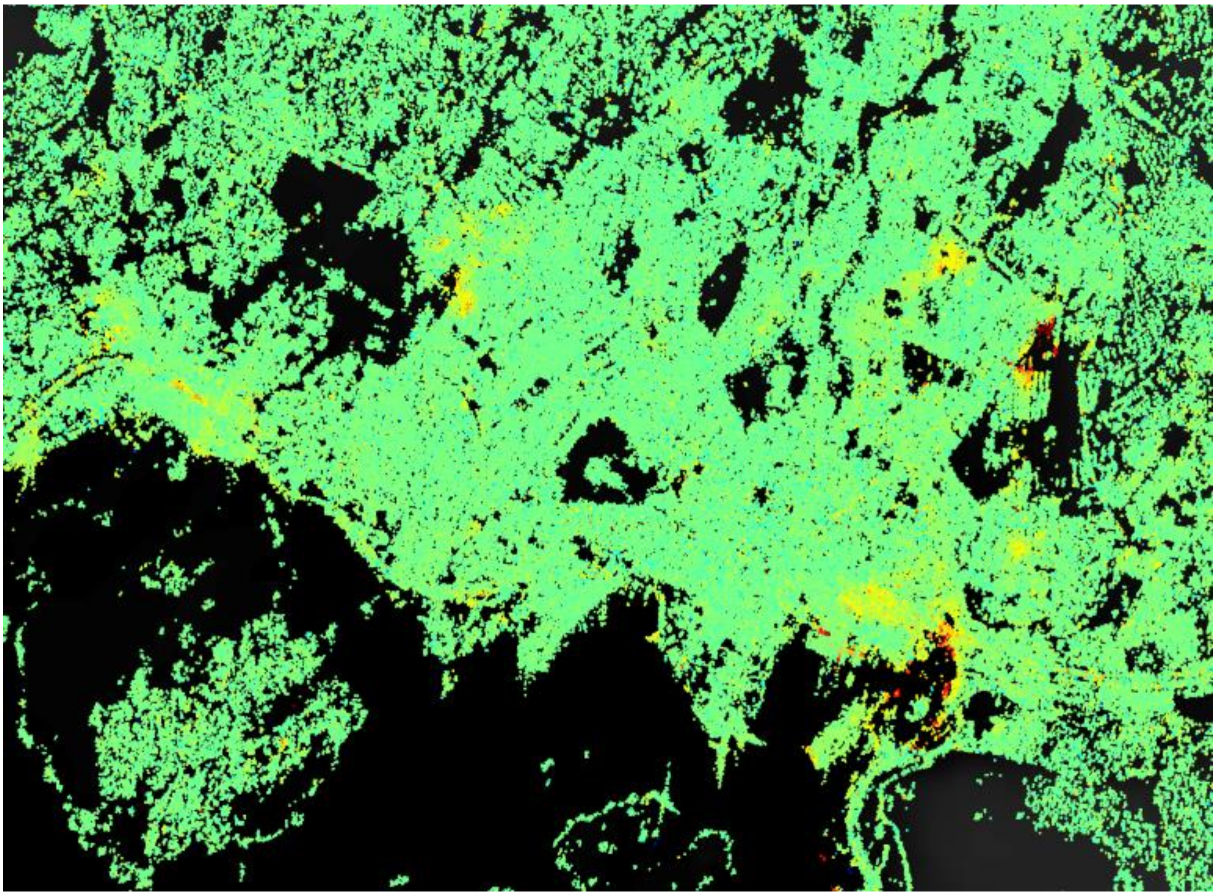


Figure 3. Screenshot from InSAR (https://insar.ngu.no/) where the yellow, orange and red dots show sinking terrain.

1.2 Chemical status

Of the 1401 groundwater bodies reported to the WFD 2022 reporting, 941 were reported as having a good chemical status, and 460 as unknown. None has been reported being in a bad status. The status was estimated based on a pressure analysis performed already in 2011-2012 on then 1276 delineated waterbodies. These data were first added to the WFD-data base in 2021 and used as a basis for the 2022 reporting on the WFD. For the 125 additional waterbodies of the total of 1401 added after 2012 there has not been run any pressure analysis.

It is important to note that the delineated groundwater bodies only cover 1.55% of the area of Norway. Most of the area of Norway has little or no pressures on groundwater aquifers, though only 1.55% does not cover all areas where there might be a significant pressure. This triggers a need for a new approach, which is proposed in this report.

For the groundwater bodies classified as having a good status, one can presume the status based on the pressure analysis to be correct, where there has not been any change in pressures within the eleven years since it was performed. A new analysis of these waterbodies is needed for the next reporting cycle to map any changes in pressures. A new delineation might lead to a change in geometry in addition to any changes in pressures.

For those registered as unknown in the 2011-2012 pressure analysis, these had indicators implying a pressure that could trigger a worse than good status. The analysis was finished in 2012, but it was decided not to focus on groundwater by then due to a lack of resources, so the further characterization and classification were not done, with a few exceptions described below.

For the 2022 reporting 14 different "worst cases" were selected for a monitoring programme on groundwater bodies under anthropogenic pressure. Six in agriculture areas and eight in urban areas (Dagestad et al. 2020; Roseth et al. 2021). In total ~40 wells and springs have been monitored with 1-2 sampling campaigns annually from 2015-2020. The samples have been analysed for inorganic parameters, as well as an extensive range of organic constituents selected according to the type of exerted anthropogenic pressures. Since 2021, the sampling campaigns in this monitoring program have been less frequent, especially in the urban areas.

In addition to the 14 selected groundwater bodies about 50 new springs, wells, and some groundwater relevant drainage systems were identified and sampled during 2020 and 2021. These were not previously monitored. Samples were sent for analysis for inorganic parameters as the sites were found and approved for this purpose during the field work. The sites were mostly selected within or in the vicinity of groundwater bodies that were expected to be under the influence of a noticeable anthropogenic pressure. Either according to the calculated sum-index from the pressure analysis or their localization in known high-intensity farming districts. For details, see the referred reports and the web site Vannmiljø (n.d.) that contains all georeferenced sites and water quality data from the data series A-C.

For reference data a national monitoring program is running for wells and springs that are *not* under anthropogenic pressure. The National Soils- and Groundwater Network (Gundersen et al. 2019; Seither et al. 2016; Gundersen et al. 2022). This consists of ~53 monitoring sites for water quality measurements of mostly inorganic parameters. From these the following parameters have monitored: water temperature, pH, O2, NH4, F, Cl, NO3, PO4, SO4, NO2, alkalinity, color, el. conductivity, turbidity, B, Se, Al, As, Cd, Co, Cr, Cu, Cs, Li, Mo, Ni, Pb, Sb, U, V, Zn, Ba, Ca, Fe, K, Mg, Mn, Na, Si, Sr and Hg. The monitoring has been running more or less continuously with one or more sampling campaigns annually since 1977. But a full national scale sampling campaign has not been done since 2018 due to other priorities.

In 2013 a guidance document with a proposal on how to do a pressure analysis, based on the work done in 2011-2012, were published (Direktoratsgruppen 2013). The guidance mentions DRASTIC as a method, but only four of the DRASTIC parameters were proposed used. These were “depth to water table”, “netRecharge”, “aquifer media” and “hydraulic conductivity of aquifer”. In addition to these parameters a pressure analysis was described where the anthropogenic pressure for each GWB based on the calculated value sum-index from Eq 1.

sum-index =

$$\frac{a * Traffic + b * Airport + c * Landfill + d * Gravel\ extraction + e * Urban\ settlement + Agriculture}{Area\ of\ groundwater\ occurrences\ within\ existing\ borders\ [m2]}$$

Factors in numerator (e.g. “Traffic”) represent area (m^2) of a groundwater body covered by each anthropogenic pressure and the letters a-e represent a coefficient weighting each of them.

Airports are considered a high pressure, and therefore b=5 whereas agriculture is referenced with a coefficient of 1. The sum of different anthropogenic pressures is represented with the overall parameter; sum-index. For a groundwater body 100 % covered by an airport, sum-index would then be *5* whereas it would be 0,5 if 50% were covered by agriculture (and no other anthropogenic pressures).

In addition to the sum-index, the anthropogenic pressure on the groundwater bodies was quantified as individual indexes for each of the impacting activities (urban settlement, agriculture etc.).

The guidance stated that groundwater bodies at risk according to the result of the pressure analysis needed a more thorough characterization and/or should be subjected to surveillance monitoring before conclusions on quality status may be drawn (KLD 2006).

Two works give a hint to the need for more focus on the monitoring of the groundwater bodies delineated at present and a need for a new delineation of groundwater bodies covering all of Norway. Seither et al. (2019) concludes that the monitored groundwater bodies under anthropogenic pressure from *urbanization* (described in chapter 1.2.3.A) are generally in a good chemical state, compared to the threshold values in the water regulations (KLD 2006, Appendix IX). However, there are exceptions. Both inorganic and organic compounds above the specified threshold values have been found at some sites. The monitoring at these sites has revealed elevated concentrations of potentially environmentally harmful compounds in the groundwater for which no threshold values are specified in the water regulations (e.g. Cu and Zn). Roseth et al. (2022) reported results from surveillance monitoring in 93 groundwater samples taken 2019-2021 in the six groundwater bodies with pressure in *agricultural areas* (described in chapter 1.2.3.A). For pesticides and metabolites, water regulations threshold values for single substances (0.1 µg/l) were exceeded in 14 cases (15% of the samples) and above the turning point value (0.075 µg/l) in additional six cases. Three of the samples showed concentrations of pesticides exceeding threshold value for the sum of substances (0.5 µg/l). In agricultural areas as well as in the urbanized, parameters such as Cu and Zn were also occasionally quite high, although they are so far not part of the list of prioritized substances for groundwater in Appendix IX in the Water Regulations (KLD 2006).

1.3 Knowledge gaps and recommendations for moving forward with groundwater management in Norway

Groundwater monitoring and mapping have had and still have a low priority in Norway. The main reason for the very low attention to groundwater in Norway is probably that the authorities have not seen any large public utility. Groundwater use within Norway is currently limited due to the country's abundant surface water resources, with most of the country supplied by piped network coverage. Groundwater abstraction for drinking water is often limited to private borehole supplies. Nonetheless, the extent of groundwater utilization has undergone significant changes over the past decade. Groundwater heat pump systems, both for individual residences and larger urban structures, have seen substantial growth in recent years (http://geo.ngu.no/kart/granada_mobil/). Furthermore, the use of groundwater has witnessed an upsurge within the aquaculture fish farming industry.

This is evident among others through the escalating number of water-related lawsuits and disputes regarding drilling, especially in urban areas. Drilling wells may alter groundwater fluxes significantly. Among severe consequences are the drainage of clay deposits, leading to subsidence and damage to buildings adjacent to new energy wells in cities. An increasing amount of costly and juridically challenging incidents have occurred the recent years. Geological survey or Norway, Norwegian Water Resources and Energy Directorate, the drilling company association “MEF” among and others are working on these issues to find measures. Among them are revising legislation, insurance, and technical practices as well as increasing the general knowledge among drilling companies. These are urgent measures to address and bring solutions to.

Governmental resources give priority to surface water whereas groundwater is mainly downgraded. Of seven transborder groundwater bodies registered, only two have harmonised geometry and coding for the reporting to WISE (Flem et al., 2022). As concluded by Flem et al. (2022): There is a need to establish transnational joint projects for increasing the knowledge and harmonisation of transborder groundwater between Norway and Sweden to fulfil the obligations given by international legislation. In addition to improve the delineation of transborder groundwater in superficial deposits (Fig. 2), there is a need to revise delineation and characterisation of groundwater bodies of the whole of Norway. Scotland, with similar bedrock and quaternary geology to Norway, has chosen an approach where both bedrock and sedimentary groundwater are delineated as waterbodies (https://www.sepa.org.uk/data-visualisation/water-environment-hub/). This could be a methodology in a future groundwater body delineation also for Norway. Countries such as Poland, the Czech Republic, Slovakia and other countries in the EU have followed the approach with several horizons which is in line with the WFD (Čerńak and Michalko, 2005; Velstra, 2005; Flem et al., 2022). The need for the separation of groundwater bodies into two horizons: a shallow layer of superficial groundwater bodies, and a deep layer of bedrock groundwater bodies is obvious when the map portals Vann-Nett, showing the delineated groundwater bodies, and GRANADA, showing the groundwater boreholes, are compared (Fig. 3). The locations of the national groundwater monitoring network can be viewed in GRANADA. Looking closely, one will here notice that most of the stations is not within a delineated groundwater body. The lack of sufficient delineation is obviously an obstacle for proper groundwater management.

The most significant challenge in managing groundwater resources in Norway today lies in the accessibility of knowledge and information. This management is hindered by a lack of understanding concerning various aspects, including total groundwater usage, the location and capacity of groundwater reservoirs, interactions with terrestrial ecosystems, the quantity of boreholes, and the economic importance of groundwater. Successful resource management necessitates a comprehensive grasp of what is being regulated and the consequences of different measures. The deficiency in comprehending groundwater is also apparent in the regulations: there are limited legal references to groundwater in Norwegian law, and much of the regulatory structure, initially designed for surface water, is subsequently applied to groundwater. Furthermore, a considerable portion of the regulations for surface water does not encompass groundwater. This circumstance is partly due to the complexity of regulating groundwater and, to some extent, reflects a lack of political determination to prioritize this resource. Table 1 gives a catalogue of key recommendations for moving forward within groundwater management in Norway.

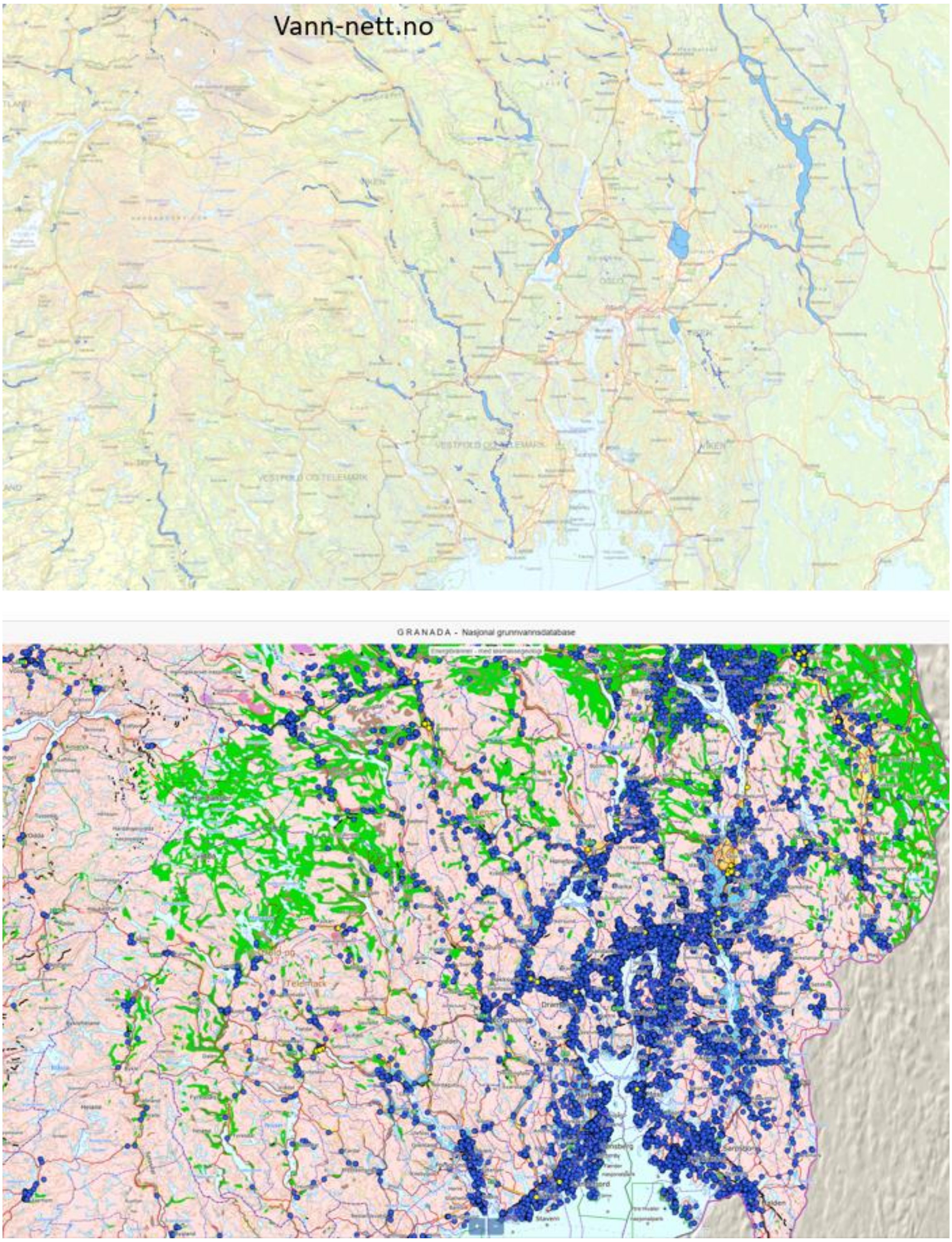


Figure 4. Screen shot from Vann-Nett (top figure) showing the delineated groundwater bodies around the Oslo fjord and GRANADA (bottom figure) showing the large number of drilled groundwater wells in bedrock (blue dots).

As mentioned above an option is to use the Scottish method for delineation. Belove, we present a first approach using the first steps of this method. This method uses available geological data to create groundwater bodies in two horizons, one for bedrock aquifers and one for superficial aquifers. An important part of the delineation into waterbodies is the vulnerability to anthropogenic pressure. This was found by using a groundwater vulnerability map created from datasets on aquifer productivity, permeability, superficial deposits thickness and aspects of soil thickness, permeability, and saturation. In addition to the vulnerability map, background groundwater chemistry was mapped to create reference and threshold values for chemical substances. To be able to interpret and characterise groundwater chemistry, the bedrock aquifers were categorized according to their influence on groundwater chemistry. Based on these digital data, in addition to catchment data, a generalisation was done to create baseline groundwater bodies. For the final delineation these groundwater bodies have to be split in relation to significant pressures, quantitative and chemical status.

Since Norway has a similar geology, we found that we could test the Scottish method on Norwegian data. The initial test uses the bedrock layers in the scale of 1:1350 000, the sediment layers in the scale of 1:50 000 from NGU, the river basin layer in 1:50 000 from NVE. In addition, population data from Statistics Norway were used to decide if small polygons should be removed or not. The generalisation based on these data followed the same approach as the Scottish.

Bedrock groundwater body delineation based on the geological data has not been done before in Norway. First of all the areas mapped outside the land area had to be removed from the bedrock layer. The next step, as in Scotland, was to remove islands smaller than 1 km^2, with an exception from the Scottish approach those with a population lager than 50 persons were kept. Then all islands smaller than 10 km^2 were identified and those with a population less than 50 persons were removed. The resulting bedrock aquifers were grouped by their rock type and their geological age. This was done by grouping the rock types in the NGU bedrock layer according to the over-arching groups in the bedrock map in the scale of 1:3 million as seen in figure 5 (Morland 1997: 24). The new bedrock layer was then intersected with the river basin layer to create bedrock polygons within each river basin. This layer has to undergo a more thorough analysis where the final groundwater bodies might cross catchment boundaries in addition to other aspects influencing the waterbody delineation. The Scottish approach was to merge small and insignificant polygons within another rock type, where there is no significant groundwater potential. In addition, there will be created multi polygons where this is possible, to reduce the number of waterbodies and to ease the administrative burden.

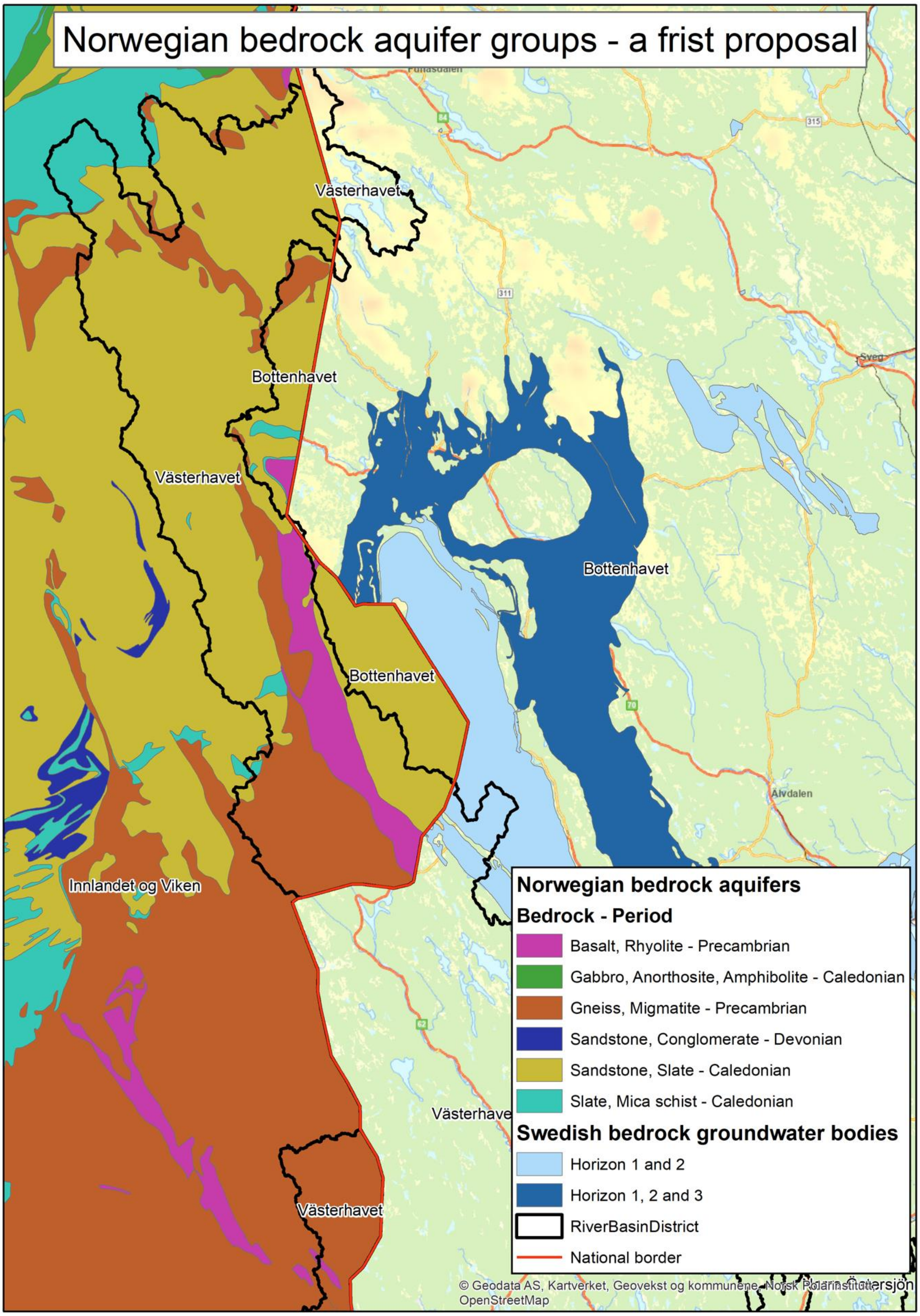


Figure 5. The map shows the simplified bedrock aquifers in Norway and the groundwater bodies reported by Sweden for the WFD 2022 reporting (https://cdr.eionet.europa.eu/). There are no bedrock groundwater bodies reported for Norway in the map area. There are only two reported for Norway located on the southern coast. The map in addition shows the river basin districts on both sides with names (Sweden to the right). Data from NGU: https://geo.ngu.no/download/ and from NVE: https://nedlasting.nve.no/gis/.

As in Scotland, superficial deposits were deposited in the Quaternary geological period. Large areas of Norway are covered by moraine in addition to fluvial and glacifluvial deposits which in varying degree contains groundwater aquifers. As for the bedrock layer, the parts of the sediment layer covering the seabed has been removed. The Scottish approach has here too been to remove all polygons smaller than 1 km^2, then to remove all less than 10 km^2 and larger than 1 km^2 with a population less than 50 people. The areas where polygons are removed are then covered administratively by the underlaying bedrock groundwater body. In the Norwegian layer we have still not removed any of the polygons used in figure 6. The layer has been intersected with the river basin layer to create potential groundwater bodies within each river basin.

The superficial aquifer layers have to undergo a further delineation after the removal of some of the smaller unimportant polygons and due to a difference in pressure, quantitative and chemical status. It is important to note that the resulting groundwater bodies will to a large degree be multi polygons which will ease the administrative burden.

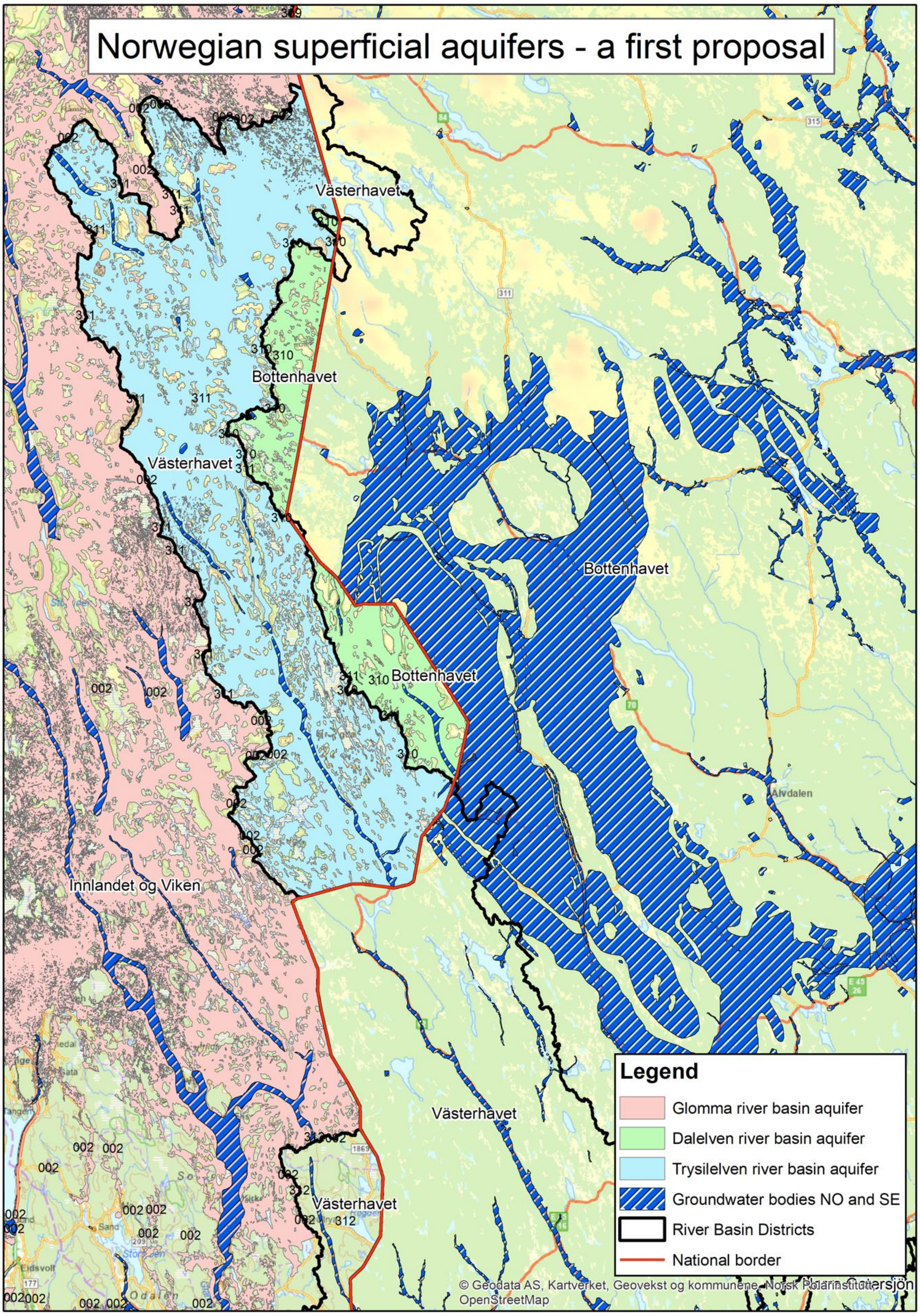


Figure 6. The map shows potential superficial aquifers in Norway and groundwater bodies reported by Norway and Sweden for the WFD 2022 reporting (https://cdr.eionet.europa.eu/).

The map in addition shows the river basin districts on both sides with names (Sweden to the right). Data from NGU: https://geo.ngu.no/download/ and from NVE: https://nedlasting.nve.no/gis/.

When the bedrock and superficial aquifers are delineated based on their natural properties, they have to undergo a further delineation based on vulnerability and pressures. In addition, there will probably be a further need to subdivide do to difference in quantitative and chemical status and the need for measures. For the vulnerability and pressure analysis all available digital data for this will be used to define risk with the help of GIS. A further investigation for those at risk have to be performed, and we propose to use the Scottish model for this too. See a detailed description in the paper 11b(i) and 11b(ii) produced by the UK Technical Advisory Group on the Water Framework Directive and released in 2019. Note that the link to paper 11b(ii) is in paper 11b(i), since the reference below is only to paper 11b(i) (KTAG Paper 11 b (i) - Guidance on Groundwater Chemical Classification 1997).

Table 1

Catalogue of key recommendations for moving forward within groundwater management in Norway.

Legislation	Revising the legislation, insurance- and technical practices for drilling, and increasing knowledge among drilling companies.
Threshold values and methodology for assessment of ecological potential, and methodology for the assessment of upward trends in groundwater.	Establishment of threshold values linked to the pressures and impacts analysis required by Article 5 of the WFD, and to the strategies to prevent and control pollution of groundwater in Article 17 of the WFD for all chemical substances is needed. Specified statistical significance of trends must be verified using a recognised statistical trend assessment technique (Flem et al., 2023)

Groundwater bodies delineation	Groundwater bodies must be delineated in two horizons, a shallow layer of superficial groundwater bodies, and a deep layer of bedrock groundwater bodies. This will give administrative units for the whole country.
Administration	Measures must be taken to ensure that the fragmented water management is better co-ordinated
Groundwater data	National technical standards, following ISO standards, should be developed, and adopted by all parties collecting groundwater data to obtain harmonised comparable data. (Flem et al., (2023)
Remodelling the national monitoring network	Conceptual models should be made for each monitoring station where e.g., the geology represented by the station is described.

References

Aller, L., T. Bennet, J.H. Lehr & R.J. Petty 1987. DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeologic settings. 1987. U.S. EPA Report 600/2-85/018

Čerńak, R., Michalko, J., 2005. Brief characteristic of the hydrogeological situation along the Polish-Slovak boundary belt. Pol. Geol. Inst. Spec. Pap. 18, 15–21. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BUS6-0021-0028

Brodahl, V. & Cogorno, I.R. (2023, 3 December). Kan gå alvorlig galt: Store sprekker og ødelagte bygg. Sagene Avis, https://www.sageneavis.no/kan-ga-alvorlig-galt-store-sprekker-og-odelagte-bygg/f/5-144-121194?key=2023-12-03T19:00:00.000Z/opoint/6f439d4ac09caaa3ee7c0849a60e23a549ef3470

Dagestad, A; Gundersen, P.; Seither, A. 2023. Kartlegging av kjemisk tilstand i utvalgte grunnvannsforekomster 2020-2021 (in Norwegian). Geological survey of Norway. NGU Rapport 2023.004. 49 pp. https://www.ngu.no/upload/Publikasjoner/Rapporter/2023/2023_004.pdf

Direktoratsgruppen. 2013. Karakterisering av norske grunnvannsforekomster med forslag til påvirkningsanalyse. Veileder 03:2013. [The Directorate Group for the Implementation of the Water Management Regulations”. *Classification guide 03:2013]* https://www.vannportalen.no/veiledere/2013---03-karakterisering-av-norske-grunnvannsforekomster/

Direktoratsgruppen. 2018. Klassifiseringsveileder 02:2018. Klassifisering av miljøtilstand i vann. Økologisk og kjemisk klassifiseringssystem for kystvann, grunnvann, innsjøer og elver. *[*The Directorate Group for the Implementation of the Water Management Regulations”. *Classification guide 02:2018: Classification of environmental condition in water. Ecological and chemical classification system for coastal waters, groundwater, lakes, and rivers].* 220 pp. https://www.vannportalen.no/veiledere/klassifiseringsveileder/

EEA EIONET Central Data Repository. https://cdr.eionet.europa.eu/

Flem, B., Bukovska, I., Demidko, J., Gundersen, P., Klos, V., Kolos, H., Marandi, A., Raidla, V., Stalsberg, L., Wyszomierski, M., 2023. Bridging gaps in groundwater management in international River Basin Districts (IRBDs) – through harmonized monitoring and data sharing. J. Hydrol. Reg. Stud. Studies 50 (2023), 101540. https://doi.org/10.1016/j.ejrh.2023.101540

Flem, B., Stalsberg, L., Seither, A., 2022. Groundwater governance in international river basins - An analysis of the Norwegian-Swedish. Transbord. Area J. Hydrol. Reg. Stud. 44 (2022), 101216 https://doi.org/10.1016/j.ejrh.2022.101216

Gundersen, P; Finne, T. E.; Dagestad, A.; Jensen, H.; Nordgulen, Ø.; Romundset, A.; Kvam, M. 2022. Grunnvanns- og jordkjemi i Pasvik – Jarfjord; status og trender. Geological survey of Norway. NGU-rapport 2022.0022. https://www.ngu.no/upload/Publikasjoner/Rapporter/2022/2022_022.pdf

Gundersen, P.; Jæger, Ø.; Seither, A.; Sæther, O.M. 2019. Landsomfattende mark- og grunnvannsnett- årsrapport for 2017 og 2018. Norges geologiske undersøkelse. NGU-rapport 2019.30. 68 pp. https://www.ngu.no/upload/Publikasjoner/Rapporter/2019/2019_030.pdf

Halleraker, J.H., Sorby, L., Keto, A., Guðmundsdóttir, H., (eds.) 2013. Nordic collaboration on implementation of the Water Framework Directive – Status and further challenges. A report for the Nordic Council of Ministers, Umhverfisstofnun, Reykjavík, 2013, 37 pp. ISBN 978-9979-9818-1-7

InSAR Norway. https://insar.ngu.no/

Jager, N.W., Challies, E., Kochskamper, E., Newig, J., Benson, D., Blackstock, K., Collins, K., Ernst, A., Evers, M., Feichtinger, J., Fritsch, O., Gooch, G., Grund, W., Hedelin, B., Hernandez-Mora, N., Huesker, F., Huitema, D., Irvine, K., Klinke, A., Lange, L., Loupsans, D., Lubell, M., Maganda, C., Matczak, P., Pares, M., Saarikoski, H., Slavikova, L., van der Arend, S., von Korff, Y., 2016. Transforming European water governance? Participation and river basin management under the EU Water Framework Directive in 13 Member States. Water 8 (4), 156. https://doi.org/10.3390/w8040156

KLD. 2006. The Water Regulation; FOR-2006-12-15-1446; Ministry of Climate and Environment: Oslo, Norway, https://lovdata.no/dokument/SF/forskrift/2006-12-15-1446

KLD. 2018. Forskrift om forbud mot bruk av mineralolje til oppvarming av bygninger; FOR-2018-06-28-1060; Ministry of Climate and Environment: Oslo, Norway, https://lovdata.no/dokument/SF/forskrift/2018-06-28-1060

Miljødirektoratet (2023, November). Kunnskapsgrunnlaget; Karakterisering. Regulations"https://www.vannportalen.no/kunnskapsgrunnlaget/karakterisering2/

Morland, Geir, 1997. Petrology, Lithology, Bedrock Structures, Glaciation and Sea Level. Important Factors for Groundwater Yield and Composition of Norwegian Bedrock Boreholes? NGU Rapport 97. 122 I & II.

NGU datasett og nedlastning. https://geo.ngu.no/download/

Nielsen, H.O., Frederiksen, P., Saarikoski, H., Rytkonen, A.M., Pedersen, A.B., 2013. How different institutional arrangements promote integrated river basin management. Evidence from the Baltic Sea Region. Land Use Policy 30, 437–445. https://doi.org/10.1016/j.landusepol.2012.04.011

NVE nedlast. https://nedlasting.nve.no/gis/

O Dochartaight, B.E.; MacDonald, A.M.; Fitzsimons, V.; Ward, R.. 2015 Scotland´s aquifers and groundwater bodies. Nottingham, UK, British Geological Survey, 63 pp. (OR/15/028) (Unpublished). https://nora.nerc.ac.uk/id/eprint/511413/.

Roseth, R.; Kværner, J.; Carr, C. H.; Rognan, Y.; Dagestad A.; og Gundersen, P. 2022. Overvåking av grunnvann påvirket av jordbruk 2019-2021. Haslemoen, Rimstadmoen, Lærdal,Horpestad, Grødalen og Skogmo. NIBIO Rapport Vol. 8 no 71 (122) 2022. https://nibio.brage.unit.no/nibio-xmlui/handle/11250/3036880

Sagene

Seither, A., Dagestad, A., Jæger, Ø., Gundersen P,. Roseth, R., Kværner, J., Rognan, Y., Reinemo, J., Mæland, T. 2020. Overvåking av belastede grunnvannsforekomster i Norge, 2015 – 2018. Typelokaliteter og resultater fra urbane områder og jordbruksarealer. Geological survey of Norway. NGU-rapport 2019.013. 120 pp. https://www.ngu.no/upload/Publikasjoner/Rapporter/2019/2019_013.pdf

Seither, A.; Gundersen, P.; Jæger, Ø.; Sæther, O. M. 2016. Landsomfattende mark- og grunnvannsnett (LGN) – Fortid og framtid etter 39 års drift. NGU-rapport 2016.039. 158 pp. https://www.ngu.no/upload/Publikasjoner/Rapporter/2016/2016_039.pdf

Sigmond, E.M.O. 1992. Bedrock map of Norway and adjacent ocean areas. Scale 1: 3 million. Norges geologiske undersøkelse

Solli, G.S., 2020. Ute av syne, ute av sinn - om rettigheter til og forvaltning av grunnvann i norsk rett. (Out of sight, out of mind - about rights to and management of groundwater in Norwegian law). In Norwegian, 2020. University of Oslo, Norway, p. 470.

UK Technical Advisory Group on the Water Framework Directive 2019. UKTAG Paper 11b (i) – Guidance on Groundwater Chemical Classification. https://wfduk.org/sites/default/files/UKTAG%20Paper%2011b%28i%29%20Guidance%20on%20Groundwater%20Chemical%20Classification%20-FINAL%2020190402%20-%20amended%2020191001.pdf

Vannmiljø (n.d.). https://vannmiljo.miljodirektoratet.no/

Vann-Nett Portal. (n.d.). https://vann-nett.no/portal/

Vannportalen (2023, December 8). Regionale vannforvaltningsplaner 2022-2027 med tilhørende dokumenter [Regional RBMPs with related documents 2022-2027]. https://www.vannportalen.no/plansyklus/planperioden-2022---2027/

Velstra, J.D., 2005. Guidelines on groundwater for the WFD Slovakia – guidelines for the implementation of the groundwater aspects of the water framework directive in Slovakia. Project number 9P1342, Client EVD N. van der Straaten. 123 pp. Reference 9P1342/R00001/JoVe/Amst

Vannportalen. (2018). Klassifiseringsveileder 02:2018: Klassifisering av miljøtilstand i vann. Økologisk og kjemisk klassifiseringssystem for kystvann, grunnvann, innsjøer og elver *[Classification guide 02:2018: Classification of environmental condition in water. Ecological and chemical classification system for coastal waters, groundwater, lakes, and rivers]*. Retrieved from https://www.vannportalen.no/veiledere/klassifiseringsveileder/